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Bulletin 255

Night Visibility: 1960

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Bulletin 255

Night Visibility: 1960

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Contents

Traffic Operations as Related to Highway Illumination and Delineation

A. TARAGIN, Chief, Traffic Performance Branch, U.S. Bureau of Public Roads, Washington, D.C.; and BURTON M. RUDY, Senior Highway Engineer, Connecticut State Highway Department, Wethersfield

Increasing construction of freeways has stimulated much discussion of highway illumination and its possible value in providing more comfortable night driving, in the possibility of increasing night usage of the highway, and in reducing traffic accidents. Because of lack of factual knowledge on the subject, the Connecticut State Highway Department in cooperation with the U.S. Bureau of Public Roads undertook a comprehensive study of illumination and delineation on the Connecticut Turnpike. Driver behavior data were recorded under nine different conditions of highway illumination and delineation at one onramp and one offramp on a mercury-illuminated section of the Connecticut Turnpike. Accident data were obtained on the 53-mi continuous illuminated section and on the 76-mi nonilluminated section.

For the various conditions of illumination and delineation, the results showed no significant differences with respect to average vehicle speeds, lateral placements, and clearances between vehicles. The manner of night use of speed change lanes, particularly the acceleration lane, improved with increased illumination. In general, it appears that some beneficial results of illumination in the deceleration area are derived when it is used at the full level and that even greater service is provided when illumination is combined with roadside delineation; and that illumination of the "interchange area only" does not appear to be advantageous insofar as the onramp site is concerned. The importance of delineation, with or without illumination, is demonstrated.

Analysis of the accident data for the lighted and unlighted sections of the Connecticut Turnpike did not provide conclusive results because of the extreme variance in traffic volumes and other characteristics.

●TRAFFIC AT night has always had accident rates which average about twice that of day rates. Awareness of the magnitude of this problem and increased efforts to develop remedial measures, stems not from any significant changes in this problem, but rather from the greater accident rates at night and from the rapid growth in annual vehicle-miles of travel. Night driving involves not only the problems of darkness, but hazards of fatigue, drowsiness, and other factors. The ultimate solution in avoiding darkness, of course, would be to illuminate the roadways at night to the same intensity as exists during daylight, but this is obviously an impractical approach. It remains to be determined, therefore, at what level of illumination would drivers operate their vehicles at night in the same manner as they do during daytime.

Although it is an accepted fact that good visibility is a prerequisite in good traffic operations, there have been no accredited warrants set forth for highway lighting. Similarly, there has been no correlation between the effects on traffic operations of delineation (reflector buttons) and illumination.

BACKGROUND

Increasing construction of freeways has increased the demand for highway lighting installations. Little is known on the effectiveness of highway lighting on freeways with respect to driver behavior, accidents, night use, and capacity. The subject of highway lighting and its effect on highway capacity, accidents, and driver behavior was discussed during the January 1958 Annual Meeting of the Highway Research Board by representatives of the U.S. Bureau of Public Roads, Connecticut State Highway Department and the Night Visibility Committee of the Board. It was generally agreed that there was a lack of data on the subject and that it would be desirable to conduct the needed research.

The importance of highway lighting is of such magnitude that the executive committee of the American Association of State Highway Officials assigned their committee on Planning and Design Policies to prepare a report on lighting controlled-access highways. This matter was discussed in detail during the October 1959 annual meeting of AASHO and their deliberations resulted in the distribution of a preliminary guide on highway lighting for use by the member States of the Association.

Construction of the 129-mi long Connecticut Turnpike with continuous highway lighting scheduled for 53 mi, presented an unusual opportunity to obtain factual data of the effects of illumination and delineation on traffic operations. The Connecticut State Highway Department in cooperation with the U.S. Bureau of Public Roads initiated such a study during the spring of 1958, and the results are described herein.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the effectiveness of highway lighting per se, with roadside delineation, with pavement markings and with combinations of these under full, partial, and no illumination. The effects to be ascertained would be those manifested in accidents, and in drivers' actions, such as speeds, lateral placements, headways, lane use and utilization of acceleration and deceleration lanes. A total of some 183,000 vehicles were observed under nine principal study conditions. This multitude of data could not be treated by normal tabulating procedures and the data were processed by high-speed electronic equipment.

STUDY SITES

When first conceived, the study was to include tangent, curve, grade, bridge, onramp and offramp sections, both in fluorescent- and mercury-illuminated areas. However, time limitations later dictated that studies should be limited to a smaller number of locations.

The nine variable conditions selected for study at these sites were as follows:

No Illumination

1. Lane lines only.
2. Lane lines and edge lines.
3. Lane lines, edge lines and delineation.

Half Normal Illumination

4. Lane lines, edge lines and ½ normal illumination.
5. Lane lines, edge lines, delineation and ½ normal illumination.
6. Lane lines, edge lines, delineation and ½ normal illumination in interchange area only.

Full Illumination

7. Lane lines, edge lines, delineation and normal illumination in interchange area only.
8. Lane lines, edge lines and normal illumination.
9. Lane lines, edge lines, delineation and normal illumination.

The white reflectorized 6-in. wide lane lines were dashed, with both the dashes and spaces being 25 ft long. All edge lines were reflectorized, solid white to the left of the traffic stream and solid yellow to the right. Six-inch widths were used on the Turnpike proper, whereas 4-in. widths were used on the ramps.

Delineation consisted of acrylic plastic reflex reflectors, 3 in. in diameter mounted at a height of 4½ ft above the pavement, about 12 ft from the pavement edge on the shoulder side and about 5 ft on the median side, spaced at 200-ft intervals on the Turnpike and at reduced spacings on the ramps. Installations on the Turnpike consisted of single white reflectors on both sides of the roadways whereas dual amber reflectors were used on both sides of the ramps.

Highway lighting consisted of mercury luminaires throughout. Specific details of installation are shown later.

Conditions 1, 2 and 8 were observed during 1958 (Table 1). The analyses of the data for these three conditions, which were initiated immediately following the start of field observations, indicated the necessity for streamlining the program of studies so that a worthwhile report could be completed in a reasonable period of time. Accordingly, it was agreed to limit the study of all nine conditions to the onramp (site 4M) and offramp (site 5M) in one interchange with appreciable ramp volumes. This was accomplished during the summer of 1959. This concept evolved from the premise that of all the locations originally selected for study, these two sites would reveal the most significant effects evidenced by the nine conditions of the study.

The Connecticut Turnpike is a multilane freeway with full control of access which stretches from the New York State line in Greenwich easterly 129 mi to its intersection with US 6 at the Rhode Island State line in Killingly (Fig. 1). It serves primarily as an urban arterial in its westernmost 53 mi where the road way follows the general coastline and is comprised basically of three 12-ft portland cement concrete lanes either side of a median that varies in width from 4 ft to 30 ft. East of the 6-lane sec-

TABLE 1

TRAFFIC DISTRIBUTION BY LANES

Condition		Day					Night				
		Total Traffic	Percent of Total Traffic in				Total Traffic	Percent of Total Traffic in			
No.	Description	(vph)	Ramp	Lane 1	Lane 2	Lane 3	(vph)	Ramp	Lane 1	Lane 2	Lane 3
	(a) Site 4M										
1.	Lane lines only	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2.	EM	672	51.0	22.6	21.3	5.1	313	48.4	29.5	18.4	3.7
3.	D-EM	1236	36.8	17.8	34.0	11.4	491	35.6	27.7	29.8	6.9
4.	EM-½ LTS	1219	42.4	19.1	27.6	10.9	519	35.2	23.1	27.0	14.7
5.	D-EM-½ LTS	1174	38.7	17.1	34.7	9.5	580	40.0	20.8	31.6	7.6
6.	D-EM-½ 1 LTS	1264	40.6	19.2	30.8	9.4	553	37.0	21.7	34.4	6.9
7.	D-EM-1 LTS	1096	40.5	20.0	30.3	9.2	533	38.5	23.1	30.4	8.0
8.	EM-LTS	798	52.0	21.6	21.2	5.2	376	28.5	47.0	20.0	4.5
9.	D-EM-LTS	1296	39.8	19.0	31.1	10.1	576	40.3	22.0	30.9	6.8
	Average	1094	42.7	19.6	28.9	18.8	494	37.9	26.9	27.8	7.4
	(b) Site 5M										
1.	Lane lines only	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2.	EM	629	38.8	17.2	32.6	11.4	420	48.9	21.4	24.5	5.2
3.	D-EM	1503	47.2	10.7	26.0	16.1	666	44.2	20.8	27.9	7.1
4.	EM-½ LTS	1509	51.2	10.6	22.8	15.4	570	45.1	19.8	24.5	10.6
5.	D-EM-½ LTS	1488	48.6	10.7	24.5	16.2	656	49.2	14.8	26.9	9.1
6.	D-Em-½ 1 LTS	1478	48.4	11.7	25.4	14.5	563	47.0	22.0	24.4	6.6
7.	D-Em-1 LTS	1567	48.4	10.8	25.5	15.3	582	43.8	22.0	27.2	7.0
8.	Em-LTS	1401	46.5	10.7	27.1	15.7	810	59.8	18.4	17.5	4.3
9.	D-Em-LTS	1443	47.7	10.8	25.6	15.9	588	48.5	17.8	27.2	6.5
	Average	1377	47.1	11.6	26.2	15.1	607	48.3	19.6	25.0	7.1

Note: D = Roadside delineation.
E = Pavement edge markings.
LTS = Normal highway illumination.
½ LTS = ½ Normal highway illumination.
1 = Highway illumination in interchange area only.
NA = Not available.

tion, the Turnpike is a 4-lane divided arterial with a considerable mileage of bituminous concrete pavement. This section continues to follow the coastal line to its east intersection with US 1 and US 1A in the New London area where it turns to a northeasterly course.

The whole 53-mi section of the Turnpike west of Cherry Hill Road in Branford (about 8 mi east of New Haven), and all adjoining ramps were illuminated to a level of 0.8 foot-candle maintained on the mainline and onramps and a somewhat lower level on the offramps. East of this area illumination is confined to the more heavily traveled interchange areas.

It is of further interest to note that the western section of the Turnpike traverses the central or inner business districts of many cities and in some instances serves as a primary crosstown artery. The eastern section crosses the less densely populated areas although quite close, time-wise, to the central business districts.

The general area of study was the West Broad Street interchange in the Town of Stratford (Fig. 2). This location was selected because of the relatively high traffic volumes present and the relative ease in changing light intensities. Average daily traffic volumes on the Turnpike just west of this interchange are 17,000 vehicles in each direction. Close to 7,000 of the eastbound vehicles exit via the offramp to West Broad Street. Similarly, some 7,000 of the vehicles traveling in the opposite direction originate from the westbound access ramp. The 6-lane pavement is portland cement con-

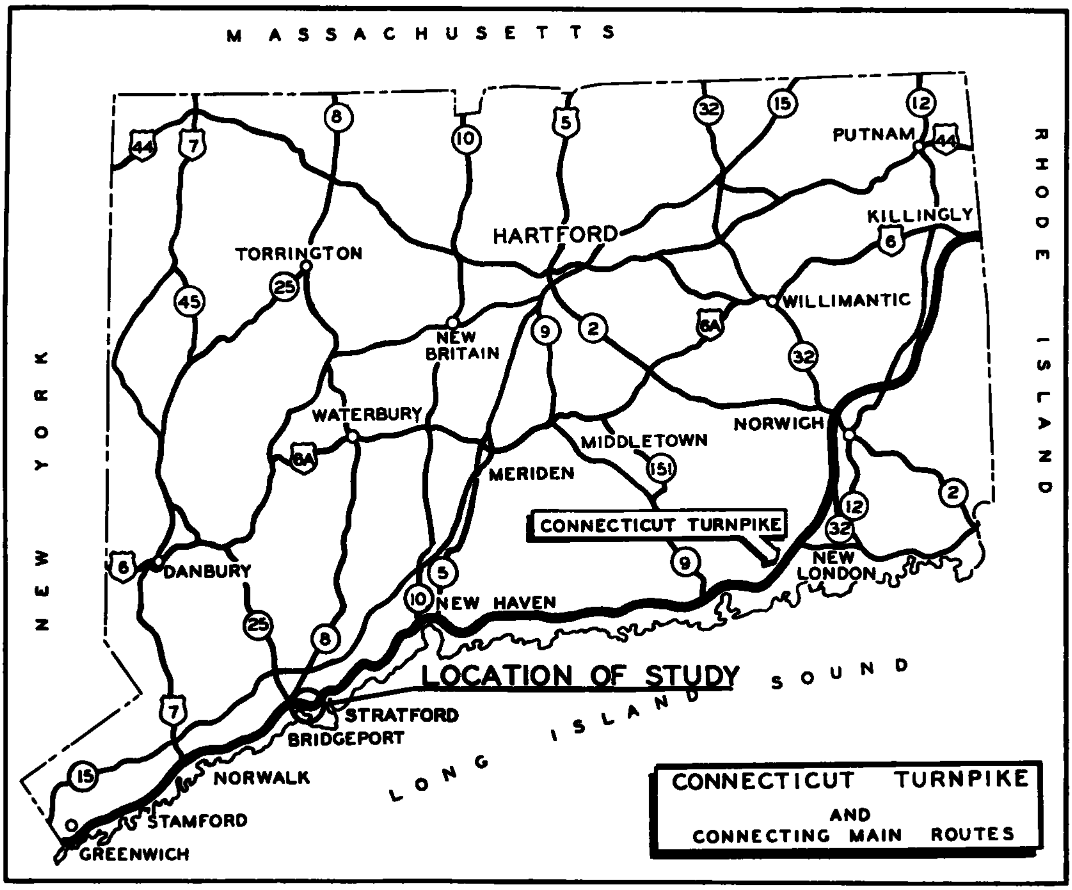

Figure 1. Location of study.

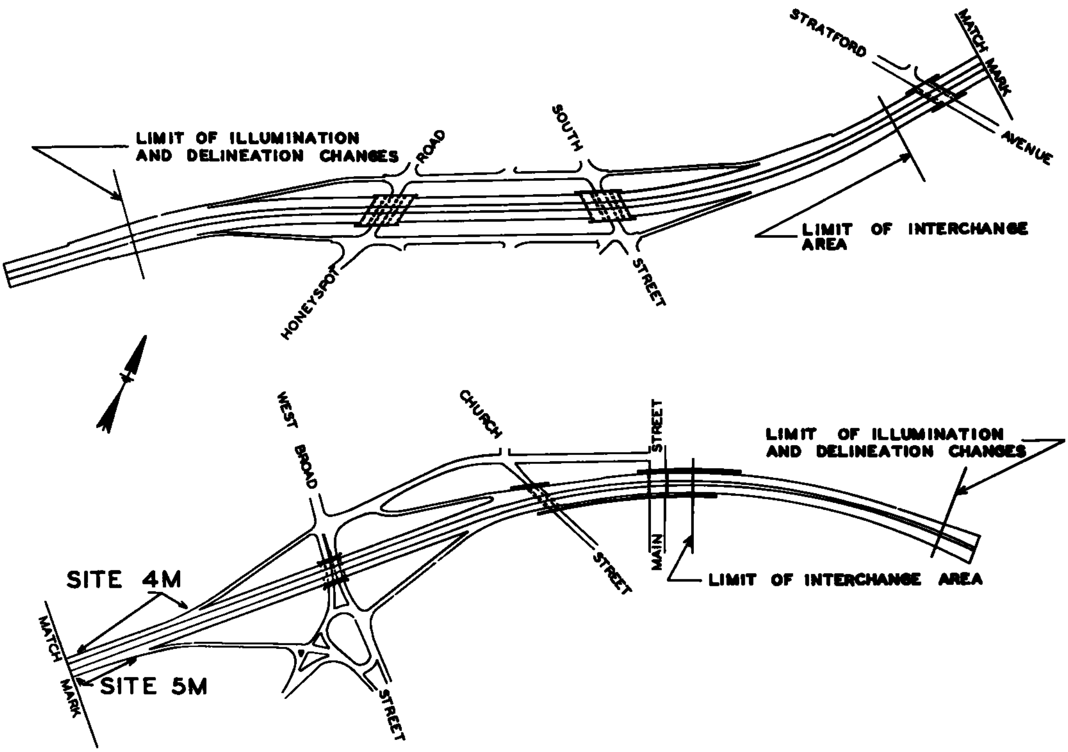

Figure 2. Plan of general study area.

crete with 2-ft wide bituminous concrete gutter strips and 10-ft wide bituminous concrete shoulders. The depressed grass median in this location averages 30 ft in width. An important item shown in Figure 2 is the limit of illumination and delineation changes and the limits of the interchange area. Lights were controlled within these limits.

Specific observations were obtained at both the westbound onramp and the eastbound offramp. Figure 3 shows the roadway geometry and details of the pavement markings, illumination, delineation, positions of the recording and detecting equipment, and the locations of the informatory and regulatory signs in the vicinity of the study sites. Figure 4 shows the view of the onramp site (4M) looking easterly on the westbound lanes. Figure 5 shows a similar view of the offramp site (5M) on the eastbound lanes.

The one-half normal level of illumination for conditions 4, 5 and 6 was achieved by changing lamps and ballasts as well as by using specially constructed lamps with the existing ballasts. The actual levels of illumination achieved were determined by the standard practice for measurement as recommended by the Illuminating Engineering Society. The actual values measured by the light meter and the calculated average foot-candles of illumination are shown in Figures 6 and 7. Generally, the ratio of the average to the minimum is 4 or 6 to 1. The different appearances of the highway under the two levels of illumination were readily discernible visually (Figure 8 shows normal illumination and Figure 9 shows half normal illumination).

FIELD OBSERVATIONS

The equipment utilized to record observed data was the Mobile Traffic Analyzer designed and constructed by the U.S. Bureau of Public Roads. During the field work, this vehicle was parked on specially constructed platforms located behind the wire rope railing (Fig. 10).

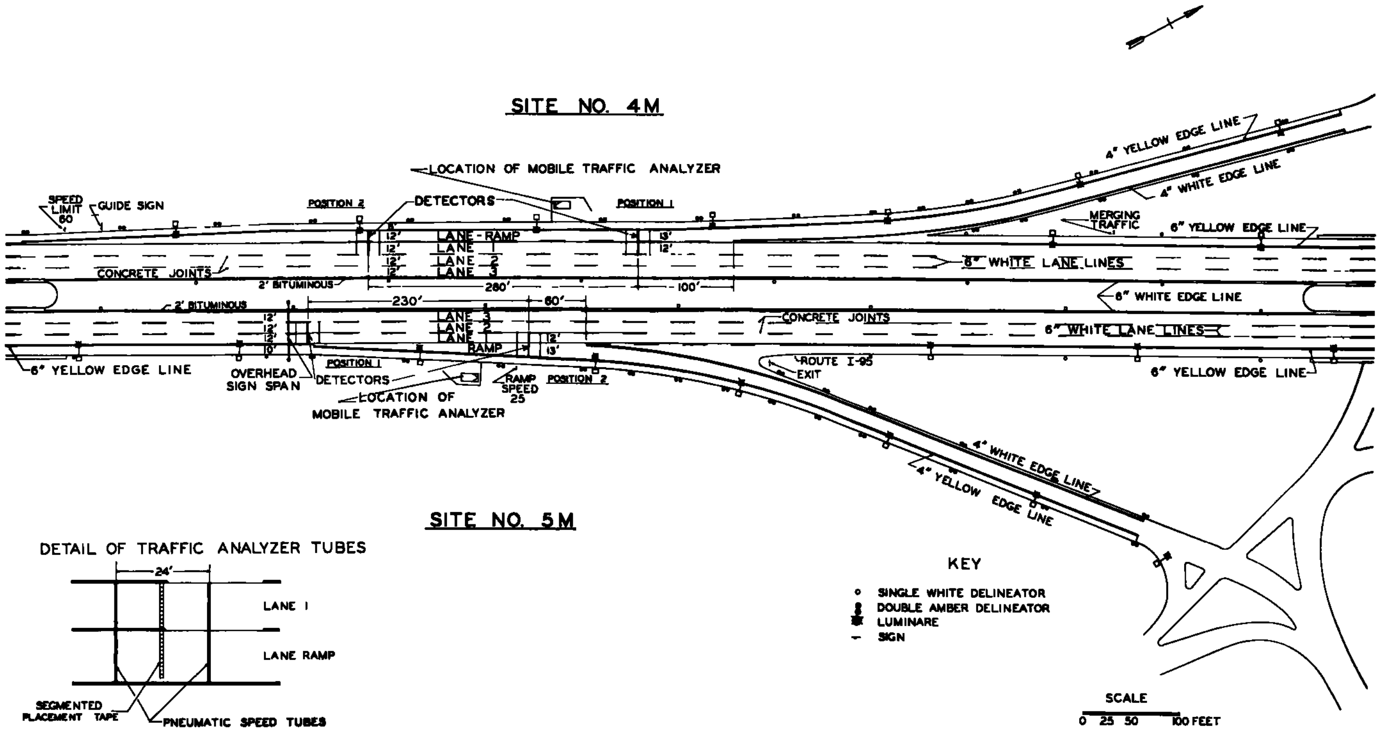

Figure 3. Plan of study sites.

Figure 4. Study site 4M.

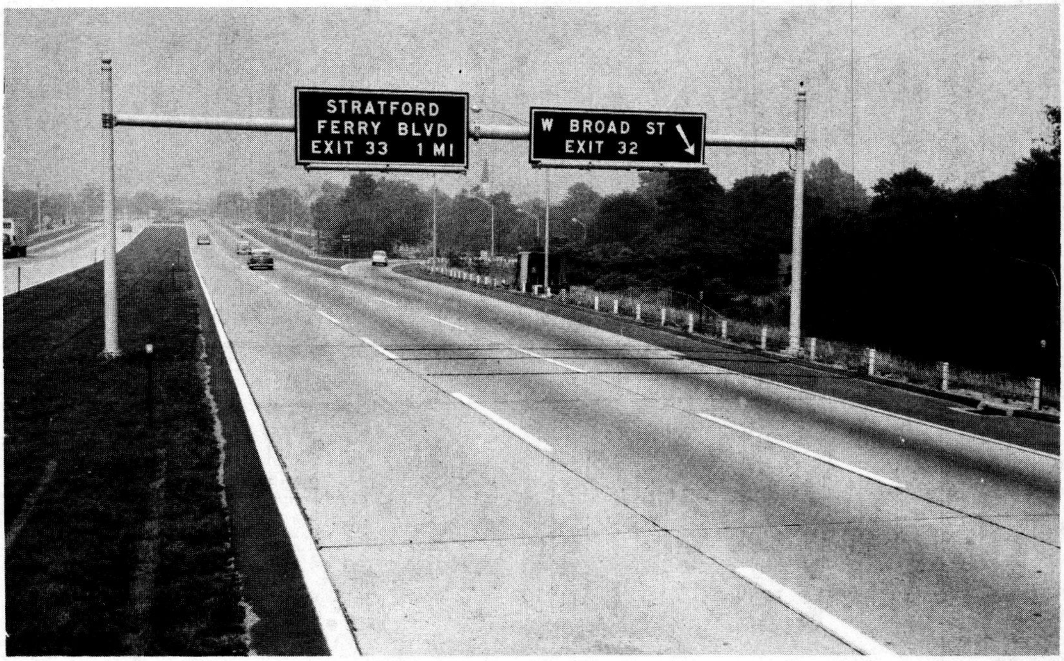

Figure 5. Study site 5M.

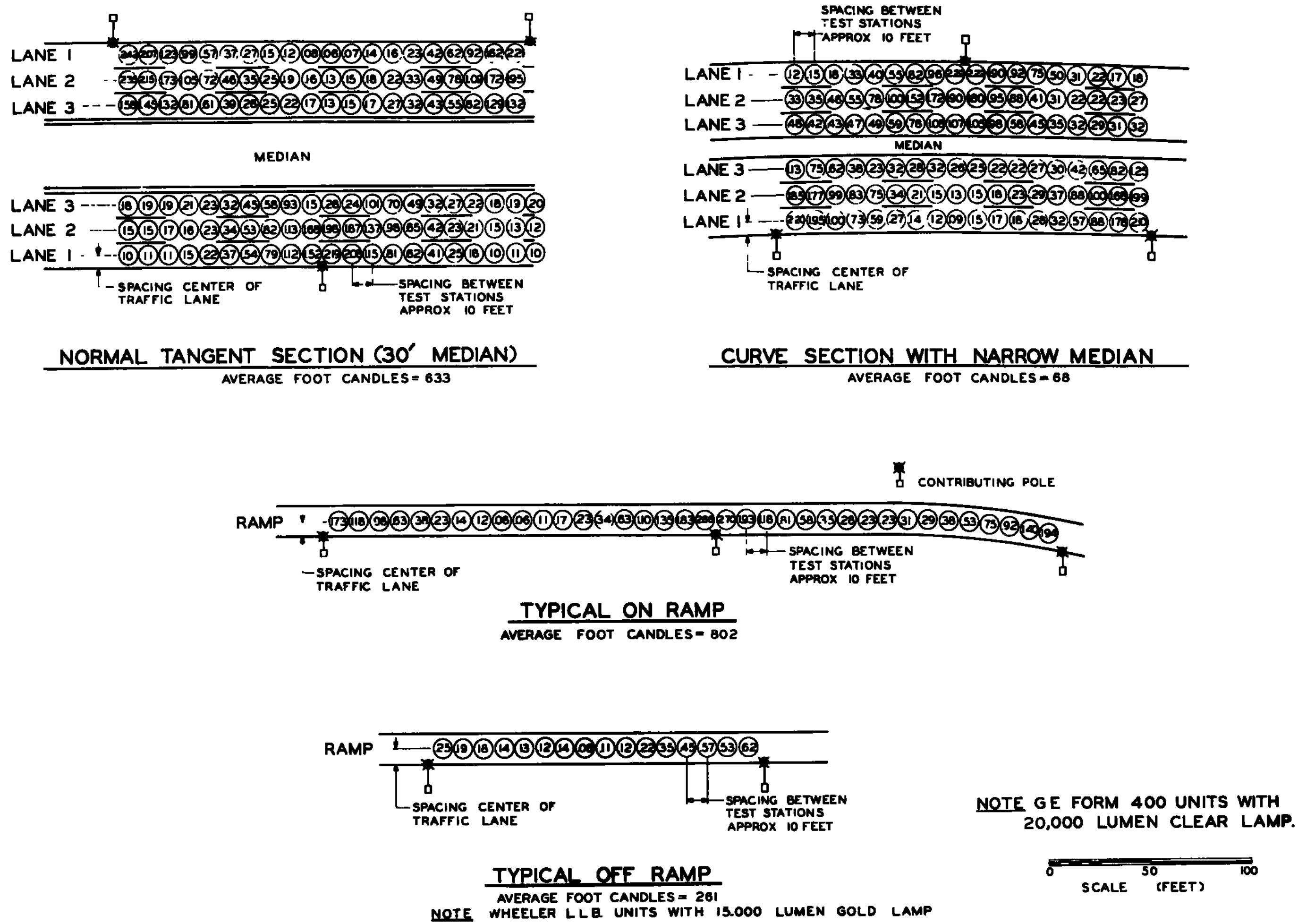

Figure 6. Measured illumination values, normal illumination.

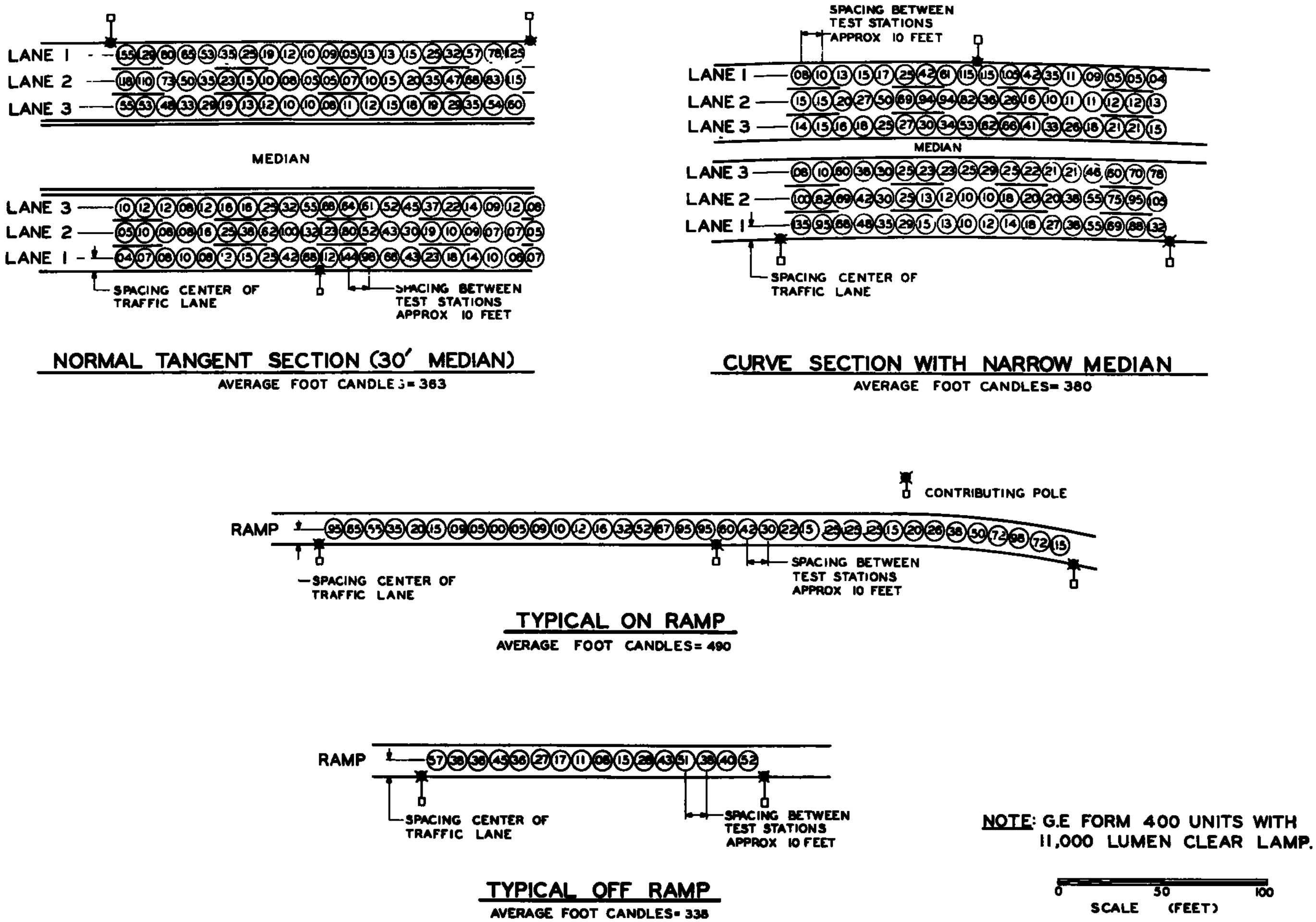

Figure 7. Measured illumination values, one-half normal illumination.

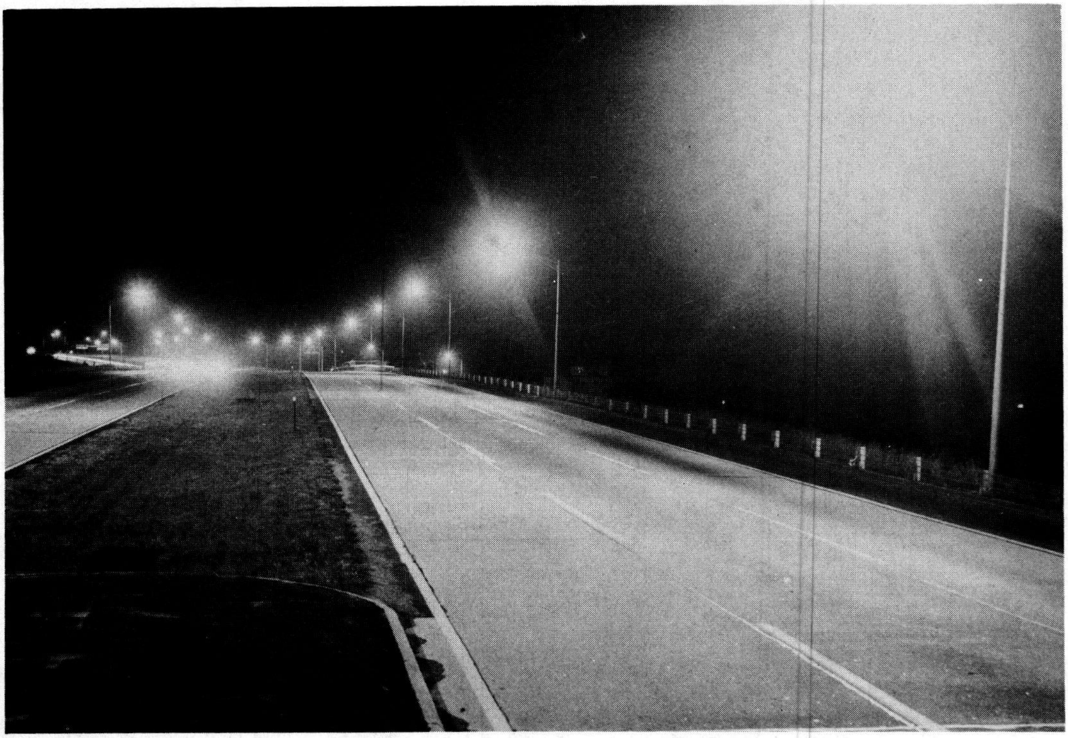

Figure 8. Normal illumination.

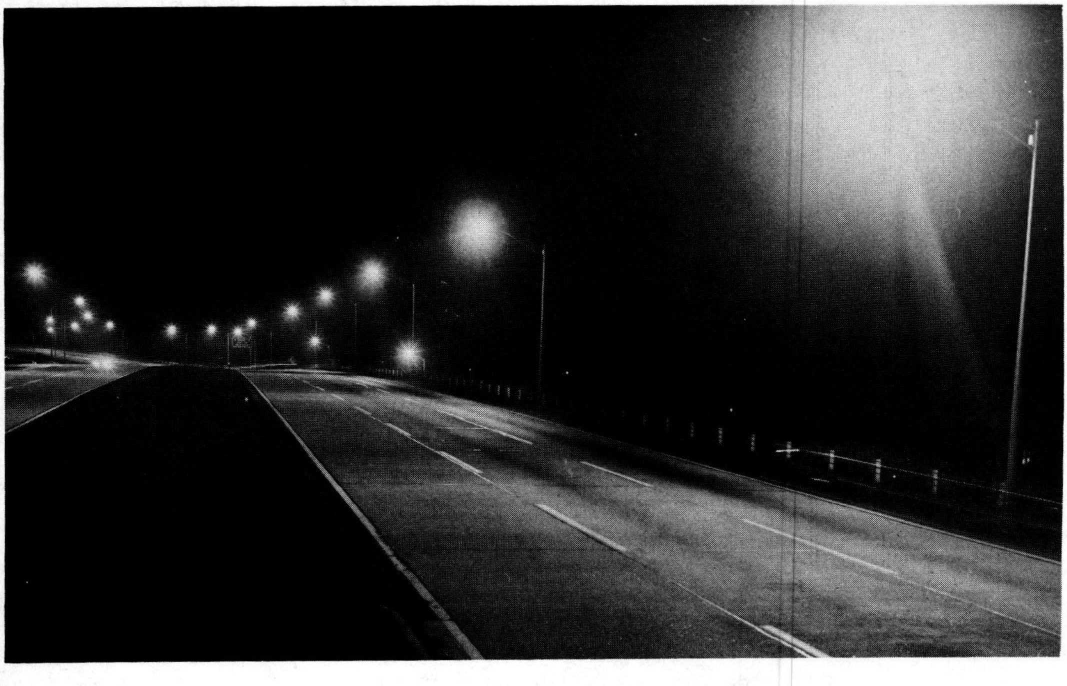

Figure 9. One-half normal illumination.

Figure 10. Mobile traffic analyzer—location at site 4M.

Specific equipment included four solenoid-operated adding machines, chronometer, telegraph keys, and other supporting equipment, all electronically interconnected and housed in a revamped delivery truck (Fig. 11). The major portion of the data was recorded by a crew of nine persons, four machine operators plus a supervisor located inside the vehicle and four others located outside, but in the immediate proximity of the vehicle. Electronic impulses were received via multiconductor cables which connected the recording apparatus to its detectors at the four locations in each site. Observations were made during both daylight and darkness for each day of the study and the number of observations for each traffic maneuver are given in Tables 7 and 8.

Data recorded automatically consisted of speed, lateral placement (from which lateral clearances between vehicles were calculated) and time of day to the nearest $^1/_{10,000}$th of an hour (from which traffic maneuvers and headways were calculated). The observers operated certain keys manually to introduce onto the recording tapes such items as vehicle classification and drivers' actions in the merging and diverging areas.

At both sites, complete data were recorded mechanically at each of four positions (Fig. 3); one set of road tubes was placed in lane 1 (curb lane) and on the onramp near both the beginning and end of the acceleration lane (site 4M); also, in lanes 1 (curb) and 2 (middle) near the beginning of the deceleration lane and in lane 1 and the offramp near the gore area (site 5M).

Simultaneously with the traffic analyzer, observers recorded the manner in which drivers utilized the acceleration and deceleration lanes including various driving actions such as use of brakes, sudden slowdown, etc. Volumes and lane changing were also recorded for those lanes not fitted with detector tubes.

Accident data were obtained by close liaison with the Connecticut State Police with specific information coming from accident reports submitted by their investigating troopers. This information was compiled for both illuminated and nonilluminated areas. The only period of Turnpike accidents considered for comparative analyses was the first eight months of 1959. Data prior to this date on the Turnpike are not considered too indicative because of the partial openings to traffic in 1958. The accident information for the Merritt Parkway and for all state highways combined, was obtained from the last full year of accident tabulations available from motor vehicle reports at the present time.

ANALYSES AND DISCUSSION OF DATA

In the analyses of speeds and lateral placements, the vehicles were grouped into two main categories: passenger cars and commercial vehicles. Each of these were then classified as to their proximity to other vehicles on the roadway. These consisted of the following: (1) free moving, (2) adjacent and not trailing, (3) adjacent and trailing, (4) trailing and not adjacent, and (5) all others.

Free-moving vehicles are those whose longitudinal spacing to the nearest vehicle (ahead or behind) in any lane is more than 7 sec.

Adjacent vehicles are those whose longitudinal spacing to the nearest vehicle in an adjoining lane is 1.4 sec or less.

Trailing vehicles are those whose longitudinal spacing to the preceding vehicle in the same lane is 3 sec or less.

Volumes

The volumes passing through the study sites and their distribution by lanes are given in Table 1. It will be noted that for nearly all conditions of study, the ramp carried more traffic than any other single lane and that lane 3 (the median lane) generally carried the least amount of traffic. Lane 2 (middle lane) carried about twice as many vehicles as did lane 1 (curb lane). It appears, therefore, that the selection of these ramps as study sites were appropriate.

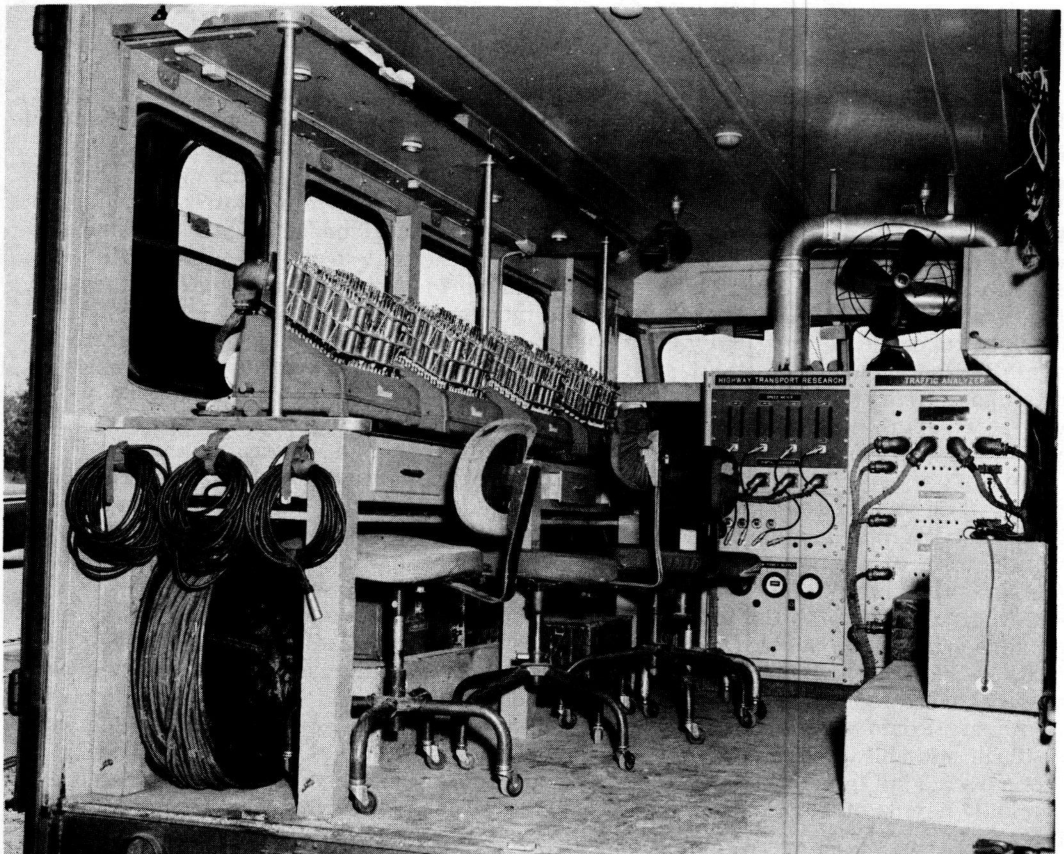

Figure 11. Mobile traffic analyzer—interior view.

Daytime volumes observed were greater than those at night mainly because of the normal distribution at the time of the year studied. This was further accentuated because the daytime observations embraced the late afternoon peak hour.

TABLE 2

COMMERCIAL TRAFFIC[1]

Condition	Site 4M Day	Site 4M Night	Site 5M Day	Site 5M Night
Lane lines only	22	23	12	17
EM	16	17	10	13
D-EM	10	15	7	12
EM-½ LTS	11	15	7	13
D-EM-½ LTS	16	13	9	10
D-EM-½ 1 LTS	11	11	9	13
D-EM 1 LTS	11	11	5	8
EM LTS	14	12	10	15
D-EM-LTS	9	12	8	8
Average	12.4	12.6	8.6	12.1

[1]Percent of total volumes.

Table 2 indicates that commercial traffic accounted for an average of some 12 percent of the total vehicles passing through site 4M and 10 percent through site 5M. The values ranged from 9 to 23 percent at site 4M and 5 to 17 percent at site 5M. From an analysis of data not given in tables, it was found that the through traffic streams carried a higher percentage of commercial vehicles. The smaller percentage and lesser amount of commercial vehicles passing through the offramp site (5M) is due in part to the location of a toll plaza easterly of this area and in part to the fact that the preceding exit ramp leads more directly to US 1 in Stratford.

Speeds

There does not appear to be any significant relation between vehicle speeds and the nine conditions of this study. The summary data are shown in Figures 12 and 13 and Table 3. Variations among daytime speeds were as great or greater than between day and night of a particular day, or for that matter, between night observations on different dates (Tables 9 and 10). These analyses hold true for passenger cars as well as commercial vehicles and for the various categories of traffic maneuvers such as free-moving, trailing, adjacent, etc.

The difference between the average speeds for the nine conditions rarely exceeded 3 mph, and was usually 1 mph, for any single combination of site, location, lane and light condition. Table 3 gives these comparisons for through passenger cars. These vehicles were observed in the curb lane for the onramp site and the middle lane for offramp site, because these lanes carried the greatest proportion of through vehicles.

A review of the distributions of observed speeds indicated that the percentage of through passenger cars traveling below 40 mph might provide a good index for comparing the relative advantages of the several conditions of study. The index derived for each condition of study was the variation (expressed in percent) of the percentage of nighttime vehicles traveling below 40 mph from the percentage of the total daytime vehicles observed at the same site traveling below 40 mph during the average day. For example, if 35 percent of the vehicles traveled below 40 mph during the "average day" and 30 percent of the vehicles traveled below 40 mph at night for a given condition, the percent variation was -14 percent. If the nighttime percentage of vehicles traveling below 40 mph is lower than the daytime figure, then the variation is minus. In the converse case, the variation would be plus. The seemingly large values that appear for some conditions in Figures 14 and 15 result usually from the fact that during the daytime the average percent of observed speeds below 40 mph is quite low. Figure 14 shows the results for the onramp, site 4M. The least percent variation occurred for conditions of normal illumination with and without delineation, half level of illumination with delineation, and no illumination with delineation. Illumination in the interchange area only with delineation for both conditions resulted in greater variances. It appears that at this site, roadside delineation exhibits strong influence toward maintaining

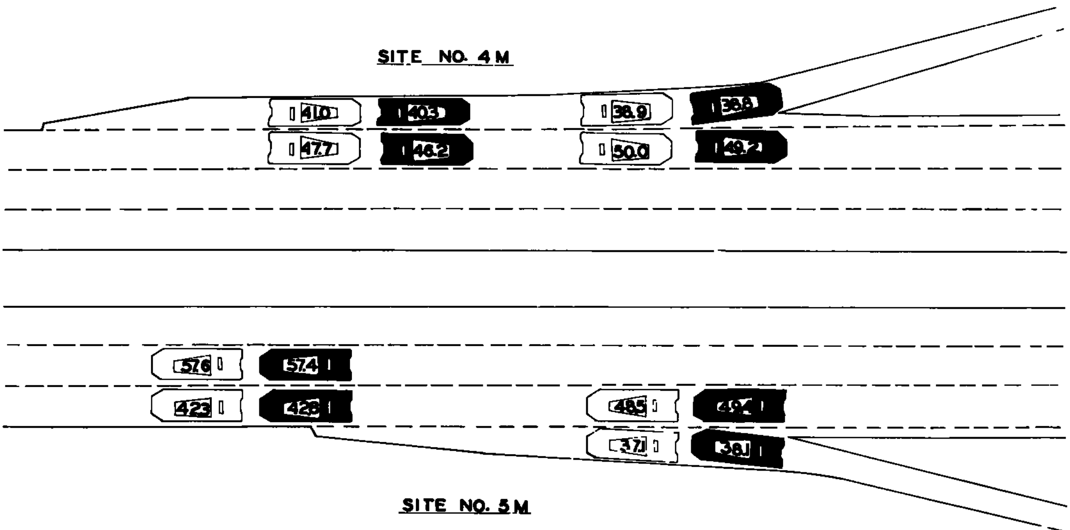

Figure 12. Average speeds for passenger cars (mph, day and night).

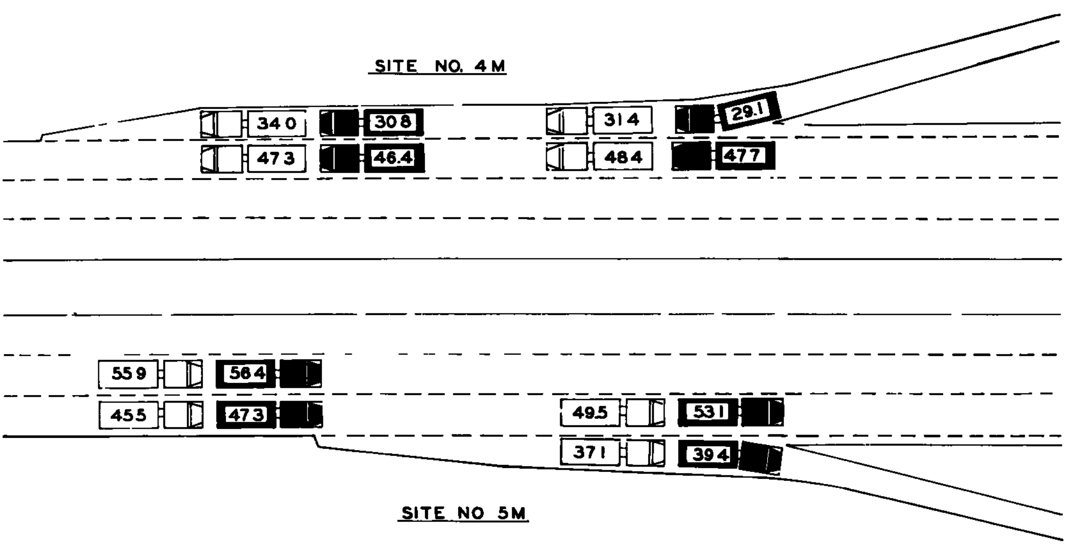

Figure 13. Average speeds for commercial vehicles (mph, day and night).

TABLE 3

SUMMARY OF AVERAGE SPEEDS, PLACEMENTS AND CLEARANCES FOR THROUGH PASSENGER CARS ONLY

Conditions of Study[1]	Near the Onramp(Site 4M)						Near the Offramp(Site 5M)					
	Speed		Placement[2]		Clearance[3]		Speed		Placement[2]		Clearance[3]	
	Day (mph)	Night (mph)	Day (ft)	Night (ft)	Day (ft)	Night (ft)	Day (mph)	Night (mph)	Day (ft)	Night (ft)	Day (ft)	Night (ft)
1. Lane lines only	49.8	47.0	6.6	6.1	6.9	6.2	55.9	57.2	6.4	6.0	8.6	8.0
2. Edge markings	51.3	48.1	6.7	6.8	7.4	6.8	56.8	56.5	6.7	6.5	8.0	7.3
3. Edge markings and delineation	49.2	47.2	6.7	6.4	7.4	7.0	58.5	57.7	6.8	7.2	8.3	8.3
4. Edge markings and ½ illumination	50.3	51.2	6.9	6.4	7.4	6.2	57.5	58.4	6.8	6.9	8.4	8.0
5. Edge markings, delineation and ½ illumination	50.8	50.0	6.5	6.5	7.1	7.8	56.9	55.5	6.6	6.7	8.1	8.5
6. Same as 5, but ½ illumination in interchange area only	49.8	50.5	6.6	6.6	7.2	6.8	57.4	56.7	6.8	6.6	8.1	7.9
7. Same as 6, but full illumination in interchange area only	48.8	49.7	6.5	6.6	7.1	7.6	58.9	58.3	7.1	6.7	8.4	8.2
8. Edge markings and full illumination	51.0	49.0	6.9	6.5	8.3	7.6	59.1	58.5	6.9	6.9	8.2	8.4
9. Edge markings, delineation and full illumination	49.5	49.8	6.7	7.0	7.6	7.3	57.8	57.5	7.2	6.8	8.4	7.9
Average	50.0	49.2	6.7	6.5	7.4	7.0	57.6	57.4	6.8	6.7	8.3	8.1

[1]Lane lines were present for all conditions.
[2]Distance in feet center of car to right edge of lane.
[3]Clearance in feet between bodies of adjacent cars.

minimum speed differentials. Continuous illumination of the lower level exhibits no improvement over "no illumination."

The data for the offramp (site 5M) shown in Figure 15 revealed entirely different trends. It is found that a smaller percentage of "through passenger cars" traveled below 40 mph during nighttime than during daytime for all conditions except with edge and lane lines and half illumination. One possible explanation for the exception is that the reduced illumination in the area of heavy diverging maneuvers resulted in a loss of confidence and subsequent lowering of speed. Cumulative speed curves for each condition were compared to the similar curve for the "average day" at the pertinent site. The trends noted support the results in Figures 14 and 15.

Placements

The summaries of all placement data given in Tables 3, 11 and 12 indicate that the lateral placements of vehicles were not significantly different for the nine conditions of the study. There are certain trends indicated by the average day-night placements shown in Figures 16 and 17, but there was none that could be used as a criteria in evaluating the study conditions. Figure 16 shows the placements of passenger cars averaged for all nine conditions. The values shown are distances that centers of cars were from the right edge of lane at the specific points of study. The darkened silhouettes are for night observations. Figure 17 shows similar data for commerical vehicles. Interesting observations of the placement data are as follows:

1. All vehicles in the ramps at both sites generally traveled closer to the through lanes at night.

2. All vehicles in the lane nearest the ramp at both sites generally traveled closer to the right edge of pavement at night.

3. For passenger cars at the start of the offramp and near the end of the onramp, there was considerable difference between the average placements in the outer lane and the inner lane for both day and night observations.

Headways

It would be reasonable to suppose that the manner in which motorists select their position on the highway with relation to the preceding vehicle in the same lane would be a good measure of their confidence of operating conditions. The percent of the headways below 1.4 sec was selected as a criteria in evaluating the conditions of study because 1.4 sec is the approximate time equivalent of the recommended safe distance between vehicles traveling in the same lane at the posted speed of 60 mph. The percent of headways below 1.4 sec, between 1.4 and 2.8 sec, and over 2.8 sec are given in Table 13. A review of these data indicated no definite relation between the headway distributions and the various study conditions.

Clearances

The term "clearance" as used in this report relates to the lateral distance in feet between adjacent vehicles. Clearance measurements for through passenger cars are given in Table 3. The average clearances for all lanes are summarized in Table 14. Average clearances for the offramp (site 5M) were generally higher than those at the onramp (site 4M). As in the case of speeds, placements and headways, analyses of the average clearance for each study condition showed that they followed no set pattern and that the differences in clearances for the nine study conditions were small in magnitude.

Lane Use

The most significant findings of this study related to the way in which the motorists made use of the acceleration and deceleration lanes. Data for this phase of the analyses were obtained by manual counts. For this purpose the ramps were divided into

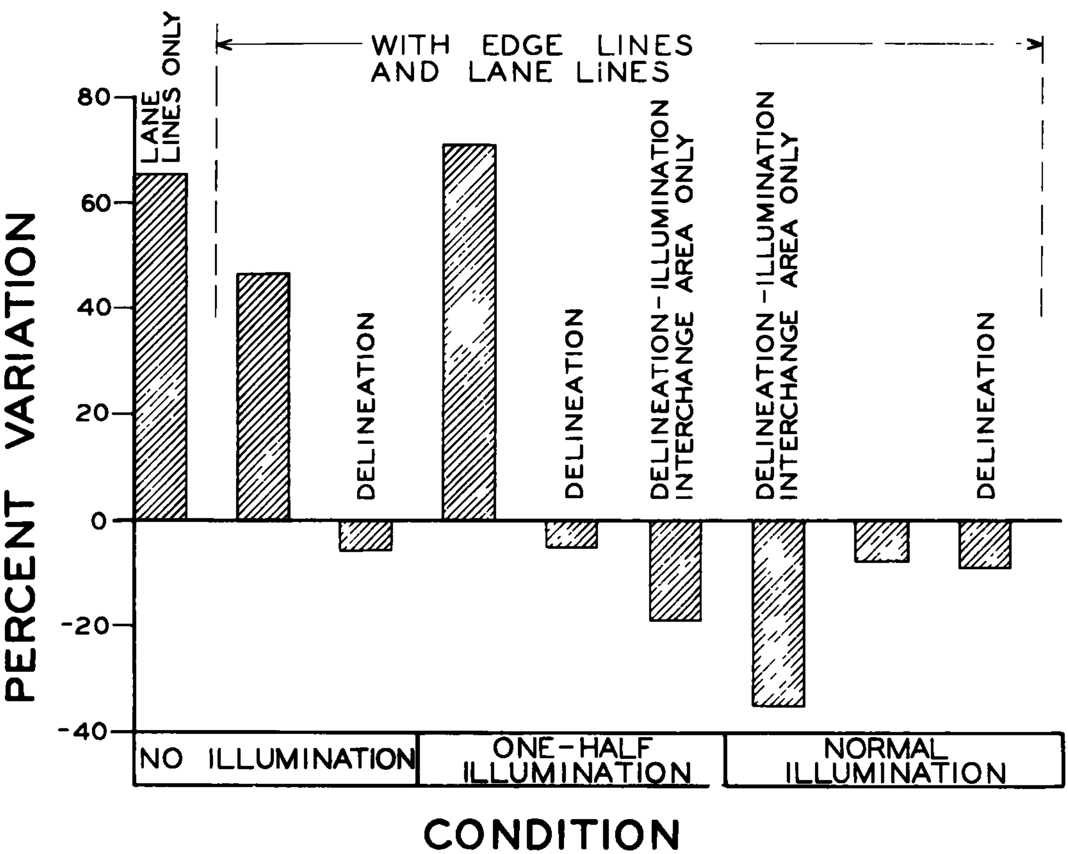

Figure 14. Site 4M near onramp—variation in percentages of speeds below 40 mph for through passenger cars only in the right lane (night from average day).

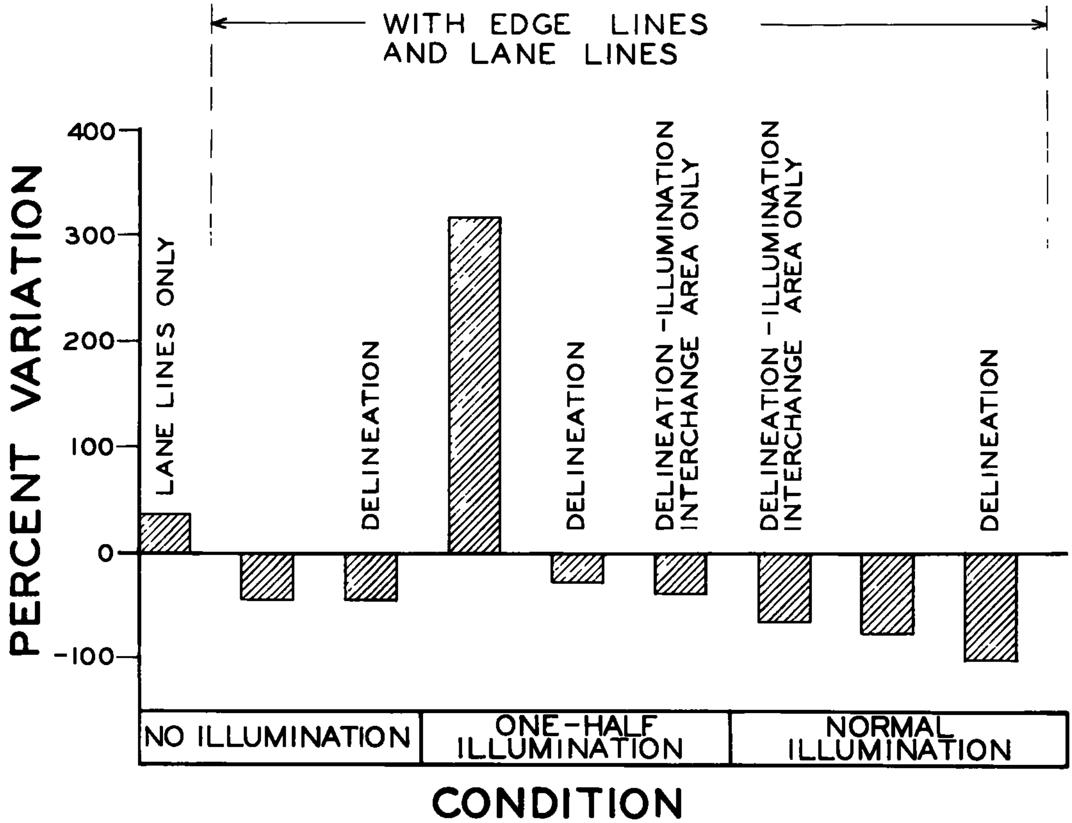

Figure 15. Site 5M near offramp—variation in percentages of speeds below 40 mph for through passenger cars only in the middle lane (night from average day).

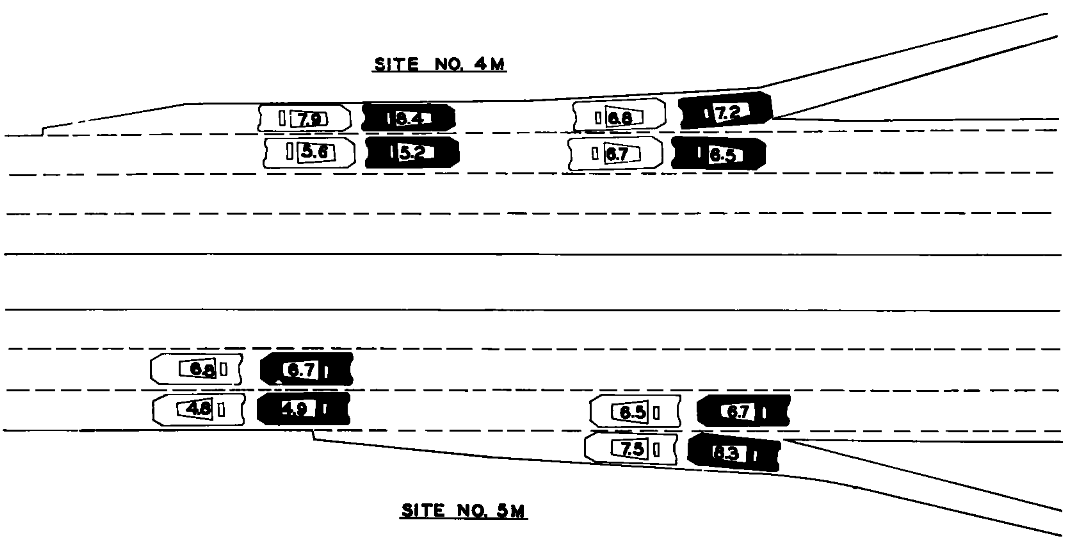

Figure 16. Average placements for passenger cars (feet, night and day).

three equal parts. Observers noted the number of vehicles using the onramp and the proportion of the length of the acceleration lane which was traversed by each vehicle before crossing to lane 1. The opposite movement was recorded at the offramp.

The percentage of the total vehicles crossing in each third of the lane for each condition at night was then paired with the similar figures for the "average day." The difference between each pair of percentages was then expressed as a percent of the "average day," and the percentages for the 3 sections of the speed change lanes were averaged. The averages of the three percent variations from the "average day" as thus determined are plotted in Figures 18 and 19 for each condition of study. The average percent variation is another measure of how close night operation approaches daytime operation.

For the onramp (site 4M), Figure 18 (data for condition 1 not available), it was found that under same conditions of delineation, drivers' use of the acceleration lane at night was directly related to the level of illumination. As the amount of illumination increased, night use of the acceleration lane more nearly approached daytime use.

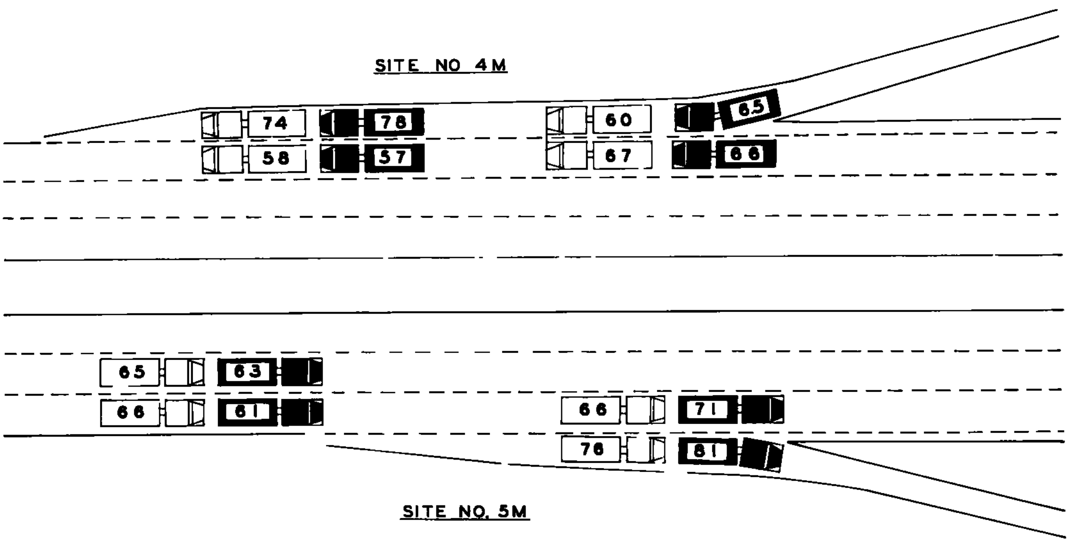

Figure 17. Average placements for commercial vehicles (feet, day and night).

For example, with delineation and no illumination night use was 37 percent different from the average day; with one-half illumination this variation dropped to 23 percent, and with full illumination the variation was about 17 percent.

In case of the deceleration lane (offramp site 5M), Figure 19 (data for condition 1 not available), shows that full illumination yielded the best results. One-half illumination on the average produced slightly larger variations from daytime operations than no illumination. The importance of delineation is again demonstrated.

The other maneuvers considered in relation to the manner in which the motorists made use of the acceleration and deceleration lanes were "use of brakes," "sudden deceleration," "cutting over," and "changing lanes." All observations in these categories revealed nothing of importance. There was more "sudden slowing" and use of "brake lights" at the offramp site 5M for the condition of only lane and edge lines than the others during hours of darkness. During daylight hours, there was an even higher total of such maneuvers at both study sites.

ACCIDENTS

Correlation of traffic operations with accidents was rather inconclusive because of the limitations of the data available at the time the study was concluded. Traffic vol-

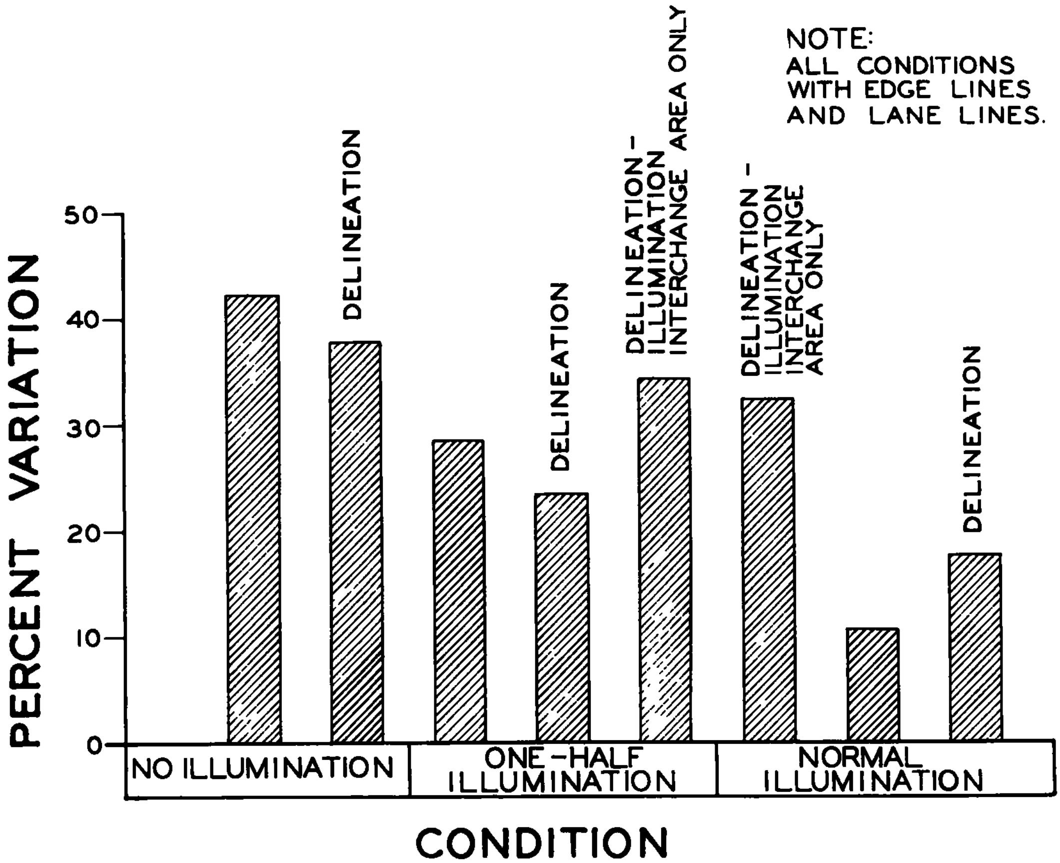

Figure 18. Site 4M—variation in percentages of use of acceleration lane (night from average day).

umes and other highway characteristics were different for the illuminated and nonilluminated section of the Turnpike. Incomplete roadway openings, general construction cleanup, etc., made it necessary to limit the surveillance of Turnpike accidents to the first eight months of 1959.

A summary of the general accident statistics for the "illuminated" and "nonilluminated" sections of the Turnpike are given in Table 4 along with similar data for the nonilluminated Merritt Parkway and all state highways.

The accident rates for both day and night travel on the Turnpike are considerably lower than either of the other facilities. This is to be expected because of the higher standard of design of this limited-access facility and its traffic appurtenances.

Analyses of the dark vs illuminated sections of the Turnpike reveal a slightly higher rate for the illuminated section during day and an appreciable higher rate for the illuminated section during night. On the illuminated area the night rate is 1.71 times that of the day rate; on the nonilluminated area the night rate is 1.36 times that of the day rate. The difference between the accident rates did not prove to be statistically significant. Also, they must be evaluated with respect to the wide variation in volumes and other characteristics between the dark and illuminated sections.

Analysis was then conducted of the relative exposure to accidents. This basically involved a comparison of the traffic volumes, frequency of ramp intersections, and general roadway features. Immediately it appeared that conditions in the illuminated section were considerably more conducive to accidents than in the nonilluminated sec-

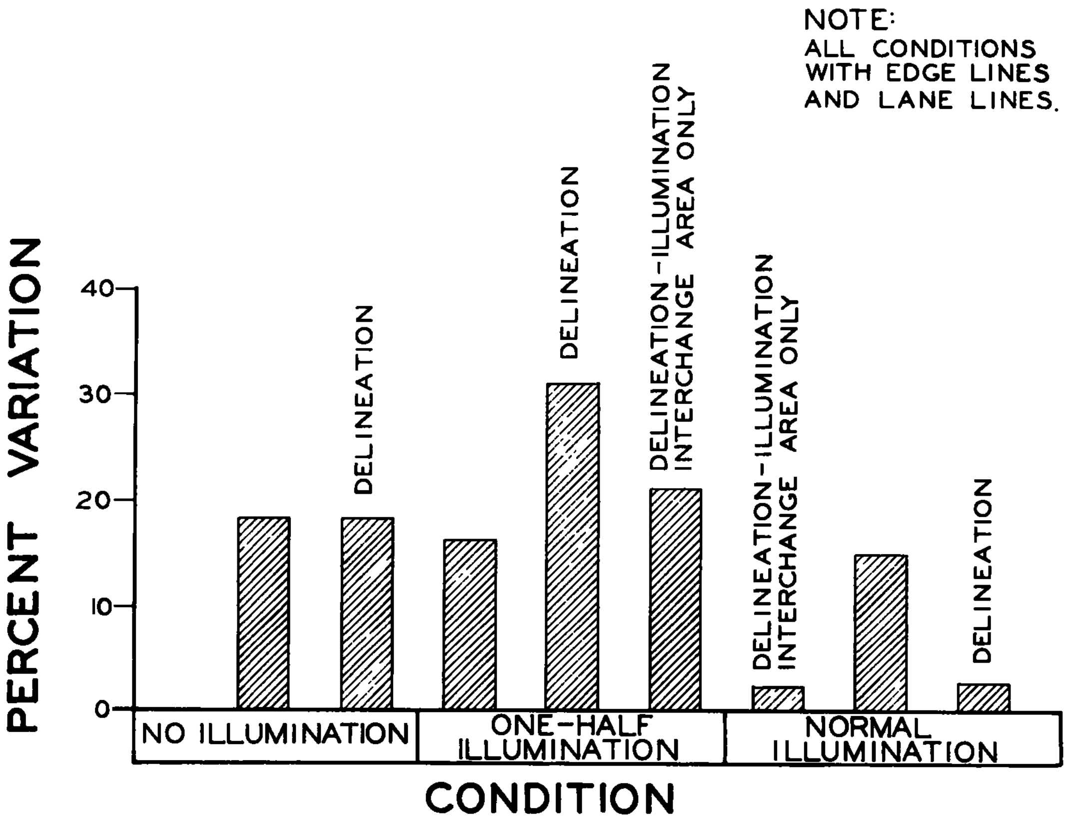

Figure 19. Site 5M—variation in percentages of use of deceleration lane (night from average day).

TABLE 4

ACCIDENT SUMMARY

CONNECTICUT TURNPIKE VS OTHER FACILITIES

		Vehicle-Miles (10^8)		No. of Accidents		Accident Rate (per 10^8 veh-mi)	
	Length	Day	Night	Day	Night	Day	Night
Connecticut Turnpike							
1/1/59 to 8/31/59 incl.							
Illuminated area	53.0	2.40	1.29	177	168	74	130
Non-illuminated area	75.69	0.99	0.53	71	52	72	98
Total	128.69	3.39	1.82	248	220	73	121
Merritt Parkway							
1/1/57 to 12/31/57 incl. (Non-illuminated)	37.46	3.45	0.97	493	402	142.9	414.4
All state highways							
1/1/57 to 12/31/57 incl.	3224.66	39.07	16.75	8736	6117	223.6	365.2

tion. Whereas the general roadway design standards in the two sections were the same for maximum curvature, maximum gradient, and ramp intersections, special note was made of the following:

1. The average daily traffic volume on the illuminated section was approximately 3.6 times that on the nonilluminated section.
2. There are twice as many ramp intersections per mile on the average along the mainline in the illuminated area.
3. The illuminated section follows a more undulating course than the nonilluminated section.

Importance of these items is evidenced by the fact that within the illuminated area alone, some 43 percent of the accidents occurred in only 27 percent (14.3 mi) of the total 53 mi of roadway involved. The average daily traffic volumes in this specific area ranged from 30,000 to 40,000. A portion of this 14.3-mi section, 6.9 mi with the

TABLE 5

CONNECTICUT TURNPIKE — ACCIDENT SUMMARY

HIGH VOLUME AREAS IN THE ILLUMINATED SECTION

		Vehicle-Miles (10^8)		No. of Accidents		Accident Rate (per 10^8 veh-mi)	
	Length	Day	Night	Day	Night	Day	Night
High volume areas							
Total	14.3	0.85	0.45	80	70	94	156
6.9-mi section	6.9	0.44	0.23	50	31	114	135
Total illuminated area	53.0	2.40	1.29	177	168	74	130

highest volume, was also subjected to a comprehensive examination, and the results are given in Table 5.

Several important facts are evident from the accident summary contained in Table 5. In connection with these findings it should be noted that the average daily traffic volume on the 6.9-mi section was about 1.6 times that for the total 53 mi.

1. The day accident rate on the 6.9-mi section was 114 per 100 million vehicle-miles or 1.54 times the day rate (74) for the entire 53 mi of illuminated roadway.
2. The night accident rate on the 6.9-mi section was 135 per 100 million vehicle-miles or 1.18 times that of the day rate and only 1.04 times the average night rate for the 53 mi.

The day accident rate increased with the traffic volumes whereas the night rate remained substantially the same and was then only slightly greater than the day rate on the same section. It must be realized that in the areas under discussion the traffic volumes during the day are about double those during the night.

It would appear from the study of accident rates for the illuminated sections of varying volumes that highway illumination may have a beneficial effect on accident experience. However, it was most evident that the value of accident experience in establishing criteria for highway illumination would require considerably more data than were available, if statistically significant results were to be obtained.

CONCLUSIONS

The conclusions drawn from the analyses of the data included in this report would naturally apply to a freeway similar in design and traffic volumes to that of the Connecticut Turnpike. However, it is believed that the results obtained here can be generally used with confidence because the interchange studied is typical of freeways both from the standpoint of geometrics and traffic volumes.

The more important results evolved from this study are as follows:

1. Neither average speed, placement, headway, nor lateral clearance showed any

consistent change between day and night conditions by virtue of highway illumination or delineation.

2. Nighttime use of the acceleration lane approached daytime use as the level of illumination increased. A similar pattern existed at the deceleration lane, although it was more variable.

3. In general, it appears that beneficial results of illumination in the deceleration area are derived when it is used at the full level and that even greater services are derived when illumination is combined with roadside delineation, and that illumination of the "interchange area only" does not appear to be desirable insofar as the onramp site is concerned.

4. Analysis of the accident data for the lighted and unlighted sections of the Connecticut Turnpike does not provide conclusive results because of the extreme variance in traffic volumes and other characteristics.

It is ironical that the extensive analysis with a high-speed computer of the tremendous volume of data does not reveal such positive trends that definite warrants for highway lighting can be formed. However, the results do point up the value of roadside delineation with or without illumination and the need for using adequate intensity of illumination if highway lighting is to be provided. Above all, the experience gained will be most helpful in the planning and conducting of future highway lighting research. It appears that criteria other than those used in this report must be studied to evaluate properly the effect of highway lighting on traffic operations. The conclusions reached in this report are gleaned from studies of a modern facility operating well below its practical capacity, and may not be applicable to a similar facility carrying a heavier volume of traffic.

Appendix

TABLE 6

SCHEDULE OF FIELD OPERATIONS

Site	Date	Hours of Operation (p.m.)	Condition No.	Description of Condition[1]
4M (Onramp)	3-11-58	2:00- 5:30 6:30-10:00	1	No illumination and without delineation
5M (Offramp)	3-12-58	2:00- 5:30 6:30-10:00		
4M	5-20-58	3:30- 7:00 8:00-11:00	2	With edge markings, no illumination and without delineation
5M	5-21-58	4:00- 7:30 8:30-11:00		
4M	7-13-59	3:00- 7:00 9:00-12:00	3	With edge markings, no illumination and with delineation
5M	7-16-59	3:00- 7:00 9:00-12:00		
4M	6-23-59	3:00- 6:30 9:30-12:00	4	With edge markings, ½ normal illumination and without delineation
5M	6-29-59	3:00- 7:00 9:00-12:00		
4M	7- 1-59	3:00- 7:00 9:00-12:00	5	With edge markings, ½ normal illumination and with delineation
5M	6-30-59	3:00- 7:00 9:00-12:00		
4M	7- 8-59	3:30- 7:00 9:00-12:00	6	With edge markings with delineation and ½ normal illumination in interchange area only
5M	7- 7-59	3:00- 7:00 9:00-12:00		
4M	7-22-59	3:00- 7:00 9:00-12:00	7	With edge markings, with delineation and normal illumination in interchange area only
5M	7-17-59	3:00- 7:00 9:00-12:00		
4M	9-30-58	2:30- 6:30 7:30- 9:30	8	With edge markings, normal illumination and without delineation
5M	10- 2-58	2:30- 6:30 7:30-10:30		
4M	7-21-59	3:30- 7:00 9:00-12:00	9	With edge markings, normal illumination and with delineation
5M	7-23-59	3:00- 7:00 9:00-12:00		

[1]Lane lines were present for all conditions.

TABLE 7

SAMPLE SIZE

(FOR PASSENGER CARS ONLY FOR EACH CONDITION BY TRAFFIC MANEUVER)

	Site 4M								Site 5M							
	Day				Night				Day				Night			
Condition	Ramp Loc 1	Lane 1 Loc 1	Ramp Loc 2	Lane 1 Loc 2	Ramp Loc 1	Lane 1 Loc 1	Ramp Loc 2	Lane 1 Loc 2	Lane 1 Loc 1	Lane 2 Loc 1	Ramp Loc 2	Lane 1 Loc 2	Lane 1 Loc 1	Lane 2 Loc. 1	Ramp Loc 2	Lane 1 Loc 2
Free-moving vehicles																
Lane lines only	238	67	168	127	304	52	128	232	134	25	13	44	319	91	325	78
EM	355	95	241	191	245	70	136	175	248	80	336	50	242	47	229	65
D-EM	217	79	170	141	208	112	135	193	125	47	330	55	214	73	280	86
EM-½ LTS	236	80	155	162	187	70	118	136	122	43	277	42	271	87	297	79
D-EM-½ LTS	211	60	154	107	281	61	162	164	163	36	282	44	254	70	343	48
D-EM-½ 1 LTS	239	87	178	149	248	72	139	184	146	41	305	55	232	59	260	73
D-EM 1 LTS	218	79	163	128	245	76	139	197	58	34	300	67	159	122	290	73
EM LTS	358	133	243	200	322	150	100	218	214	60	339	87	286	56	388	154
D-EM LTS	245	84	169	148	277	80	167	184	112	34	213	48	202	71	276	61
Adjacent and not trailing																
Pass car vs pass car																
Lane lines only	23	38	41	45	21	25	25	19	50	165	16	65	34	54	7	6
EM	64	88	79	79	18	20	26	28	77	149	16	47	15	22	7	12
D-EM	87	129	110	126	18	19	17	16	143	343	28	99	58	102	10	24
EM-½ LTS	69	109	120	111	15	14	16	21	96	318	25	131	39	64	9	13
D-EM-½ LTS	49	79	74	98	21	27	29	31	122	320	33	117	65	101	17	31
D-EM-½ 1 LTS	65	121	106	110	23	25	25	23	128	388	44	149	44	78	12	17
D-EM 1 LTS	77	105	100	115	26	26	26	22	164	373	35	141	106	131	19	27
EM LTS	78	127	89	96	52	69	53	37	90	242	46	121	47	86	18	30
D-EM LTS	79	128	101	125	23	27	28	24	82	217	20	84	41	63	13	17
Pass car vs comm veh																
Lane lines only	15	6	10	5	7	5	4	3	7	10	3	1	5	3	4	1
EM	23	6	23	3	9	0	5	0	6	15	10	1	10	2	7	0
D-EM	36	7	24	7	12	0	4	1	15	17	6	1	19	12	7	0
EM-½ LTS	40	5	21	8	8	2	3	0	10	25	14	1	17	15	6	0
D-EM-½ LTS	28	1	16	5	23	0	11	0	17	18	9	1	13	5	3	0
D-EM-½ 1 LTS	36	8	38	10	15	0	7	1	17	17	9	1	9	6	4	0
D-EM 1 LTS	39	10	25	6	20	1	5	1	16	33	7	1	14	13	0	0
EM LTS	19	0	36	0	9	0	33	0	1	94	4	6	0	39	0	0
D-EM LTS	27	7	24	10	14	0	12	0	10	22	5	0	16	6	9	0
Adjacent and trailing																
Pass car vs pass car																
Lane lines only	21	4	21	12	9	6	5	6	258	72	65	9	19	9	0	1
EM	39	14	26	24	6	4	5	1	150	50	35	4	13	4	6	1
D-EM	98	26	92	42	3	3	4	0	879	395	106	24	74	31	9	0
EM-½ LTS	97	30	72	60	2	1	3	1	619	235	128	22	31	12	0	1
D-EM-½ LTS	66	18	66	31	7	3	9	7	525	189	123	17	53	18	4	1
D-EM-½ 1 LTS	100	37	90	62	4	2	6	4	894	260	138	20	42	14	5	3
D-EM 1 LTS	70	30	68	41	6	4	2	7	977	537	122	22	92	64	11	2
EM LTS	55	13	32	27	52	24	22	24	312	100	92	21	57	18	8	1
D-EM LTS	103	39	81	57	11	6	5	8	408	146	71	4	49	20	5	1
Pass car vs comm veh																
Lane lines only	2	2	2	2	0	0	0	0	33	5	11	0	6	1	0	0
EM	15	0	3	5	1	0	1	0	22	3	2	0	3	0	1	0
D-EM	29	2	14	7	5	0	1	0	81	14	17	0	17	3	4	0
EM-½ LTS	27	6	14	9	3	1	1	0	94	9	13	0	11	2	2	0
D-EM-½ LTS	26	0	12	2	6	0	2	0	102	6	19	0	20	2	3	0
D-EM-½ 1 LTS	32	2	20	6	1	0	0	0	89	16	18	8	12	2	1	0
D-EM 1 LTS	30	1	12	8	2	0	0	0	75	25	12	1	7	4	5	0
EM LTS	34	0	17	0	16	0	11	0	0	62	40	0	0	9	0	0
D-EM LTS	43	2	18	9	2	0	2	0	71	8	10	1	19	2	3	0
Trailing not adjacent																
Lane lines only	190	25	81	63	108	6	34	54	842	38	855	18	160	20	117	13
EM	375	26	152	96	56	11	17	45	589	60	791	19	152	12	100	0
D-EM	618	62	302	168	69	16	38	49	1294	164	1507	36	329	54	272	21
EM-½ LTS	692	56	304	213	67	9	23	28	1463	142	1658	31	287	21	197	15
D-EM-½ LTS	521	40	206	167	154	17	44	58	1383	110	1478	38	346	29	293	15
D-EM-½ 1 LTS	668	63	300	212	97	6	33	52	1385	152	1548	39	237	29	178	18
D-EM 1 LTS	538	43	282	142	122	16	34	72	1255	331	1727	50	243	121	181	24
EM LTS	527	42	218	102	322	42	89	154	890	75	1316	27	313	16	361	24
D-EM LTS	648	55	318	157	149	17	52	65	877	99	988	32	226	24	202	9
All others																
Lane lines only	237	84	177	143	151	33	82	108	461	224	486	143	230	98	189	74
EM	350	141	316	250	116	44	80	63	517	260	446	143	590	69	138	45
D-EM	539	253	461	384	172	61	107	119	802	590	752	255	381	224	298	110
EM-½ LTS	528	213	448	363	136	37	90	61	773	485	713	218	317	148	254	73
D-EM-½ LTS	424	187	384	294	201	60	156	127	781	413	781	217	372	148	301	68
D-EM-½ 1 LTS	607	262	494	442	161	70	97	112	840	541	770	261	278	115	225	70
D-EM 1 LTS	488	221	413	347	189	82	108	150	908	817	789	244	392	318	251	122
EM LTS	587	282	517	329	333	205	223	222	614	384	699	277	318	123	289	116
D-EM LTS	554	260	499	378	201	71	131	118	528	339	514	144	279	135	199	55
Totals																
Lane line only	724	226	500	397	600	127	278	422	1785	539	1590	280	776	274	642	173
EM	1221	370	840	648	451	149	270	312	1609	617	1636	284	155	158	488	130
D-EM	1624	558	1173	875	507	211	306	373	3139	1470	2738	470	1092	499	878	241
EM-½ LTS	1689	499	1134	926	418	134	254	247	3167	1257	2828	443	973	347	765	181
D-EM-½ LTS	1325	383	912	704	693	168	413	387	3073	1092	2705	434	1123	371	964	150
D-EM-½ 1 LTS	1745	580	1214	991	549	175	306	376	3279	1395	2830	525	854	305	885	180
D-EM 1 LTS	1450	489	1073	787	610	205	314	449	3451	2140	2982	526	1013	773	757	248
EM LTS	1658	597	1152	754	1006	490	531	655	2130	1017	2536	539	1019	337	1064	325
D-EM LTS	1687	575	1208	882	677	201	397	399	2088	865	1819	313	832	321	707	133

Note For definitions see footnotes (Table 1)

TABLE 8

SAMPLE SIZE

(FOR COMMERCIAL VEHICLES ONLY FOR EACH CONDITION BY TRAFFIC MANEUVER)

Condition	Site 4M								Site 5M							
	Day				Night				Day				Night			
	Ramp Loc 1	Lane 1 Loc 1	Ramp Loc. 2	Lane 1 Loc 2	Ramp Loc. 1	Lane 1 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc 2	Lane 1 Loc 1	Lane 2 Loc 1	Ramp Loc 2	Lane 1 Loc. 2
Free-moving vehicles																
Lane lines only	19	33	28	43	10	77	15	82	29	3	172	20	76	15	25	66
EM	16	50	12	65	2	72	1	85	34	3	12	33	60	6	11	55
D-EM	13	51	9	58	4	104	2	118	20	2	4	28	52	5	6	66
EM-½ LTS	9	61	9	56	0	68	4	86	12	3	6	18	57	2	4	70
D-EM-½ LTS	16	36	10	49	2	74	4	93	27	4	11	27	46	5	4	55
D-EM-½ 1 LTS	8	36	12	48	3	75	1	81	19	2	6	25	54	4	3	67
D-EM 1 LTS	9	53	8	71	4	84	2	92	9	2	6	31	39	2	6	67
EM LTS	0	3	0	18	0	3	0	70	41	0	5	6	74	0	1	2
D-EM LTS	8	48	8	50	0	86	0	84	14	3	9	18	51	7	4	49
Adjacent and not trailing																
Comm veh vs pass car																
Lane lines only	5	16	7	10	4	5	3	3	7	25	1	15	5	11	1	5
EM	5	30	5	20	0	10	0	5	6	16	0	10	2	13	0	8
D-EM	3	60	6	30	0	15	1	4	14	33	1	22	11	25	0	11
EM-½ LTS	6	61	16	34	2	10	1	5	10	45	0	21	12	26	0	7
D-EM-½ LTS	3	51	8	23	0	23	0	10	7	49	0	30	2	26	0	9
D-EM-½ 1 LTS	7	58	9	34	0	17	1	6	13	32	1	25	5	17	0	9
D-EM 1 LTS	6	55	11	33	1	20	1	4	21	26	1	21	9	17	0	5
EM LTS	0	44	0	46	0	16	0	23	27	0	0	29	14	0	0	0
D-EM LTS	4	67	15	30	0	14	0	11	9	35	0	16	5	28	0	12
Comm veh vs comm veh																
Lane lines only	2	2	1	1	0	0	0	0	2	1	0	0	10	6	0	0
EM	2	2	0	0	0	0	0	0	0	0	0	0	4	7	0	0
D-EM	2	3	4	2	0	0	0	0	3	2	0	0	6	9	0	0
EM-½ LTS	1	3	3	2	0	0	0	0	0	1	0	0	3	4	0	0
D-EM-½ LTS	1	0	1	1	0	0	0	0	1	3	1	2	5	7	0	0
D-EM-½ 1 LTS	1	0	2	1	0	0	0	0	1	3	1	1	2	2	0	0
D-EM 1 LTS	1	1	1	0	0	0	0	0	1	2	0	1	7	9	0	0
EM LTS	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
D-EM LTS	1	3	1	1	0	0	0	0	2	2	0	0	2	5	0	0
Adjacent and trailing																
Comm veh vs pass car																
Lane lines only	1	1	0	0	0	0	0	0	11	7	1	2	1	4	0	1
EM	1	5	2	7	0	0	0	0	6	9	1	2	0	0	0	0
D-EM	3	4	3	6	0	2	0	0	27	29	2	3	3	10	0	1
EM-½ LTS	4	9	1	7	0	0	0	0	19	27	1	4	7	6	0	0
D-EM-½ LTS	1	7	0	6	0	3	0	2	20	35	0	1	2	6	0	1
D-EM-½ 1 LTS	6	9	6	10	0	1	0	1	17	28	2	3	1	6	0	1
D-EM 1 LTS	5	3	3	6	0	1	0	1	41	47	0	1	7	8	0	0
EM LTS	0	12	0	14	0	6	0	21	200	1	5	3	20	0	0	0
D-EM LTS	2	9	4	8	0	4	0	1	12	20	1	1	1	6	0	1
Comm veh vs comm veh																
Lane lines only	0	0	0	0	0	0	0	0	4	1	1	0	0	1	0	0
EM	0	0	0	0	0	0	0	0	1	0	0	0	4	1	0	0
D-EM	0	0	0	1	0	0	0	0	5	2	0	0	3	0	0	0
EM-½ LTS	3	0	0	0	0	0	0	0	3	2	0	0	1	1	0	0
D-EM-½ LTS	0	0	0	0	0	0	0	0	6	0	1	0	1	0	0	0
D-EM-½ 1 LTS	0	0	0	0	0	0	0	0	2	2	0	0	2	1	0	0
D-EM 1 LTS	1	2	0	1	0	0	0	0	1	1	1	0	3	4	0	0
EM LTS	0	0	0	0	0	0	0	0	6	1	0	0	0	0	0	0
D-EM LTS	1	0	1	0	0	0	0	0	6	3	0	0	3	0	0	0
Trailing not adjacent																
Lane lines only	7	6	4	5	1	8	1	13	50	3	19	7	27	2	12	8
EM	4	14	1	23	0	3	0	1	33	4	14	7	18	3	6	3
D-EM	9	20	3	32	1	13	0	25	62	22	14	19	28	3	0	20
EM-½ LTS	6	32	8	45	0	10	0	14	65	14	15	13	36	5	1	13
D-EM-½ LTS	5	17	4	28	0	10	1	13	62	11	16	13	26	5	2	11
D-EM-½ 1 LTS	7	26	3	40	0	13	0	19	54	9	11	14	22	7	0	14
D-EM 1 LTS	8	14	7	25	0	8	0	12	48	16	17	16	33	10	1	18
EM LTS	1	6	0	72	0	1	0	93	541	1	48	1	158	0	0	0
D-EM LTS	16	15	6	24	1	7	0	12	56	6	17	6	29	3	0	9
All others																
Lane lines only	19	55	15	44	12	51	5	34	59	32	12	66	47	22	8	34
EM	18	91	21	72	2	43	1	38	45	37	12	41	131	23	8	29
D-EM	29	119	29	123	1	54	0	45	75	85	9	87	76	31	0	76
EM-½ LTS	38	127	31	121	0	54	1	47	80	55	10	91	59	29	1	68
D-EM-½ LTS	11	109	14	103	0	83	3	79	82	62	15	100	54	35	0	65
D-EM-½ 1 LTS	20	142	19	140	0	43	0	35	82	46	12	100	57	24	0	50
D-EM 1 LTS	28	130	26	109	1	52	2	46	83	62	15	85	54	26	2	46
EM LTS	0	27	1	117	0	15	0	121	212	2	12	23	98	0	1	2
D-EM LTS	24	128	17	130	1	68	2	55	69	43	10	66	49	34	1	58
Totals																
Lane lines only	63	113	55	103	27	141	24	132	162	72	47	110	166	61	46	114
EM	46	192	41	187	4	128	2	129	125	69	39	93	43	53	25	95
D-EM	59	257	54	252	6	188	3	192	206	175	30	159	179	83	6	174
EM-½ LTS	67	293	68	265	2	142	6	152	189	147	32	147	175	73	6	158
D-EM-½ LTS	37	220	37	210	2	193	8	197	205	164	44	173	136	84	6	141
D-EM-½ 1 LTS	49	271	51	273	3	149	2	142	188	122	33	168	143	61	3	141
D-EM 1 LTS	58	258	56	245	6	165	5	155	204	156	40	155	152	76	9	136
EM-LTS	1	92	1	297	0	41	0	328	1027	7	7	62	364	0	2	4
D-EM LTS	56	260	52	243	2	179	2	163	766	112	37	109	140	83	5	129

Note: For definitions see footnotes (Table 1).

TABLE 9

AVERAGE SPEEDS
(FOR PASSENGER CARS ONLY FOR EACH CONDITION BY TRAFFIC MANEUVER)

	Site 4M								Site 5M							
	Day				Night				Day				Night			
Condition	Ramp Loc. 1	Lane 1 Loc 1	Ramp Loc 2	Lane 1 Loc 2	Ramp Loc. 1	Lane 1 Loc 1	Ramp Loc 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc 1	Ramp Loc. 2	Lane 1 Loc. 2
Free-moving vehicles																
Lane lines only	39.5	52.6	40.1	47.4	40.8	49.8	41.6	45.7	46.1	59.8	39.8	53.2	45.0	59.2	40.2	50.2
EM	40.5	55.0	41.3	49.4	39.2	50.6	41.9	47.8	46.0	58.1	40.7	53.0	45.5	56.0	40.0	51.3
D-EM	38.5	53.3	41.5	48.6	36.3	47.7	36.8	43.8	44.7	59.8	39.8	52.2	45.7	61.7	38.4	50.9
EM-½ LTS	40.2	52.9	40.9	49.6	39.5	53.2	40.6	48.4	44.4	56.0	39.6	50.7	42.4	59.4	37.1	45.3
D-EM-½ LTS	39.7	52.3	37.7	48.8	39.7	52.3	42.8	48.5	45.5	59.1	40.7	50.6	42.5	56.5	36.6	48.9
D-EM-½ 1 LTS	40.7	52.8	42.7	50.3	40.4	53.4	39.8	46.6	46.2	58.9	40.4	51.4	43.1	57.6	38.0	49.5
D-EM 1 LTS	39.6	50.8	41.1	47.8	39.5	50.3	41.8	46.0	47.1	59.8	40.6	52.8	43.6	58.7	37.9	50.1
EM LTS	40.4	52.8	42.2	50.3	38.2	49.5	40.5	48.7	48.5	61.0	42.8	53.9	45.6	58.0	40.3	53.3
D-EM LTS	39.1	53.7	42.6	49.6	38.7	51.5	40.5	46.3	45.2	58.7	37.5	47.1	43.9	58.3	38.5	51.0
Adjacent and not trailing																
Pass car vs pass car																
Lane lines only	37.7	45.6	37.8	45.4	35.6	45.3	38.1	42.0	43.6	55.5	38.8	47.3	44.6	55.0	42.8	50.5
EM	37.7	47.2	39.4	48.4	37.4	43.5	39.2	46.6	43.9	55.7	41.4	44.8	46.1	56.5	42.0	51.0
D-EM	37.5	47.4	39.1	46.1	32.4	43.7	34.8	38.1	43.0	58.1	39.0	44.0	45.2	57.5	37.5	45.8
EM-½ LTS	40.5	49.4	41.4	47.0	35.1	49.1	38.3	45.6	45.3	57.2	39.7	42.5	42.8	58.4	36.2	45.8
D-EM -½ LTS	39.3	47.7	36.0	46.0	38.4	46.5	36.9	44.7	44.4	56.7	38.5	44.0	41.7	54.7	34.5	42.0
D-EM-½ 1 LTS	39.7	47.5	39.2	45.6	38.7	46.9	38.4	45.0	45.0	57.4	41.9	45.5	44.3	56.0	35.9	50.4
D-EM 1 LTS	37.6	48.2	40.0	46.1	38.9	47.0	39.8	46.4	46.5	58.3	41.4	46.1	44.8	58.0	38.1	45.2
EM LTS	39.4	50.2	40.8	50.8	37.4	48.5	40.4	47.3	46.5	59.8	41.5	47.8	43.4	58.6	42.3	50.6
D-EM LTS	37.8	47.5	39.6	45.4	37.9	48.5	37.6	45.3	44.3	57.8	39.5	45.1	45.7	56.7	38.5	44.4
Pass car vs comm veh																
Lane lines only	38.2	39.6	38.8	42.0	38.3	36.7	41.3	46.0	42.8	49.1	38.1	-	45.1	57.9	41.1	62.0
EM	38.8	44.7	40.3	34.3	39.0	-	45.7	-	41.4	57.1	41.6	49.2	41.4	63.8	44.1	-
D-EM	39.3	35.3	41.1	40.3	35.5	-	35.0	37.2	45.4	59.6	43.8	54.0	41.4	56.3	42.2	-
EM-½ LTS	39.8	43.6	41.7	43.5	38.6	42.8	35.4	-	42.2	58.4	40.5	44.0	41.1	61.8	40.3	-
D-EM-½ LTS	39.3	34.2	36.7	43.4	37.4	-	36.5	-	45.2	58.3	40.9	55.8	39.3	56.5	40.0	-
D-EM-½ 1 LTS	41.2	45.1	40.7	46.7	37.9	-	43.7	55.8	43.2	58.0	43.4	54.0	41.2	56.9	39.1	-
D-EM 1 LTS	38.5	46.1	41.7	43.3	39.0	45.2	43.9	49.2	41.2	59.3	40.3	42.9	46.0	57.5	-	-
EM LTS	34.1	-	37.3	-	34.7	-	38.0	-	55.8	57.7	37.3	46.5	-	57.9	-	-
D-EM LTS	37.5	45.5	39.9	42.3	39.3	-	38.1	-	43.9	59.3	34.3	-	43.6	54.1	40.4	-
Adjacent and trailing																
Pass car vs pass car																
Lane lines only	35.4	44.4	35.7	47.3	36.0	42.9	38.5	43.5	41.6	55.0	36.3	44.2	44.4	56.3	-	40.8
EM	38.1	48.7	39.9	49.1	33.4	41.5	35.8	50.7	39.7	56.2	34.7	44.2	47.7	53.7	37.4	45.2
D-EM	35.4	44.0	38.8	43.7	38.8	53.4	35.2	-	40.1	58.4	32.4	41.3	39.1	56.0	39.4	-
EM-½ LTS	37.1	46.0	39.8	45.9	35.2	59.8	36.4	29.2	38.5	56.2	30.3	32.7	40.9	58.0	-	47.2
D-EM-½ LTS	37.1	47.5	36.2	43.4	37.4	38.8	39.4	46.2	39.9	55.3	35.7	42.8	38.5	53.2	34.9	46.5
D-EM-½ 1 LTS	36.9	45.5	39.5	46.5	39.1	42.3	34.1	43.0	39.7	56.5	34.5	43.9	41.6	56.6	39.2	42.7
D-EM 1 LTS	36.9	45.4	39.5	46.5	39.1	42.3	34.1	43.0	39.9	58.1	33.6	42.9	42.8	57.5	34.8	44.0
EM LTS	37.9	51.7	41.3	48.6	37.5	50.6	39.7	45.1	43.3	57.1	38.5	47.2	41.3	58.7	37.4	46.5
D-EM LTS	36.5	43.9	39.8	44.8	38.1	47.4	39.0	42.8	39.8	56.5	36.7	49.0	39.6	55.6	29.4	45.2
Pass car vs comm veh																
Lane lines only	36.1	44.0	46.5	40.3	-	-	-	-	39.2	57.7	31.5	-	49.2	52.3	-	-
EM	38.7	-	39.9	40.2	36.4	-	31.7	-	40.5	58.6	39.8	-	36.6	-	39.8	-
D-EM	35.0	48.4	36.9	44.3	36.6	-	42.9	-	42.7	58.8	35.0	-	38.3	56.9	34.4	-
EM-½ LTS	37.2	42.7	34.7	45.0	38.2	38.9	37.2	-	39.0	56.3	38.6	-	45.5	56.7	36.9	-
D-EM-½ LTS	36.3	-	35.2	40.5	36.3	-	31.3	-	39.3	56.4	36.8	-	39.5	55.8	35.6	-
D-EM-½ 1 LTS	38.8	39.6	40.9	47.0	38.1	-	-	-	41.3	56.5	37.0	-	43.2	55.8	34.2	-
D-EM 1 LTS	39.7	37.2	40.3	40.9	42.4	-	-	-	39.9	59.2	34.7	49.2	46.5	60.4	40.2	-
EM LTS	36.8	-	41.6	-	35.1	-	41.1	-	-	58.1	36.3	-	-	57.5	-	-
D-EM LTS	37.5	38.2	39.0	46.1	33.2	-	34.2	-	37.6	59.1	34.7	38.9	40.8	54.0	38.1	-
Trailing not adjacent																
Lane lines only	39.4	48.7	40.3	47.2	40.3	42.9	41.7	43.9	40.5	56.4	36.1	48.3	43.7	59.2	38.1	51.2
EM	39.4	51.5	40.4	48.8	37.9	44.2	37.6	46.5	42.1	57.7	36.3	51.1	43.0	56.2	39.1	49.6
D-EM	37.0	48.0	40.0	46.5	35.0	48.6	37.8	42.3	41.8	58.9	33.8	45.0	39.7	58.2	35.8	50.8
EM-½ LTS	38.9	49.1	41.1	47.4	38.1	48.4	39.1	46.4	39.2	56.4	32.9	47.8	40.5	55.4	34.6	43.4
D-EM-½ LTS	38.0	51.4	36.5	46.4	38.9	48.1	41.1	46.1	40.9	57.4	35.6	48.1	40.4	56.1	34.6	45.8
D-EM-½ 1 LTS	38.9	49.4	41.0	47.7	38.6	47.7	38.6	44.0	40.9	57.8	35.3	48.0	43.4	56.6	36.5	52.1
D-EM 1 LTS	37.5	49.1	40.4	45.7	37.3	49.4	39.7	42.8	40.1	59.9	34.4	48.0	42.4	58.9	35.5	48.2
EM LTS	39.6	51.5	41.2	48.7	38.1	49.2	39.7	47.5	44.4	60.0	38.7	50.4	42.7	58.0	37.9	54.6
D-EM LTS	37.5	48.5	40.8	46.7	38.1	47.9	40.2	45.7	40.3	58.2	34.1	46.2	41.5	57.6	35.0	52.0
All others																
Lane lines only	40.5	50.8	40.7	45.5	41.5	47.0	41.8	44.4	43.4	56.4	39.6	49.1	45.3	56.3	40.9	49.9
EM	40.1	52.0	41.7	49.0	39.9	47.9	41.9	45.8	44.4	57.0	40.2	50.7	44.6	56.9	41.3	49.4
D-EM	38.1	50.2	41.3	47.7	36.7	48.8	38.8	43.1	43.7	58.0	38.9	47.9	44.4	58.4	39.3	48.5
EM-½ LTS	39.8	51.2	42.1	48.2	39.0	49.5	41.6	45.4	43.9	58.7	39.1	47.3	41.7	57.9	37.5	47.8
D-EM-½ LTS	39.4	51.9	36.9	47.6	38.8	50.2	40.5	46.4	44.4	57.3	40.0	49.4	41.5	55.6	37.7	46.1
D-EM-½ 1 LTS	40.3	50.9	42.1	48.0	40.6	49.3	40.6	47.7	44.7	57.6	40.3	50.5	43.4	56.6	38.6	48.4
D-EM 1 LTS	38.2	48.9	41.3	47.2	39.1	50.1	41.6	44.6	45.2	59.2	39.8	50.7	44.5	58.3	39.3	48.8
EM LTS	39.5	50.4	41.0	49.5	38.2	48.6	39.9	48.9	47.7	59.2	42.9	52.8	45.0	58.9	40.4	51.3
D-EM LTS	38.9	50.3	41.7	47.4	39.3	49.0	41.2	45.2	44.8	58.1	38.7	49.0	43.2	58.0	39.0	48.6
Totals																
Lane lines only	39.6	49.8	40.0	46.4	40.6	47.0	41.3	45.0	41.9	55.9	37.6	48.5	44.8	57.2	40.0	50.2
EM	39.8	51.3	41.0	48.9	39.1	48.1	41.3	47.1	43.3	56.8	38.3	50.0	44.6	56.5	40.2	50.5
D-EM	37.5	49.2	40.5	47.1	36.1	47.2	37.5	43.1	43.1	58.5	35.9	47.1	41.2	57.7	37.9	49.3
EM-½ LTS	39.3	50.3	41.3	47.9	38.9	51.2	40.5	47.2	40.6	57.5	35.1	45.6	41.6	58.4	36.6	46.2
D-EM-½ LTS	38.7	50.8	36.8	47.0	39.1	50.0	41.1	47.1	41.9	56.9	37.5	47.8	41.2	55.5	36.3	46.6
D-EM-½ 1 LTS	39.6	49.8	41.4	47.9	40.0	50.5	38.9	46.4	42.0	57.4	37.3	48.7	43.2	56.7	37.8	49.3
D-EM 1 LTS	38.1	48.8	40.8	46.6	38.9	49.7	41.2	45.0	41.8	58.9	36.5	49.1	43.7	58.3	37.8	48.7
EM LTS	39.5	51.0	42.2	49.7	38.0	49.0	40.0	48.3	45.7	59.1	40.4	51.5	44.2	58.5	39.5	52.4
D-EM LTS	38.1	49.5	41.2	47.1	38.7	49.8	40.4	45.7	41.7	57.8	36.0	47.3	42.8	57.5	37.6	49.2

Notes For definitions see footnotes (Table 1)

TABLE 10

AVERAGE SPEEDS
(FOR COMMERCIAL VEHICLES ONLY FOR EACH CONDITION BY TRAFFIC MANEUVER)

	Site 4M								Site 5M							
	Day				Night				Day				Night			
Condition	Ramp Loc. 1	Lane 1 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Ramp Loc. 1	Lane 1 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2
Free-moving vehicles																
Lane lines only	29.7	46.4	31.5	43.0	27.2	46.4	30.1	45.6	46.0	51.5	43.3	45.2	48.7	54.7	40.2	52.7
EM	31.2	48.6	34.1	46.6	39.6	45.6	34.9	46.6	46.8	60.6	40.1	52.2	51.8	49.3	41.9	53.8
D-EM	31.2	49.5	32.0	47.0	28.7	44.9	24.3	44.1	51.7	59.0	37.2	50.0	50.3	53.2	34.4	54.5
EM-½ LTS	29.5	49.3	33.7	49.0	-	50.6	34.9	49.3	46.6	47.6	36.4	50.3	47.7	51.5	40.9	51.4
D-EM-½ LTS	32.4	48.2	30.8	47.3	24.9	49.0	31.0	48.2	48.8	58.7	37.2	51.6	50.5	52.5	35.4	53.6
D-EM-½ 1 LTS	32.4	51.7	35.5	51.2	37.1	49.0	30.0	48.5	51.2	57.1	48.3	53.1	50.0	52.9	35.8	52.6
D-EM 1 LTS	39.1	48.3	35.5	46.6	31.1	47.7	33.6	48.0	53.7	63.2	34.3	53.5	53.1	48.8	38.6	55.0
EM LTS	-	44.9	-	47.0	-	47.4	-	44.7	47.3	-	34.7	46.9	44.3	-	23.3	65.4
D-EM LTS	29.6	47.6	37.2	48.1	-	49.0	-	48.0	46.4	56.5	38.5	47.1	51.6	58.1	39.9	54.0
Adjacent and not trailing																
Comm veh vs pass car																
Lane lines only	24.3	45.6	30.6	44.3	23.7	48.4	30.6	47.8	42.9	50.6	44.0	44.6	48.7	56.9	47.8	50.9
EM	28.2	46.9	28.3	47.5	-	44.9	-	50.9	48.9	54.6	-	44.4	44.8	55.4	-	51.6
D-EM	28.8	47.6	32.8	46.8	-	47.1	33.6	41.1	49.8	56.8	45.2	47.7	47.9	58.0	-	47.2
EM-½ LTS	29.2	48.5	30.7	45.6	29.0	49.4	25.6	48.2	48.7	55.3	-	48.9	48.9	53.4	-	53.3
D-EM-½ LTS	34.8	50.6	32.0	46.7	-	48.5	-	42.3	38.1	55.9	-	49.7	51.6	55.8	-	51.9
D-EM-½ 1 LTS	31.0	47.0	33.4	48.7	-	47.2	36.4	44.8	48.2	55.6	49.2	49.3	48.4	57.1	-	46.8
D-EM 1 LTS	28.7	27.5	30.9	47.0	23.6	48.5	24.9	46.7	46.4	55.6	39.8	49.4	51.2	58.7	-	62.0
EM LTS	-	43.8	-	44.8	-	43.1	-	46.1	44.6	-	-	44.6	39.6	-	-	-
D-EM LTS	27.2	48.7	31.2	48.0	-	49.3	-	47.0	48.8	56.3	-	52.1	49.0	55.7	-	52.8
Comm veh vs comm veh																
Lane lines only	26.9	31.6	33.6	37.2	-	-	-	-	47.1	52.3	-	-	50.9	58.7	-	-
EM	28.6	46.5	-	-	-	-	-	-	-	-	-	-	49.0	54.6	-	-
D-EM	31.1	46.3	39.9	46.6	-	-	-	-	49.0	55.7	-	-	36.2	55.0	-	-
EM-½ LTS	36.4	45.9	31.0	44.8	-	-	-	-	-	49.2	-	-	51.5	56.8	-	-
D-EM-½ LTS	29.5	-	31.1	46.5	-	-	-	-	38.9	58.7	34.2	40.8	50.2	56.3	-	-
D-EM-½ 1 LTS	37.2	-	35.8	57.7	-	-	-	-	42.9	61.3	34.2	42.9	50.5	58.7	-	-
D-EM 1 LTS	36.4	50.7	34.2	-	-	-	-	-	44.0	60.9	-	46.5	52.3	58.2	-	-
EM LTS	-	-	-	-	-	-	-	-	-	54.9	-	-	-	-	-	-
D-EM LTS	34.9	47.6	28.6	50.7	-	-	-	-	49.2	59.9	-	-	56.7	57.9	-	-
Adjacent and trailing																
Comm veh vs pass car																
Lane lines only	22.7	38.9	-	-	-	-	-	-	40.5	46.8	-	42.5	49.2	55.9	-	44.0
EM	28.6	50.9	32.1	49.2	-	-	-	-	47.9	50.0	39.8	56.7	-	-	-	-
D-EM	31.1	52.8	35.4	49.3	-	44.1	-	-	49.6	57.9	35.9	48.0	44.8	56.1	-	59.8
EM-½ LTS	31.1	47.3	45.2	46.5	-	-	-	-	45.0	55.0	34.2	47.7	49.6	51.2	-	-
D-EM-½ LTS	32.9	53.0	-	49.4	-	48.3	-	48.5	46.7	56.6	-	54.0	44.1	54.3	-	44.0
D-EM-½ 1 LTS	31.3	47.9	31.8	47.6	-	55.8	-	38.9	45.3	56.8	33.8	53.0	50.7	54.1	-	47.8
D-EM 1 LTS	29.7	48.2	34.7	48.8	-	50.7	-	46.5	44.2	56.3	-	42.9	46.4	58.2	-	-
EM LTS	-	41.6	-	43.1	-	40.7	-	43.8	41.3	55.8	25.6	46.9	41.1	-	-	-
D-EM LTS	31.7	47.3	37.3	43.9	-	52.3	-	55.8	41.9	55.7	35.7	38.1	49.2	57.3	-	59.8
Comm veh vs comm veh																
Lane lines only	-	-	-	-	-	-	-	-	38.8	62.0	30.6	-	-	62.0	-	-
EM	-	-	-	-	-	-	-	-	35.7	-	-	-	48.6	59.8	-	-
D-EM	-	-	-	39.8	-	-	-	-	48.8	-	-	-	44.7	54.9	-	-
EM-½ LTS	34.3	-	-	-	-	-	-	-	42.7	43.2	-	-	39.8	64.4	-	-
D-EM-½ LTS	-	-	-	-	-	-	-	-	46.1	-	-	-	44.0	-	-	-
D-EM-½ 1 LTS	-	-	-	-	-	-	-	-	42.1	57.7	-	-	49.9	54.0	-	-
D-EM 1 LTS	27.7	42.8	-	38.9	-	-	-	-	54.0	47.8	24.2	-	49.4	54.9	-	-
EM LTS	-	-	-	-	-	-	-	-	41.7	47.8	-	-	-	-	-	-
D-EM LTS	32.9	-	33.7	-	-	-	-	-	40.8	59.7	-	-	47.8	-	-	-
Trailing not adjacent																
Lane lines only	31.8	51.8	35.3	48.6	23.9	48.7	30.6	48.1	43.3	49.3	34.1	46.4	48.9	55.6	40.1	52.4
EM	35.7	48.6	36.4	48.8	-	44.9	-	37.2	46.1	49.1	34.9	51.4	52.8	58.0	38.8	56.6
D-EM	35.0	50.2	38.9	47.7	27.2	45.7	-	45.1	51.4	63.6	32.6	50.0	47.2	58.2	-	54.7
EM-½ LTS	35.3	49.8	38.3	48.2	-	50.0	-	50.5	49.9	50.9	33.1	49.5	49.2	51.6	36.4	50.9
D-EM-½ LTS	37.6	49.1	37.6	46.4	-	48.1	38.1	46.5	47.6	54.7	38.4	51.9	50.2	60.0	31.0	48.4
D-EM-½ 1 LTS	32.3	53.1	30.4	49.3	-	50.5	-	49.0	48.7	56.7	34.2	51.3	50.2	54.4	-	52.5
D-EM 1 LTS	34.6	49.3	39.5	47.0	-	49.1	-	48.3	48.1	58.5	32.0	53.7	53.0	62.0	29.5	54.7
EM LTS	-	45.7	-	46.1	-	40.8	-	44.7	41.6	54.0	32.3	50.7	41.0	-	-	-
D-EM LTS	32.1	48.6	38.7	47.0	24.6	52.2	-	51.6	47.2	60.9	34.3	51.4	52.3	57.7	-	55.0
All others																
Lane lines only	31.4	47.4	31.4	45.8	29.8	47.6	32.5	45.4	44.2	55.3	41.8	47.4	50.2	55.8	43.0	52.4
EM	32.6	48.4	35.7	47.2	25.7	45.7	29.0	46.1	48.3	53.5	39.6	50.9	51.5	57.0	44.1	54.5
D-EM	30.7	48.1	35.6	47.1	26.4	45.8	-	43.5	53.4	56.9	36.9	48.5	47.8	58.4	-	53.1
EM-½ LTS	31.6	49.3	35.3	47.4	-	49.4	34.2	49.7	45.5	56.8	40.2	48.0	41.7	55.0	41.8	51.1
D-EM-½ LTS	33.2	49.8	31.5	47.7	-	47.9	26.9	47.0	47.4	55.7	37.5	50.6	51.4	56.9	-	52.8
D-EM-½ 1 LTS	31.0	49.3	35.3	48.4	-	49.6	-	47.3	47.7	55.3	40.5	50.2	51.2	58.6	-	52.3
D-EM 1 LTS	31.1	47.9	35.3	47.3	38.9	48.7	27.9	49.1	47.7	56.9	37.6	50.2	53.3	57.6	34.4	55.6
EM LTS	-	42.7	44.0	45.5	-	44.1	-	43.6	45.7	52.7	33.9	49.3	43.3	-	30.0	45.6
D-EM LTS	33.6	49.1	35.8	48.7	35.7	48.2	31.2	48.2	47.8	58.3	39.9	49.9	51.8	55.7	31.7	53.1
Total																
Lane lines only	29.8	46.7	31.7	44.5	27.7	47.0	30.7	45.8	43.8	52.5	38.8	46.2	49.3	56.1	40.8	52.4
EM	31.7	48.3	34.1	47.3	32.7	45.6	32.0	46.5	47.2	53.4	38.1	50.8	51.5	55.5	42.0	53.9
D-EM	31.4	48.5	35.2	47.2	28.0	45.4	27.4	44.0	52.1	57.2	35.2	48.8	47.2	57.7	34.4	53.5
EM-½ LTS	31.6	49.1	34.3	47.6	29.0	50.0	33.3	49.5	45.8	55.0	36.0	48.5	41.6	54.0	40.3	51.3
D-EM-½ LTS	32.6	49.7	32.1	47.4	24.9	48.4	30.4	47.3	47.2	56.0	37.7	50.7	50.7	56.3	33.9	52.7
D-EM-½ 1 LTS	31.5	49.6	34.3	49.0	37.1	49.1	33.2	48.1	48.1	56.0	39.9	50.6	50.5	56.8	35.8	52.1
D-EM 1 LTS	31.4	48.0	34.7	47.0	31.2	48.2	29.6	48.3	47.2	56.8	35.5	51.0	52.6	58.2	36.6	55.4
EM LTS	-	43.3	44.0	45.7	-	43.4	-	43.3	42.7	53.2	32.2	47.5	42.2	-	26.7	55.5
D-EM LTS	32.1	48.6	35.0	48.2	30.1	49.0	31.2	48.4	46.9	57.4	36.9	49.8	51.7	56.3	38.2	53.6

Note For definitions see footnotes (Table 1).

TABLE 11

AVERAGE PLACEMENTS
(FOR PASSENGER CARS ONLY FOR EACH CONDITION BY TRAFFIC MANEUVER)

	Site 4M								Site 5M							
	Day				Night				Day				Night			
Condition	Ramp Loc. 1	Lane 1 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Ramp Loc. 1	Lane 1 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2
Free-moving vehicles																
Lane lines only	6.9	6.7	8.2	5.2	8.5	6.0	8.4	5.1	4.7	5.9	7.3	6.5	4.6	6.0	8.0	6.3
EM	6.4	6.5	7.6	4.9	7.0	7.0	7.5	5.0	5.2	6.4	8.1	6.7	5.3	6.6	8.5	6.7
D-EM	6.7	6.9	7.6	5.4	6.8	6.3	8.2	5.3	5.4	6.5	8.5	6.5	5.4	7.1	8.7	5.9
EM-½ LTS	7.2	6.9	7.9	5.2	7.5	6.6	8.7	5.1	5.1	6.6	7.7	6.8	5.4	6.8	8.8	6.3
D-EM-½ LTS	6.5	6.1	8.1	5.1	7.0	6.5	8.7	4.8	4.9	6.6	7.7	6.5	5.0	6.4	8.7	7.0
D-EM-½ 1 LTS	6.8	6.8	8.1	5.1	7.4	6.9	8.5	4.9	4.9	6.5	7.7	6.4	5.2	6.5	8.4	7.2
D-EM 1 LTS	7.1	6.9	7.9	5.1	7.5	6.6	8.8	4.9	5.7	6.9	8.1	6.7	4.9	6.3	8.1	6.8
EM LTS	6.6	6.6	7.8	5.7	7.3	6.4	8.8	6.0	5.5	6.3	7.9	6.6	5.3	6.5	8.2	6.9
D-EM LTS	7.2	6.7	7.7	5.2	7.1	7.0	8.7	5.0	5.2	6.7	7.9	6.8	5.2	6.5	8.3	6.9
Adjacent and not trailing																
Pass car vs pass car																
Lane lines only	6.8	6.5	8.1	6.9	6.9	6.0	7.9	6.3	4.4	6.6	6.7	6.9	3.9	5.6	8.6	5.9
EM	5.6	6.4	7.6	6.6	6.4	6.8	6.9	6.4	4.8	6.8	7.7	6.5	4.6	6.2	6.9	6.8
D-EM	6.4	7.1	7.4	6.5	6.2	6.4	8.0	6.0	5.0	7.3	7.7	6.3	5.2	7.4	8.1	5.9
EM-½ LTS	6.5	6.9	7.8	5.9	7.0	5.7	7.5	6.2	4.6	6.9	7.4	6.6	5.1	7.3	8.9	7.6
D-EM-½ LTS	6.4	6.6	7.7	6.7	5.7	6.5	8.3	6.1	4.6	6.6	7.1	6.1	4.6	6.9	7.5	5.9
D-EM-½ 1 LTS	6.2	6.5	7.7	6.3	6.2	6.0	8.3	5.6	5.0	6.9	7.4	6.7	4.8	6.7	8.7	7.2
D-EM 1 LTS	6.3	6.7	7.4	6.2	6.9	7.2	7.8	6.6	5.0	7.3	7.9	7.1	4.6	7.1	7.4	7.6
EM LTS	6.0	7.5	7.3	7.1	7.0	7.0	8.5	6.7	5.3	7.2	7.5	6.5	5.0	7.3	7.9	7.0
D-EM LTS	6.5	6.9	7.5	6.5	6.9	7.7	7.7	6.9	5.0	7.1	7.6	6.8	4.9	6.9	7.5	7.0
Pass car vs comm veh																
Lane lines only	5.8	7.1	7.7	6.7	8.0	6.9	8.5	7.5	5.2	6.9	6.2	5.0	4.6	8.0	7.8	10.0
EM	5.0	5.5	7.0	6.2	7.6	-	6.5	-	4.7	7.4	7.5	7.0	5.9	6.7	7.4	-
D-EM	6.3	6.6	7.4	8.0	5.4	-	8.0	-	4.5	7.5	8.2	7.0	4.8	7.1	7.9	-
EM-½ LTS	6.0	6.4	8.0	5.8	6.5	6.0	6.9	-	5.1	7.2	7.5	-	4.7	7.7	9.5	-
D-EM-½ LTS	6.3	6.0	8.3	7.8	6.0	-	8.7	-	4.3	7.0	7.2	7.0	4.0	6.9	9.3	-
D-EM-½ 1 LTS	5.6	4.9	7.1	8.6	7.3	-	7.2	8.0	5.2	7.4	7.5	8.3	4.1	6.9	5.4	-
D-EM 1 LTS	6.3	7.1	7.4	7.0	6.4	11.0	10.6	10.0	4.6	7.6	7.6	7.3	6.0	7.9	-	-
EM LTS	6.1	-	7.1	-	6.5	-	8.1	-	5.7	7.1	7.7	7.1	-	6.5	-	-
D-EM LTS	5.8	8.2	7.2	7.5	6.0	-	7.7	-	5.2	7.2	6.4	-	4.2	6.5	7.1	-
Adjacent and trailing																
Pass car vs pass car																
Lane lines only	6.7	4.0	7.8	6.8	6.6	5.8	9.3	7.9	3.9	6.8	6.5	6.5	4.2	6.7	-	1.0
EM	6.5	5.5	7.1	5.8	7.3	5.8	6.8	4.5	4.8	7.0	6.7	6.4	5.2	6.1	8.2	6.5
D-EM	6.6	4.9	7.2	5.8	5.7	6.7	6.9	-	4.4	7.1	8.2	6.5	4.8	7.3	8.1	-
EM-½ LTS	6.8	7.1	7.6	5.9	8.7	8.0	7.2	12.0	4.4	7.0	7.4	5.9	4.7	6.9	-	9.0
D-EM-½ LTS	6.8	6.4	7.8	6.1	5.9	6.0	7.9	6.3	4.6	6.8	7.5	6.8	4.4	7.5	9.2	-
D-EM-½ 1 LTS	6.3	6.5	7.4	6.9	8.5	6.0	6.8	6.2	4.7	7.0	7.5	6.6	4.5	7.7	6.5	6.6
D-EM 1 LTS	6.9	6.6	7.9	5.9	7.1	5.8	10.2	7.1	4.7	7.2	7.3	6.8	4.9	6.8	7.7	3.8
EM LTS	6.2	6.3	7.4	6.9	6.9	7.2	7.4	5.2	4.5	7.1	6.5	5.6	4.9	6.9	7.1	7.0
D-EM LTS	6.4	6.9	7.6	5.8	7.4	5.6	7.4	8.2	4.7	7.6	7.7	7.7	5.3	7.3	9.3	8.0
Pass car vs comm veh																
Lane lines only	8.5	7.2	4.5	10.1	-	-	-	-	3.8	5.2	5.7	-	5.0	9.0	-	-
EM	6.5	-	8.7	7.2	3.7	-	8.0	-	4.5	7.3	7.1	-	3.2	-	10.3	-
D-EM	6.1	7.0	7.5	7.6	7.2	-	9.3	-	4.7	7.2	8.0	-	4.9	8.3	10.5	-
EM-½ LTS	6.6	5.0	8.0	6.8	6.2	12.0	6.3	-	4.0	6.9	6.6	-	4.6	7.7	9.0	-
D-EM-½ LTS	6.2	-	7.2	6.5	6.8	-	5.5	-	4.8	6.4	6.7	-	4.2	10.5	7.4	-
D-EM-½ 1 LTS	6.6	2.2	7.5	8.0	-	-	-	-	4.3	6.4	6.9	-	4.6	8.8	4.0	-
D-EM 1 LTS	5.9	2.3	5.9	7.2	6.5	-	-	-	4.0	7.6	7.9	9.0	4.7	7.1	7.6	-
EM LTS	6.4	-	7.1	-	6.8	-	7.3	-	-	6.9	6.7	-	-	6.2	-	-
D-EM LTS	6.3	6.6	7.3	6.9	5.8	-	8.1	-	4.5	8.6	8.5	2.3	4.1	10.5	6.8	-
Trailing not adjacent																
Lane lines only	7.6	6.7	8.5	5.6	8.5	6.3	8.5	4.6	4.0	5.8	7.0	6.5	4.5	6.5	7.8	7.3
EM	7.0	6.8	7.5	5.6	7.1	6.6	7.0	5.1	5.0	6.7	7.8	6.5	4.8	6.9	8.1	7.3
D-EM	7.1	6.7	7.7	4.9	7.2	5.9	8.0	5.1	4.8	6.8	8.5	6.6	5.1	6.5	8.1	7.4
EM-½ LTS	7.0	6.8	7.9	4.9	7.0	6.1	8.5	5.2	4.6	6.6	7.9	6.4	4.9	6.7	8.7	6.2
D-EM-½ LTS	6.9	6.4	7.6	5.1	7.2	6.7	8.5	5.0	4.7	6.3	7.8	6.6	4.7	6.4	8.2	7.4
D-EM-½ 1 LTS	7.1	6.5	8.0	5.4	7.0	6.9	8.8	5.5	4.8	6.5	7.6	6.1	4.6	6.5	7.8	7.0
D-EM 1 LTS	7.1	6.1	7.9	5.2	7.4	6.1	8.2	5.0	4.8	6.8	7.8	6.7	4.9	6.8	7.5	6.9
EM LTS	7.2	6.8	7.6	6.0	7.3	6.3	8.5	5.4	4.7	6.6	7.3	5.9	4.8	7.0	7.8	6.3
D-EM LTS	7.0	6.3	7.8	5.6	7.2	6.8	8.5	5.1	5.0	7.0	8.1	6.8	5.0	6.7	7.8	7.6
All others																
Lane lines only	6.8	6.7	8.2	5.0	8.4	6.3	8.4	4.9	4.2	6.2	7.4	6.4	4.8	6.0	8.0	6.5
EM	6.2	6.4	7.7	5.0	7.0	6.7	7.6	4.6	5.0	6.5	8.0	6.6	5.0	6.5	8.3	6.9
D-EM	6.8	6.6	7.8	5.5	6.8	6.5	8.5	4.8	5.1	6.7	8.5	6.2	5.5	7.1	8.4	6.5
EM-½ LTS	6.8	6.9	7.9	5.6	7.0	6.1	8.3	5.0	4.7	6.6	7.9	6.4	5.4	6.7	8.7	7.1
D-EM-½ LTS	6.4	6.7	7.8	5.4	6.7	6.4	8.6	5.3	4.8	6.6	7.9	6.5	4.7	6.6	8.5	6.6
D-EM-½ 1 LTS	6.8	6.7	7.9	5.5	7.4	6.8	8.5	5.3	4.9	6.7	7.7	6.5	4.8	6.5	8.0	6.9
D-EM 1 LTS	6.8	6.6	7.8	5.6	7.2	6.4	9.0	4.6	5.1	7.1	8.0	6.7	5.0	6.6	8.1	6.9
EM LTS	6.5	6.9	7.6	5.9	7.1	6.5	8.7	5.7	5.2	6.9	7.7	6.6	5.2	6.7	8.3	6.8
D-EM LTS	6.8	6.6	7.5	5.3	7.4	6.7	8.9	5.2	5.2	7.1	8.0	6.7	4.9	6.8	8.4	6.7
Totals																
Lane lines only	7.0	6.6	8.2	5.5	8.4	6.1	8.4	5.1	4.1	6.4	7.1	6.6	4.6	6.0	7.9	6.4
EM	6.5	6.7	7.6	5.3	7.0	6.8	7.4	5.0	5.0	6.7	7.9	6.6	5.1	6.5	8.3	6.8
D-EM	6.8	6.7	7.7	5.6	6.8	6.4	8.3	5.2	5.0	6.8	8.5	6.3	5.1	7.2	8.4	6.3
EM-½ LTS	6.9	6.9	7.9	5.5	7.2	6.4	8.5	5.2	4.6	6.8	7.8	6.5	5.2	6.9	8.8	6.7
D-EM-½ LTS	6.6	6.5	7.8	5.5	6.8	6.5	8.6	5.1	4.7	6.6	7.8	6.4	4.7	6.7	8.5	6.7
D-EM-½ 1 LTS	6.8	6.6	7.9	5.7	7.3	6.6	8.4	5.2	4.8	6.8	7.6	6.5	4.8	6.6	8.1	7.1
D-EM 1 LTS	6.9	6.5	7.8	5.6	7.3	6.6	8.7	4.9	4.9	7.1	7.9	6.8	4.9	6.7	7.9	6.9
EM LTS	6.7	6.9	7.6	6.0	7.2	6.5	8.5	5.8	4.9	6.9	7.5	6.5	5.1	6.9	8.1	6.8
D-EM LTS	6.9	6.7	7.6	5.6	7.2	7.0	8.6	5.3	5.0	7.2	8.0	6.8	5.0	6.8	8.2	6.9

Note For definitions see footnotes (Table 1).

TABLE 12

AVERAGE PLACEMENTS
(FOR COMMERCIAL VEHICLES ONLY FOR EACH CONDITION BY TRAFFIC MANEUVER)

	Site 4M								Site 5M							
	Day				Night				Day				Night			
Condition	Ramp Loc. 1	Lane 1 Loc. 1	Ramp Loc 2	Lane 1 Loc. 2	Ramp Loc. 1	Lane 1 Loc 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc 1	Lane 2 Loc 1	Ramp Loc 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2
Free-moving vehicles																
Lane lines only	6.4	6.3	8.0	6.1	7 1	7.2	7.8	7 0	5 9	8.3	6.8	7.0	6.3	4 7	8 1	6 4
EM	5.6	6 1	7.4	5.4	5.7	6 5	10.3	5.8	6 4	6.7	7 2	6.5	7.1	5.3	8.7	7.2
D-EM	5.6	6.0	7 4	5 4	6.5	6.2	9 0	5.8	6.8	6.0	9 5	7.1	7.2	3 7	8 4	6 9
EM-½ LTS	6.7	6.3	8.0	5 8	-	6.5	7 7	5.9	5.7	7.7	8.0	6.1	6.9	5.5	7.8	7.3
D-EM-½ LTS	6 6	6.0	6.9	5.3	6 0	6.3	7.4	5 8	6.0	5.9	8.2	6.3	6.4	4.8	8.6	7.1
D-EM-½ 1 LTS	5.8	5.9	8.1	5.6	6 2	6 4	7.0	5.9	6.1	4 4	7 4	6.3	6 7	6.5	7.7	7 0
D-EM 1 LTS	6.2	6.2	7.3	5.6	7.9	6.3	6 7	6 0	6.7	4.7	8.4	6.5	7.0	2 7	9.2	7.0
EM LTS	-	4 9	-	4.1	-	7.2	-	3 4	4 9	-	8.0	4 0	4.7	-	9.0	5.5
D-EM LTS	7.8	6.2	7 9	5.7	-	6 7	-	6.0	5.8	6 3	8.7	6.7	7 0	6.1	8 4	7 2
Adjacent and not trailing																
Comm veh vs pass car																
Lane lines only	5.2	8.2	8 0	7.0	5.3	7 8	6 4	6 6	5.7	5.6	5 0	6 5	4.2	6 1	5 5	5.7
EM	5.3	7.0	8.3	7 3	-	7 2	-	7.7	6.6	5 6	-	7.0	3 2	6.4	-	7 8
D-EM	5.0	6.8	6 6	6.4	-	7.2	10.3	7.4	5.0	6 8	9.3	7.7	6.8	7 3	-	7 0
EM-½ LTS	5.1	7.7	6 6	7 0	5.0	7.8	6.3	8 6	5.5	6.6	-	6.9	6.6	6 4	-	7.2
D-EM-½ LTS	3 9	7 4	7 9	7.7	-	7 6	-	6.9	5 0	6 4	-	6.8	5.0	6.9	-	8.5
D-EM-½ 1 LTS	6.4	7 2	7 3	7.2	-	7.2	7.5	6 4	6 0	6.0	5.5	6.6	6 4	7 1	-	6 9
D-EM 1 LTS	5.1	7 4	6.9	7 1	4.0	7.7	6 5	7.5	6 1	7 1	10.3	7.6	6.2	7 6	-	7 9
EM LTS	-	4.8	-	5 9	-	4.9	-	5.4	3 9	-	-	4.9	3.4	-	-	-
D-EM LTS	5.4	7.4	6.4	7 2	-	7 5	-	7.5	5 9	6.6	-	7 4	5.5	6.8	-	7 6
Comm veh vs comm veh																
Lane lines only	5 7	3 3	9.7	4 7	-	-	-	-	2 9	6.5	-	-	6.7	5.2	-	-
EM	5 0	9 1	-	-	-	-	-	-	-	-	-	-	4.8	5.7	-	-
D-EM	5.5	8.2	9.7	4.5	-	-	-	-	6.0	6.8	-	-	6 7	9.1	-	-
EM-½ LTS	6.0	7.9	6.6	7.5	-	-	-	-	-	7.0	-	-	6.1	7 9	-	-
D-EM-½ LTS	4.3	-	6.0	3.0	-	-	-	-	2.5	7 3	4.7	6.7	6.7	6.1	-	-
D-EM-½ 1 LTS	1.0	-	4.0	7.0	-	-	-	-	2.3	6.9	8.5	6.7	6 0	7.1	-	-
D-EM 1 LTS	5.7	8 7	9.0	-	-	-	-	-	6 0	8 5	-	7.0	6.0	5 8	-	-
EM LTS	-	-	-	-	-	-	-	-	-	4.5	-	-	-	-	-	-
D-EM LTS	5.7	7.7	5.7	8.0	-	-	-	-	6 4	5 3	-	-	5.9	5.6	-	-
Adjacent and trailing																
Comm veh vs pass car																
Lane lines only	5.0	5.5	-	-	-	-	-	-	4 6	5.6	-	7.1	8 0	7.3	-	3.0
EM	4.7	6.0	6 5	7.3	-	-	-	-	3.9	7.2	5 5	8.7	-	-	-	-
D-EM	5.1	7.6	7.9	7.4	-	9.2	-	-	6.6	7 5	4.8	6.5	6.2	6.9	-	7 5
EM-½ LTS	4.4	7.9	6.3	7.1	-	-	-	-	6.1	6 5	9.0	7 1	7.1	6.9	-	-
D-EM-½ LTS	7.0	8.6	-	8.6	-	8.1	-	7.5	6.1	6.5	-	4.5	5.6	6.7	-	6.0
D-EM-½ 1 LTS	7.4	7 7	7.3	6.7	-	7.5	-	6.0	5.8	7.0	6.0	7.2	6.5	6.9	-	6 5
D-EM 1 LTS	5.4	6 7	7.7	7 0	-	4.0	-	9.5	5.6	6 7	-	5.5	6.8	6.9	-	-
EM LTS	-	5.2	-	5.6	-	5.1	-	3 9	4 2	8.0	6.1	0.1	4.4	-	-	-
D-EM LTS	9 1	7 9	6.9	7 1	-	6.7	-	5 7	5 3	7.7	10 5	6.0	3.5	6.7	-	8.0
Comm veh vs comm veh																
Lane lines only	-	-	-	-	-	-	-	-	4.4	7.0	4 3	-	-	0.5	-	-
EM	-	-	-	-	-	-	-	-	3 5	-	-	-	6.8	10.7	-	-
D-EM	-	-	-	5.0	-	-	-	-	7.6	-	-	-	5.4	7.9	-	-
EM-½ LTS	3.4	-	-	-	-	-	-	-	8.6	8 0	-	-	3 0	8 0	-	-
D-EM-½ LTS	-	-	-	-	-	-	-	-	5.4	-	4.7	-	5 5	-	-	-
D-EM-½ 1 LTS	-	-	-	-	-	-	-	-	5.5	6.6	-	-	6 3	7 5	-	-
D-EM 1 LTS	6.7	7.3	-	4.5	-	-	-	-	9.0	7 5	5.0	-	6 2	6 5	-	-
EM LTS	-	-	-	-	-	-	-	-	4.5	11.0	-	-	-	-	-	-
D-EM LTS	4.3	-	6.9	-	-	-	-	-	5 2	6 5	-	-	7 6	-	-	-
Trailing not adjacent																
Lane lines only	5.6	6 0	7 9	5 4	8.3	6.6	6.5	5.6	5.1	6 2	6.3	6 3	5 8	5 8	7 9	6 6
EM	5.7	6.2	7.5	6.0	-	7.4	-	5.7	6.4	5 9	8.3	6 3	6 9	5 4	7.3	6 5
D-EM	7.0	6.4	7 7	5.5	8.0	6.3	-	5 9	6 8	7.7	7.9	7 4	6 9	6 5	-	7 2
EM-½ LTS	6.1	6.9	7.8	6.3	-	6.2	-	6.0	6.1	5 3	8.1	6.1	7 0	6 7	7 5	6.8
D-EM-½ LTS	5.7	6 5	8.1	6.1	-	6.6	10.0	6.7	6 2	6.2	7.5	6 7	7 6	5 8	7 5	7.9
D-EM-½ 1 LTS	5.1	7 1	6.5	6.2	-	6.9	-	6.4	6.8	6 5	7.7	6.1	7.2	6 2	-	6 9
D-EM 1 LTS	6.3	6.7	6.7	6.4	-	6.4	-	5 7	6.5	6.5	6 9	6 7	7 1	4 3	5 5	6 7
EM LTS	-	3.7	-	4.3	-	4.0	-	4.6	4 2	3.5	7 5	6 0	4.3	-	-	-
D-EM LTS	6.1	6.7	7.8	5.8	4.5	6.0	-	6.4	6.2	5.1	8 0	6.5	7.5	5 6	-	8.2
All others																
Lane lines only	5.7	6.6	8 0	6.3	6 4	7 7	7 5	6.5	5.8	5.8	7 7	6 7	6.4	6.5	8 0	7.2
EM	4.7	6 4	7.4	6.0	8 5	6 6	9 5	6.0	6.2	6.4	7.4	6.6	7.0	5 3	9 0	7 7
D-EM	6 8	6.2	6.7	5.7	8.0	6.4	-	5.8	6 6	6 4	8 9	7 0	6 7	6 6	-	7.1
EM-½ LTS	6.2	7.0	7.8	5.8	-	6 6	8 3	6 2	5.8	6 2	7.5	6 5	6.8	6.1	11.0	7.3
D-EM-½ LTS	6 0	6.4	7.3	6.0	-	6 6	6.0	6.3	6.2	6 1	7 5	6.5	6 8	6 1	-	7 3
D-EM-½ 1 LTS	5.8	6.5	7.5	6.0	-	6.8	-	6.4	6.1	6.1	7.6	6.5	6 3	6 3	-	6 8
D-EM 1 LTS	6.1	6.5	7.1	5.7	6.0	6.8	8.6	6.3	5.9	6 4	7 3	6.3	6.5	5 8	5 9	6 8
EM LTS	-	5.2	6.0	4.1	-	4.9	-	4.2	4 3	5.3	6 7	5.8	4.4	-	7 0	3 8
D-EM LTS	5.9	6.5	7.0	5.9	7.0	6.9	6 2	6.5	6 2	7.3	8 2	6.9	6.9	5.9	6.0	7 3
Totals																
Lane lines only	6.0	6.7	8.0	6.2	6.5	7 4	7 5	6.7	5 5	5 9	6 7	6 7	6.2	5.8	7 9	6 6
EM	5.2	6.4	7.4	6.0	6.7	6 6	9.9	5.9	6.2	6.3	7.6	6.6	6 9	5.7	8 4	7 4
D-EM	6.8	6.4	7.2	5.7	7.0	6 4	9.6	5 9	6 6	6 8	8 2	7.1	6.7	6.8	8 5	7.0
EM-½ LTS	5.9	7.0	7.4	6 1	5.0	6 6	8.5	6 1	6.0	6.3	8 0	6 5	6.8	6.4	8 3	7 2
D-EM-½ LTS	6.0	6 6	7 4	6.1	6.0	6.6	7 4	6 1	6 1	6.3	7 5	6.5	6.8	6.3	8 2	7 3
D-EM-½ 1 LTS	5.9	6.7	7.4	6.2	6.2	6 6	7.2	6 1	6 2	6.3	7 5	6.4	6.6	6 7	7.7	6.9
D-EM 1 LTS	6.0	6.6	7 1	6.0	6.9	6.6	7.5	6.1	6.1	6.6	7 3	6.6	6.7	6 1	8.1	6 9
EM LTS	-	4.9	6.0	4.5	-	5.1	-	4.2	4.3	6.0	7.3	5.0	4.4	-	8 0	4.7
D-EM LTS	6.3	6.7	7.0	6.0	5.7	6.8	6.2	6.3	6.1	6.9	8.3	6 9	7.0	6.3	7 9	7 4

Note. For definitions see footnotes (Table 1).

TABLE 13

HEADWAYS
(PERCENTAGE DISTRIBUTION OF HEADWAYS BETWEEN SUCCESSIVE VEHICLES)

	Site 4M								Site 5M							
	Day				Night				Day				Night			
Condition	Ramp Loc. 1	Lane 1 Loc 1	Ramp Loc. 2	Lane 1 Loc. 2	Ramp Loc. 1	Lane 1 Loc. 1	Ramp Loc 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc 2	Lane 1 Loc. 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2
Less than 1 4 sec																
Lane lines only	2.0	2.2	4.6	1 8	2.4	-	0.7	1 1	13 1	3.3	10.9	2.8	1 8	2.4	1.2	1.0
EM	5 3	1.6	2.5	2.9	2.4	0 7	1.8	1.1	8 7	3.4	9.2	0 3	2.4	1.4	2.4	-
D-EM	9.6	2 0	3.8	3.2	3.3	0 5	1.0	0 9	14.1	5.7	9.1	2.2	4.8	2 4	4.2	0.2
EM-½ LTS	9.5	1.9	4.4	4.5	2 4	0.7	0 4	1 0	14 2	6.2	10.1	1.7	3.8	1.7	2.5	0.9
D-EM-½ LTS	9.7	2.3	3.8	4.0	3.0	0.3	1 7	1.0	14.9	5.7	10.3	0.7	6.4	1.3	4.9	1 7
D-EM-½ 1 LTS	9.8	2.9	4.3	4.7	4.2	0.9	1.0	2.9	14.1	6.5	10 5	1.4	4 3	3.3	3.8	1 9
D-EM 1 LTS	8 6	1.2	4.1	3 4	4.4	0.3	0 3	1 5	13.9	8.8	10.0	2.5	5.0	3 9	3.7	1.0
EM LTS	6.4	1.3	2.7	3.4	10 2	3.2	7.5	8.4	15.2	4.6	12.0	1.2	8.0	3.6	6.8	2.7
D-EM LTS	7 9	2.0	4.3	2 8	3.2	1.6	1.3	2.0	13 7	6.0	10.1	1.9	5.1	3.7	5.9	0.8
Between 1 4 and 2.8 sec																
Lane lines only	11.0	7.4	15.1	4 4	9.6	2 6	5.6	7.0	35.7	9 0	33.7	4.4	12.2	4.8	10.9	3.1
EM	19.6	5.2	11.1	9.1	7.7	4.3	2 6	4.8	26.1	10.2	30.0	5.3	16.2	4.8	11.5	3.6
D-EM	24.1	5.5	18.0	10.9	10.7	5.0	7 1	8.1	37 2	15.8	38.4	6.7	18.5	9 1	18.4	5.3
EM-½ LTS	25 1	9 0	17.1	14.3	10.5	3.3	4.2	5.8	39 5	14.7	39.0	7.3	18.1	4 5	15.7	4.7
D-EM-½ LTS	26 1	4.6	19.4	13.0	13.7	4.2	7.4	6 8	34 7	13.6	35.1	5.4	17.7	6.6	18.0	4.1
D-EM-½ 1 LTS	23.9	7.1	18.1	12.7	8 9	2.8	6.8	5.4	35.9	14.9	37.0	4.9	17.4	7.7	14.7	5.0
D-EM 1 LTS	23.3	6.2	18.4	10 9	10.4	3.5	7.2	7 1	38.1	19.9	39.0	6.8	16.1	13.1	14.8	4 9
EM LTS	19.9	4.9	12.8	10.4	20.4	6.2	10.5	12 6	34.1	11.1	33.7	5 3	22.0	5 3	19.6	2.7
D-EM LTS	25.6	8 3	18.5	11.6	12.7	2 6	8 3	6.8	36.5	13.2	35.1	5.9	18.0	5.9	15.4	2.7
Over 2.8 sec																
Lane lines only	86.6	90.0	80.0	93.2	87 8	96.7	93 4	91.7	51.1	87 5	55.3	92.5	85.9	92.5	87.8	95.1
EM	75 6	93.0	86 3	87 9	89.7	94.5	95 2	93.9	65.1	86.3	60.7	94.1	81.3	93.3	85.6	96.0
D-EM	66.2	92.3	78.0	85.7	85.8	94.2	91 6	90.8	48.7	78.4	52.5	90.9	76.6	88 3	77 3	94.3
EM-½ LTS	65.3	89 0	78.4	81 2	86.6	95.3	94.6	92.7	46.5	79.0	50.9	90.8	77.9	93.6	81.7	93.8
D-EM-½ LTS	64.2	92.8	76.7	82 8	83.2	95.3	90.8	91.9	50.3	80.5	54.5	93 4	75.8	91 9	76.9	93.9
D-EM-½ 1 LTS	66 2	89.6	77.3	82 4	86.6	95.7	91.6	90.9	49.9	78.5	52.5	93.6	78.1	88 6	81.2	92.5
D-EM 1 LTS	68.0	92.3	77.3	85.5	85 0	95.9	92.2	91.2	48.1	71.3	51.0	90.4	78.8	82.9	81.5	93 7
EM LTS	73 6	93.5	84.3	86 0	69 3	90 4	81.7	78 8	50.6	84.2	54.2	93.3	70.0	90.8	73.2	93.6
D-EM LTS	66 4	89.5	77.0	85 4	84.0	95.5	90.2	91.1	49.7	80.6	54.7	91.7	76.7	90.3	78 4	95 8
Unknown																
Lane lines only	0.4	0.4	0.3	0.6	0 2	0 7	0.3	0.2	0.1	0.2	0.1	0 3	0.1	0 3	0.1	0.7
EM	0 1	0.2	0.1	0.1	0.2	0.4	0.4	0.2	0.1	0.1	0.1	0.3	0.1	0.5	0.2	0.4
D-EM	0.1	0.2	0.2	0.2	0.2	0 3	0.3	0.2	-	0 1	-	0.2	0.1	0 2	0.1	0.2
EM-½ LTS	0.1	0.1	0.1	0.1	0.5	0.7	0.8	0.5	-	0.1	-	0.2	0.1	0.2	0.1	0.6
D-EM-½ LTS	0.1	0.2	0.1	0.1	0.1	0 3	0 2	0.2	0.1	0.2	0.1	0.5	0 1	0.2	0 1	0.3
D-EM-½ 1 LTS	0.1	0.4	0.2	0.2	0.4	0.6	0.6	0.8	-	0.1	-	0.1	0.2	0 5	0 3	0.6
D-EM 1 LTs	0.1	0.3	0.2	0.2	0.2	0.3	0.3	0.2	-	-	-	0.3	0.1	0.1	0 1	0.3
EM LTS	0.1	0 3	0.2	0.2	0.1	0.2	0.2	0.1	-	0.1	-	0.2	0 1	0.3	0.3	0.9
D-EM LTS	0 1	0.2	0.2	0.2	0.1	0.3	0.3	0 2	0.1	0.2	0.1	0.5	0.2	0.5	-	0.8

Note For definitions see footnotes (Table 1)

TABLE 14

AVERAGE CLEARENCES
(FOR ADJACENT VEHICLES ONLY FOR EACH CONDITION BY VEHICLE TYPE)

	Site 4M								Site 5M							
	Day				Night				Day				Night			
Condition	Ramp Loc 1	Lane 1 Loc. 1	Ramp Loc 2	Lane 1 Loc. 2	Ramp Loc 1	Lane 1 Loc 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc 1	Lane 2 Loc. 1	Ramp Loc. 2	Lane 1 Loc. 2	Lane 1 Loc. 1	Lane 2 Loc 1	Ramp Loc. 2	Lane 1 Loc. 2
Passenger cars																
Lane lines only	7.1	6 9	4 9	5 2	6 3	6.2	4 9	5.0	8.6	8.6	7 1	7.2	7.8	8.0	3.2	4.6
EM	7.5	7 4	5.2	4.9	6 6	6.8	5.5	5.5	6.1	8 0	6.2	6.6	7.0	7.3	6 1	5.8
D-EM	7.2	7 4	5 1	5.2	7.4	7.0	4.1	4.3	8.4	8.3	5.3	4.9	8.4	8.3	4.6	4.8
EM-½ LTS	7 5	7 4	4 5	4 5	6 1	6.2	5 5	4.9	8.5	8.4	6 3	6.1	8.0	8.0	5.0	6.6
D-EM-½ LTS	7.1	7.1	4.9	4.9	7.4	7.8	4.2	4.1	7.9	8.1	5.9	5.9	8.4	8.5	6.1	5.4
D-EM-½ 1 LTS	7 4	7 2	5 0	5.1	6 6	6.8	3 5	3 8	8 3	8 1	6.2	6 3	8.1	7.9	5 9	6.2
D-EM 1 LTS	7 0	7 1	4.6	4 8	7 0	7.6	4.4	4.8	8.6	8 4	6.6	6 3	8.2	8.2	6.6	7.1
EM LTS	7.5	8.3	5.4	5.9	6.8	7 6	3.7	4.1	8 7	8.2	6.1	6.2	8.6	8 4	5.6	5.9
D-EM LTS	7.5	7.6	4 9	5 1	7 2	7 3	5 4	5.4	8 5	8.4	5.9	6.1	7.9	7.9	6 2	6.4
Commercial vehicles																
Lane lines only	6.7	7 7	4.3	3 8	7 6	6 2	6 9	2.6	6.9	6 3	6.1	6.5	4.2	5.4	10.5	3.1
EM	7 1	7.2	3.3	5.4	-	6.0	-	6.2	6 5	6 8	7.5	6.0	7.4	6.3	-	6.1
D-EM	8.2	6.7	3 8	3.8	-	7 5	-	3.6	6 0	7.1	8 2	5.5	5.3	7.2	-	5.4
EM-½ LTS	7 4	7 5	4.7	4.3	8 0	7 2	8 2	6 8	5.8	6 9	-	6.2	6.3	6.8	-	3.4
D-EM-½ LTS	7 8	7 5	4.6	4 9	-	7.2	-	3.6	6 0	6.7	7 1	5.7	5.3	7.1	-	6.8
D-EM-½ 1 LTS	5 1	7 5	5.8	4.9	-	6.6	5 5	4.0	6.1	7.1	7 9	5 4	6 0	7.4	-	7 0
D-EM 1 LTS	7.1	7 3	5.1	4.9	13 0	7 1	6 5	2.3	6.7	7 5	5.0	5.8	5.8	5.8	-	6.0
EM LTS	-	5.1	-	4.3	-	4.8	-	1 6	7 9	8.2	7 0	3.4	8.5	-	-	-
D-EM LTS	7 3	7 4	6.4	5.1	-	6 7	-	4.6	6 6	7.0	-2.2	5 4	4 7	6.7	-	6.4

Note For definitions see footnotes (Table 1).

Influence of Tinted Windshield Glass on Five Visual Functions

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Tinted windshields and side windows in automobiles have been introduced for two purposes: (a) to eliminate a major portion of radiant infra-red energy, and (b) to reduce excessive brightness and glare. The commonly used bluish-green tinted glass has a transmission of 65 to 70 percent, which is similar to that of sunglasses of light shade. At photopic (daylight) luminance levels the absorption of the glass is hardly noticeable. At mesopic (dusk) and scotopic (night) luminance levels a 30 percent reduction in transmission may interfere seriously with vision.

To study the effects of tinted windshield glass on vision at various luminances, tests were performed on (a) dark adaptation, (b) recovery from the shock of a blinding light flash, (c) visual acuity, (d) depth perception, and (e) the effects of glare.

Dark adaptation tests showed that when looking through a tinted windshield the thresholds for recognition of a test stimulus were higher than without an absorptive filter in the light path. The rise in threshold corresponded exactly to the brightness loss produced by the tinted glass.

When the eyes were adapted to low levels of luminance or to complete darkness and were suddenly exposed to a bright flash of light, recovery from the light shock and regaining of the previous sensitivity level was not enhanced by the presence of the tinted windshield glass. The reduction of luminance of a light flash by a tinted windshield was of no advantage, because the same absorption of the windshield also reduced the visibility of a test target.

Visual acuity was reduced slightly by tinted windshield glass. When acuity was measured with targets of small differences in size (Landolt rings) it was found that with the tinted windshield the intrinsic details could be seen only if they are 10 to 20 percent larger than when seen without an absorptive filter in the path of light.

Depth perception was also influenced by tinted windshield glass. A 25 to 35 percent loss in depth perception was observed when the test object was seen through tinted windshield glass.

When test targets were identified in the vicinity of a glare source and the ratios of glare luminance / target luminance were determined when the targets are viewed through tinted windshield glass and without the filter, it was found that the ratios remained the same whether tinted windshield glass was in the path of view, or vision was not obstructed by filters.

All tests uniformly showed that with tinted windshield glass in the line of sight the eyes appeared less sensitive by an amount that corresponded to the physical absorption of radiant flux by the filter in front of the eyes. No improvement of vision of any sort was found when tinted windshield glass was used.

● BETWEEN 1950 and 1959 millions of automobiles have been equipped with heat absorbing tinted windshield glass. By eliminating more than 50 percent of the radiant solar energy in the infrared range the comfort of occupants of automobiles is probably increased. At the same time the reduction of transmissiveness decreases visibility, thus, creating a potential safety hazard.

The tint of the windshield reduces transmission to approximately 70 percent which is the limit permitted by the American Standard Safety Code (1). While a 30 percent loss in transmittance does not affect visibility adversely at photopic (daylight) luminance levels, the reduction is more serious at mesopic (twilight) and scotopic (night) luminance levels.

The purpose of the present study was to investigate by laboratory tests effects of tinted windshield glass upon various visual functions.

In an attempt to clarify this problem the distance at which low contrast targets can be detected was determined in practical situations by Heath and Finch (2) who used targets such as road signs, posts, boxes, dirt piles, etc., of varying reflectance. Sixteen square-inch panels of low reflectance were exhibited against the glare of oncoming headlights by Roper (3). Targets used by Doane and Rassweiler (4) simulated pedestrians distributed along both sides of the road, having a reflectance of 7 percent on one side, and 3 to 3.5 percent on the other. Because a number of not easily controllable factors are involved in tests of this type, differences in results are to be expected. Six percent loss in visibility was found by Roper, 3 percent by Doane and Rassweiler, but Heath and Finch found as much as 22 percent loss in visibility distance. Despite these differences the net conclusion of the investigators was that the loss in night visibility is not serious and is compensated for by the beneficial effects of glare reduction and heat absorption during daytime driving.

Clinical tests conducted by Miles (5) have shown that all tinted filters (light yellow, pink, and greenish-blue windshield glass) reduce visual acuity at mesopic luminance levels. Also, tinted windshield glass combined with pink ophthalmic lenses is particularly disadvantageous since visual acuity was reduced to 20/60. At luminance levels involved in night driving, the resolving power of the eyes was greatly reduced. Thus, a pair of targets which appeared distinctly separate at 100 ft in unrestricted vision when seen through a clear windshield, had to be brought within 25 ft of the observer when they were viewed through a tinted windshield.

In laboratory tests Blackwell (6) found a 23 percent loss in detection distance when targets were viewed through tinted windshield glass. As distance for detection without tinted filters became smaller because of a reduction of target size or luminance level the percentage loss in detection distance increased rapidly with the tinted filter. From these findings Blackwell concluded that the loss in visual detection resulting from the use of filters at low luminance levels were so great that such filters cannot be recommended unless drivers reduce vehicular speed accordingly.

The theoretical effect of tinted windshield glass upon visibility has been calculated by Haber (7). According to his findings visibility distance is reduced 9 to 15 percent when targets are viewed through a tinted windshield at distances greater than 200 ft. If, however, the contrast between target and background is low, so that detection through a clear windshield is possible only at a short distance, the percentage loss in visibility may be as high as 35 to 45 percent with a tinted windshield.

METHODS AND PROCEDURES

Tinted windshields consist of a bluish-green plastic filter material laminated between two sheets of safety glass. The thickness of each glass pane is ⅛ in. The lower three-quarters of a windshield are uniform in density but the upper one-quarter represents a darker band increasing in density toward the top edge. Because only the homogeneous part is in the path of vision at eye level or below, studies have been made with filters taken from the midsection of the homogeneous part of the windshield.

The spectral transmission curves for two types of tinted windshield glass are shown in Figure 1. Both types transmit similar spectral ranges. The total transmission of A is greater than that of B. The transmission maximum for A is near 500 millimicrons, and for B near 480 millimicrons. Filter B has a lower transmission at both ends of the spectrum than filter A. By holding an A and a B filter side by side, the higher density and more bluish color of B can be noticed. Only filters of type A windshield glass were used in the experiments to be described. Measurements of various samples of A-glass with a Macbeth illuminometer yielded transmission values between 65 and 69 percent.

Inasmuch as tinted windshield glass cannot be regarded as a "neutral" filter it was necessary to use other filters having different spectral characteristics but having approximately the same percentage transmission. Such filters are Cruxite B which has a brownish tint and a transmission of 72 percent, and Noviol C which is deep yellow and has a percentage transmission comparable to that of the other filters, provided two sheets of filter glass are combined.

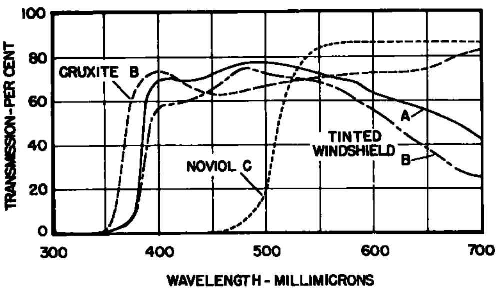

Figure 1. Spectral transmission curves for two types of tinted windshield glass, for a yellow filter (Noviol C, and for a tinted ophthalmic glass—Cruxite B).

The present investigation included studying the effects of tinted windshield glass on (a) dark adaptation, (b) recovery from light "shock," (c) visual acuity, (d) depth perception, and (e) glare.

The Effect of Tinted Windshield Glass on Dark Adaptation

In studies of dark adaptation it is customary to expose one or both eyes to a light of high luminance for a given length of time. Then on cessation of exposure to light, sensitivity thresholds are determined at intervals during the course of adaptation. The shape of the dark adaptation curve varies with pre-exposure luminance, pre-exposure time, and spectral character of pre-exposure light, as well as with the size and retinal location of the testfield, duration of the testflash, and the spectral characteristics of the testlight (8, 9, 10, 11).

Any specific changes in the pre-exposure or testing conditions will affect the course of dark adaptation. If, for instance, a dark adaptation function has been reliably established for a given testfield, retinal location, and testflash duration, the interposition of an absorptive filter such as tinted windshield glass should alter the shape of the dark adaptation curve relative to the absorptive properties of the filter, and thereby provide a direct measure of the effect of the filter on visual sensitivity.

In this study dark adaptation tests were made with the aid of a visual discriminometer (12). The testfields were squares subtending 1.3 deg on a side in the fovea and 2 deg in the parafovea. In foveal tests a red fixation point was placed at the center of the testfield. In parafoveal tests the distance between fixation point and the proximal edge of the testfield was 10 deg. The presentation time was 0.04 sec. When it was desirable to present the testfield against a surround luminance, the entire visual field of approximately 40-deg angular subtense (as limited by the dimensions of the apertures of the eyepieces) was evenly illuminated.

The observer was exposed to a luminance of 1,510 footlamberts for 10 min before the tests. The pre-exposure light was a tungsten filament lamp in front of which was mounted a lens system providing a collimated beam wide enough to illuminate evenly both eyes. The observer viewed the light source through two +20D crown lenses. These were mounted in adjustable frames which permitted correcting for interpupillary distance.

When the pre-exposure period was completed the observer shifted to the discriminometer and looked steadily at the fixation point. By means of a shutter in the path of the testlight the testfield was then presented, and the observer indicated whether he could

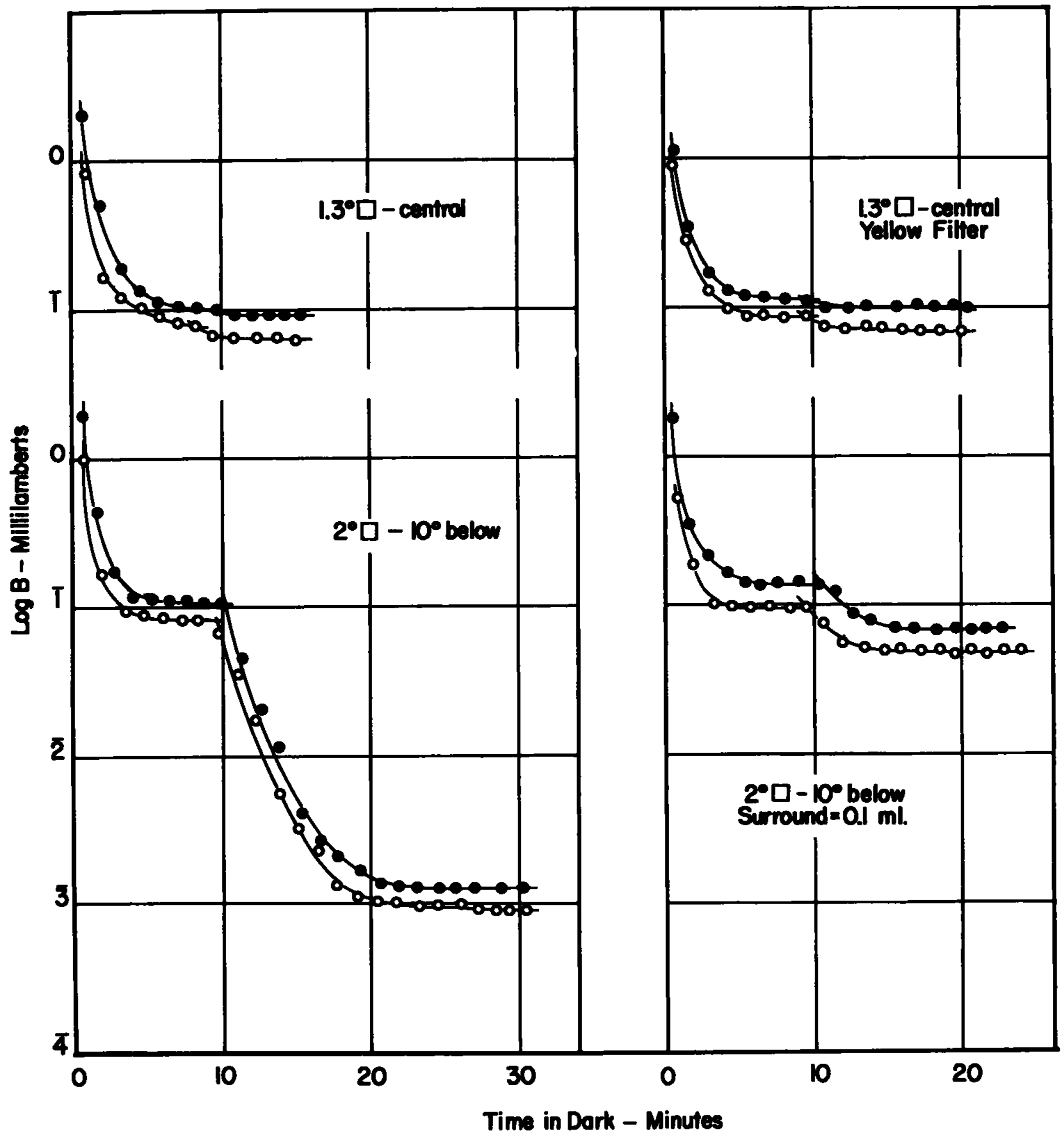

Figure 2. Dark adaptation functions obtained after 10-min pre-exposure to a luminance of 1,510 millilamberts when the testlight is not screened (open circles), and when the testlight is screened by tinted windshield glass (black circles).

see it. When just perceptible, namely, when threshold level was reached, elapsed time and threshold luminance were recorded. The tests were repeated at intervals of 1 to 1.5 min and continued until adaptation had reached a steady level.

After the dark adaptation function was established for a given retinal area, tests were repeated with a piece of windshield glass placed between the eyes of the observer and the testfield. All other conditions were kept constant. All observations were made binocularly since binocular vision is more likely to be involved than monocular observation in everyday life. The experimental results are shown in Figure 2.

Central Stimulation Without Surround Lighting.—When 1.3-deg-square testfield was shown centrally the stimulating light fell within the fovea. The resulting dark adaptation curve should have been simplex having only a cone segment. For the 1.3-deg field, however, a slight break was indicated after about 8.5 min which suggested that a small extrafoveal rod population was involved in threshold response. According to measurements on sections through the retina the rod-free fovea subtended a visual angle of 1.5 to 2 deg. It was assumed that any rod vision was due to involuntary eye tremor (13). Similar indications of rod vision with testfields of 1-deg angular subtense in the fovea have been found in studies on critical flicker frequencies in relation to luminance (14).

The final dark adapted level found with the central testfield was log B = $\bar{2}.80$. When windshield glass was inserted in the path of the testlight, the curve obtained was shifted upward on the log luminance scale. The final level of the curve was 0.16 log units higher than when no filter was in the light path. This would indicate that 1.45 times more light was required for threshold recognition when the testfield was seen through the tinted windshield glass (Fig. 1, upper left).

Parafoveal Stimulation Without Surround Lighting.—When a 2-deg-square testfield was presented parafoveally 10 deg below center, the resulting dark adaptation curve showed the typical duplex character (Fig. 1, lower left). Initially the thresholds dropped to the cone plateau at log B = $\bar{2}.90$. The break occurred after 9.5 min. The rod thresholds dropped rapidly over a total range of nearly 2 log units. Only a slight decline in threshold level occurred beyond 20 min. At 30 min a final threshold level of log B = $\bar{4}.95$ was reached. When the tinted windshield glass was used the resulting dark adaptation curve again was shifted to higher luminance levels. At the cone plateau the difference between the two curves was 0.14 log unit, and at the final rod level the difference was 0.16 log unit.

Dark Adaptation with Surround Lighting.—Because the human eye is practically never required to attain its maximal sensitivity in the performance of ordinary visual tasks it was necessary to investigate the course of dark adaptation under conditions in which the testfield was presented against a surround luminance of 0.1 millilambert instead of against total darkness. The surround level was similar to that usually found during night driving. In this case dark adaptation will proceed only to the level of the surround luminance, and the perception of a testfield represents a Δ I (differential threshold) value in relation to the background luminance (15).

Results of such tests are shown at the lower right of Figure 2. The curve taken without a filter had a cone plateau at log B = $\bar{2}.98$ which is slightly higher than without surround illumination. The break occurred at 9.5 min, and the drop of the rod thresholds was only slight, reaching a steady level at log B = $\bar{2}.69$ after about 18 min of adaptation. When the windshield glass was in the light path, the dark adaptation curve was again shifted to higher threshold levels. At the cone plateau the difference was 0.14 log unit and 0.16 log units at the final rod level. The break was delayed about 1 min when the tinted windshield was used.

The windshield reduced the radiant energy reaching the eyes by surface reflection, the transmission characteristics of the glass, and the tinted laminated material. Therefore changes in visual thresholds, namely, increases in luminance necessary to obtain a threshold response may be due to (a) light loss as such, and/or (b) the specific spectral characteristics of the absorptive filter. To investigate these possibilities, it was necessary to perform tests in which a filter with approximately the same over-all luminance reduction but with decreased transmisssion in the blue-green, and increased transmission in the yellow and red was used in the test beam. Such a filter was found by combining a Noviol C filter 3.38 mm thick with a Noviol D filter 3.05 mm thick. The reduction in luminance produced by the tinted windshield glass and the yellow filter combination did not vary by more than 4 percent. When dark adaptation was tested at the retinal center with a 1.3-deg testfield, the curve obtained with the unobstructed testfield was almost identical to the curve shown at the upper left in Figure 2. The curve taken with the yellow filter combination in the light path was very similar to the corresponding curve taken with the tinted windshield glass in the light path. The final threshold difference was 0.16 log units shown at the upper right in Figure 2.

In all tests the threshold level was from 0.14 to 0.16 log unit higher when tinted windshield glass was used. According to transmission measurements made on the windshield glass an increase in threshold luminance of 0.15 to 0.18 log unit would have been expected. The experimental findings with tinted glass therefore agree closely with those expected to occur because of mere physical loss in luminance. A shift of the same magnitude was obtained with filters of different absorption characteristics but with approximately equal percentage of transmission. This would indicate that the luminance loss produced by the filter rather than the color is responsible for the reduction in threshold sensitivity.

The Effect of Tinted Windshield Glass on Recovery from Light "Shock"

One of the reasons for using an absorptive filter as windshield glass was to reduce the effect of headlight glare during night driving. It is obvious that a filter with a transmission of only 70 percent must reduce the glare effect of oncoming headlights. However, the same absorption which decreases glare also decreases the visibility of objects on the road. It is therefore of importance to determine whether any advantage is gained by using tinted windshields.

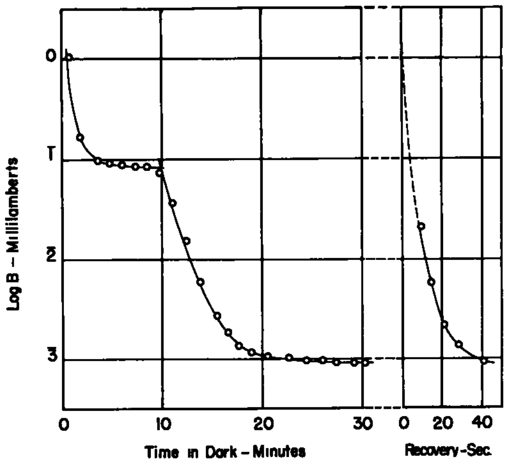

Figure 3. Dark adaptation curve obtained with a 2-deg square testfield presented 10 deg below center, after pre-exposure for 10 min to 1,510 millilamberts at 30 min a bright flash of 0.04 sec duration is presented, and the return to the previous sensitivity level followed. The time from the flash to the attainment of the final threshold level represents the recovery time from the light shock.

To ascertain whether tinted windshield glass influenced recovery from light shock several laboratory tests were conducted. The time required to perceive a target in the visual field following light shock was measured when (a) the target was seen without a filter in the path of vision, and when (b) tinted windshield glass was interposed between the observer and the target.

The visual discriminometer served as the test instrument. A square testfield subtending a visual angle of 2 deg on a side was presented in the center or 10 deg below center. Observations were made binocularly. The exposure time was 0.04 sec. After 30 min of dark adaptation the threshold level for perception of the light stimulus was determined and was found to be similar to the final levels shown in Figures 2 and 3. The observer then was exposed to a luminance of 370 millilamberts for 0.04 sec reflected into his eyes from a white screen embracing a large visual field. Immediately after light shock the fixation point was located in the discriminometer. At intervals of 2 sec the operator exhibited the testfield until the observer indicated that he was able to see the testlight. The time from cessation of exposure to the light shock to first recognition of the stimulus was the measure of recovery time.

Figure 2 shows the course of dark adaptation for a 2-deg square testfield presented 10 deg below center. After 30 min in the dark a steady final level of adaptation had been reached. Then the intense light flash was presented. The initial thresholds following shock were about 2 log units higher than the final level. The recovery curve descended rapidly, and after about 40 sec the final threshold level was regained (16).

In the case illustrated, the testfield luminance was set at five predetermined levels in rapid succession, and for each predetermined level perception time was determined. Such tests were strenuous and required long rest periods between trials since cumulative effects of light exposure contributed to a higher final threshold level. The experimental procedure was therefore modified. A value was chosen for the threshold luminance which was 0.3 log unit above the level recorded at 30 min. This luminance level corresponded to twice the final level, or one-half the completion of recovery. This may be compared in meaning to the chronaxie of Lapicque (17, 18).

The shock source consisted of a projector mounted in a light tight housing about 4 ft behind the observer. In front of the objective was a compur shutter which could be released by the experimenter by means of a cable. The projector illuminated a white surface of high reflectance located above the discriminometer head. The white area subtended a visual angle about 50 deg in width and 30 deg in height at the position of the observer's eyes. About 6 deg to the right of the center of the bright field was the fixation point at which the observer looked during exposure to the shocklight.

With headlight glare no large retinal area is suddenly flooded by light. Instead, two distinct sources of high luminance are seen by the motorist. To simulate this condition a second arrangement for reflecting the shocklight into the eyes was used. Thus, the light from the projector was reflected by two small concave mirrors placed side by side. They were separated by a distance corresponding to the distance between headlights seen at 100 ft. In this experimental situation the observer again fixated a point on the same level but 6 deg to the right of the right mirror. The luminance reflected by one mirror was 28,400 footlamberts. Because of extremely bright and vivid after images which go through a rapid series of color changes there was great difficulty in finding the fixation point in the discriminometer; both types of shock exposure were extremely annoying.

To reduce the luminance of the light shock instead of exposing the observer to the full shock luminance, a tinted windshield filter could be placed in fromt of the projector. Although the manipulation of the filter at the projector occurred behind the observer, he was not ignorant of the change. The absence or presence of a filter was known to him also in terms of a change in color of the shocklight. However, subjects did not know that velocity of recovery from light shock was being measured.

Tests were performed with a 2-deg-square testfield presented centrally and 10 deg below center (a) when the testfield was exhibited against a black background, and (b) when the testfield appeared against a surround luminance of 0.1 and 0.01 millilamberts.

For each testfield location and surround luminance there were 4 experimental conditions where, (1) both the shocklight and the testlight were unfiltered, (2) the shocklight was unfiltered while tinted windshield glass was in the path of the testlight, (3) the shocklight passed through tinted windshield glass while the testlight was not filtered, and (4) both shocklight and testlight passed through tinted windshield glass.

Condition (1) in a practical situation corresponded to shock by headlight glare and recovery when no tinted windshield was present. Condition (4) corresponded to a situation in which a tinted windshield was used. Conditions (2) and (3) are not found in a practical situation. Condition (2) required that headlight glare influenced vision without passing through a tinted windshield while targets must be recognized through the tinted windshield glass, and condition (3) required that the headlights of oncoming cars be dimmed by the tinted windshield while the vision of the driver was not impeded by the tinted glass.

The mean recovery times were calculated for the various filter conditions, retinal location of testfield, and surround luminances. Usually 40 exposures were made during an experimental session, 10 exposures for each filter condition. A typical example for measurements of recovery time is given in Table 1.

It may be seen that the recovery times in the four groups overlapped to a certain extent. When the shock source was not shielded the recovery time of 26.7 sec found without a filter in the path of the testlight increased to 31.1 sec when tinted windshield glass was placed in front of the testfield. The presence of the tinted glass increased the recovery time by 4.4 sec, or by a factor of 1.2. When the testfield was shown against an illuminated surround this value rose to 1.4. When the luminance of the shock light was reduced 30 percent by interposition of tinted windshield glass recovery time was shortened from 26.7 sec to 23.8 sec. Recovery was accelerated by a factor of 1.2.

The Effect of Tinted Windshield Glass on Visual Acuity

Acuity may be influenced (a) by loss in luminance occasioned by the absorption of a filter, (b) by its spectral transmission, and (c) by prismatic effects introduced by the curvature of a filter and other differences in refraction of the two laminated sheets of glass. For an evaluation of tinted windshield glass it was necessary to study visual acuity at various luminance levels with and without tinted windshield glass in the path of vision.

TABLE 1

No Filter in Front of Shock Source.				Tinted Windshield in Front of Shock Source.			
No Filter in Testbeam		Tinted Glass in Testbeam		No Filter in Testbeam		Tinted Glass in Testbeam	
28	+1.3	29	-2.1	25	+1.2	27	-0.3
27	+0.3	30	-1.1	23	-0.8	24	-3.3
29	+2.3	32	+0.9	22	-1.8	28	+0.7
27	+0.3	31	-0.1	23	-0.8	24	-3.3
24	-2.7	34	+2.9	22	-1.8	31	+3.7
25	-1.7	31	-0.1	26	+2.2	25	-2.3
24	-2.7	34	+2.9	23	-0.8	28	+0.7
30	+3.3	33	+1.9	23	-0.8	30	+2.7
29	+2.3	30	-1.1	24	+0.2	28	+0.7
24	-2.7	27	-4.1	27	+3.2	28	+0.7
26.7		31.1		23.8		27.3	
	19.6		17.4		13.6		18.0

Visual acuity is usually tested by Snellen charts composed of letters of various sizes and types. In the conventional Snellen chart the changes from one size letter to the next are coarse and therefore are inadequate for measuring of visual acuity limited by a filter such as tinted windshield glass.

Reading charts were therefore prepared of Landolt rings of 10 different sizes varying from 4.0 mm to 1.2 mm in diameter. The gaps were 1/5 of the diameter of each ring. The rings were arranged in blocks of 25 symbols, the gaps appearing in random positions (Fig. 4). The blocks of rings were mounted on a strip of white cardboard. This moved in a frame behind a white screen 4 ft wide and 3 ft high in the center of which only the 25 rings of a particular block were visible through a square opening. The screen was mounted vertically on the wall of a darkroom and could be evenly illuminated over a wide range of luminances. In the present tests only a luminance level of 55.25 footlamberts in the photopic range, and a luminance level of 0.089 footlamberts in the mesopic range were employed. The task was to identify the random position of the

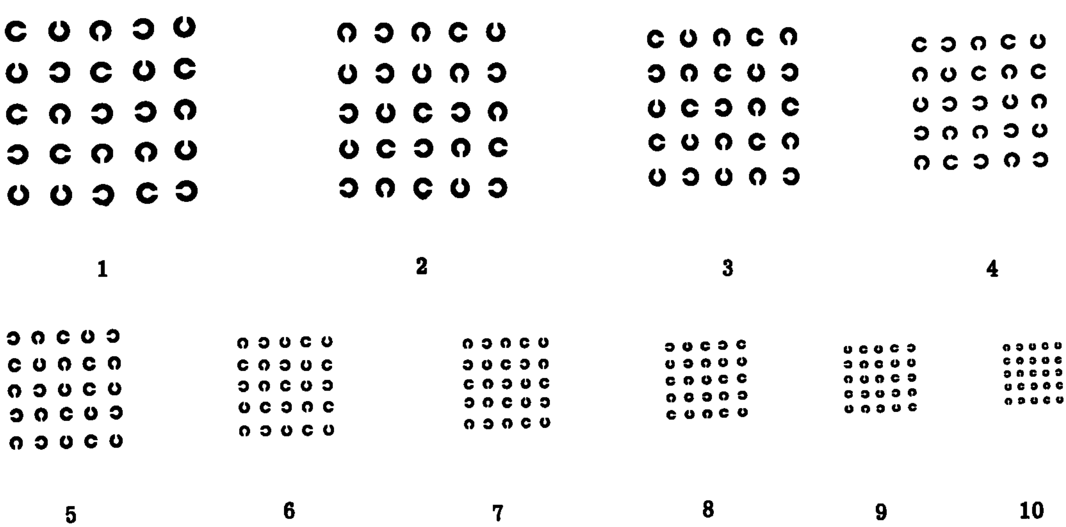

Figure 4. Sample blocks of 25-Landolt rings used for visual acuity tests.

gaps. The observer was seated 187 cm (6 ft) from the screen with his chin on a rest so that his eyes are at the same level as the test targets. At this distance the gaps in the largest ring size were easily recognizable. The visual acuity ratings of the intrinsic criterion, namely, the size of the gaps in the Landolt rings are given in Table 2.

The visual acuity values for the 10 rings indicate that only one-half of maximal acuity were needed for seeing the gaps in the smallest rings under optimal luminance conditions. At a luminance of 55 footlamberts size 7 and 8 should be identified accurately, provided visual acuity were normal. When illumination would be reduced to 0.089 footlamberts the critical ring size should be larger. The experimental results indicate a close correspondence to the findings of earlier investigators (19, 20, 21).

TABLE 2

Ring Size	Visual Acuity Value
1	0.068
2	0.076
3	0.085
4	0.096
5	0.114
6	0.230
7	0.303
8	0.342
9	0.390
10	0.455

In the tests an observer had to identify the position of the gaps in the rings of each block reading the lines in conventional manner as long as he was able to recognize the gaps. The time for completing the reading of each block and any errors were recorded. In order to study the effect of tinted windshield glass on visual acuity, a windshield was placed at a distance of 18 in. from the observer's eyes, and the results obtained were compared with those obtained when no windshield or other filters were in the path of vision.

Twenty-one observers participated in the tests, each serving 3 to 5 times as subject. If corrective lenses were customarily worn, they were used during the tests. Most observers were able to identify the gap positions correctly up to ring size 7 or 8; sizes 9 and 10 were clearly seen only by a few. The numbers of correct identifications in each block of 25 symbols obtained (a) without the windshield, and (b) with the windshield in a typical test series are given in Table 3.

TABLE 3

Ring size	1	2	3	4	5	6	7	8	9	10
No filter	25	25	25	25	25	25	25	12	0	0
Tinted windshield	25	25	25	25	25	25	16	4	0	0

These results clearly indicated that visual acuity was reduced by tinted windshield glass.

In these tests comparisons were made between visual acuity determinations obtained under unequal luminance conditions. Because the tinted windshield glass has an absorption of about 30 percent, the better visual acuity recorded without a filter could be attributed to the loss of light when the tinted glass was in the path of vision. For this reason it was necessary to study visual acuity with the tinted windshield and to compare the results with those obtained when the screen brightness was reduced by 30 percent. This reduction could have been achieved in either of two ways: (1) by placing absorptive filters of the proper density in front of the light source illuminating the screen, or (2) by placing filters of proper density in front of the eyes of the observer. For such purposes neutral filters were used. However, they have the disadvantage of not being large enough to be used as a shield at 18 or more inches from the eyes. They are also flat and therefore are not suitable for use as eyeglasses. To overcome these difficulties plano ophthalmic lenses with a 6-base curvature of A0 Cruxite B type glass were used (Fig. 1).

Twenty observers were tested with Cruxite B and with tinted windshield glass. With both types of filters the tests were continued until the subjects were unable to specify the position of the gaps in the rings. The results of the best and the worst observer are given in Table 4.

TABLE 4

				Best Observer						
Ring size	1	2	3	4	5	6	7	8	9	10
Cruxite B	25	25	25	25	25	25	25	25	22	0
Tinted windshield	25	25	25	25	25	25	25	24	6	0
				Worst Observer						
Cruxite B	25	25	25	25	25	25	14	0	0	0
Tinted windshield	25	25	25	25	25	12	2	0	0	0

These two cases typify the general outcome of the tests. In approaching the limit of acuity, each observer was capable of indicating the positions of the gaps in the rings easier without a filter, or with Cruxite B, than when the tinted windshield glass is in the path of vision. In comparing the tests without a filter with those obtained with the tinted windshield the difference in visual acuity could be regarded as the result of difference in luminance. But the comparative results obtained with the tinted windshield glass and Cruxite B (two filters of approximately the same density), showed that the difference in acuity was due either to the bluish-green color of the glass or to prismatic effects produced by the heavy laminated shield. Comparisons of results obtained with a clear windshield and with a tinted windshield showed that visual acuity was better with a clear windshield.

When the tests are performed at a luminance level of 0.089 footlamberts, the limiting ring size at which the gaps could just be recognized was 3 to 4 sizes larger than when the luminance was 55.25 footlamberts. The scores of two observers are presented in Table 5.

TABLE 5

				Best Observer						
Ring size	1	2	3	4	5	6	7	8	9	10
Cruxite B	25	25	25	25	25	0	0	0	0	0
Tinted windshield	25	25	25	25	8	0	0	0	0	0
				Worst Observer						
Cruxite B	25	25	25	24	20	0	0	0	0	0
Tinted windshield	25	25	25	20	13	0	0	0	0	0

At photopic and mesopic luminance levels tinted windshield glass reduced visual acuity more than a neutral filter of equal percentage transmission of better optical quality.

The Effect of Tinted Windshield Glass on Depth Perception

Depth perception was studied with the aid of a Verhoeff stereoptor (22, 23). The experimental arrangement is shown in Figure 5. The ½- by 2-in. opening of the stereoptor containing the three vertical bars of different width and at different depth was illuminated by a 50-watt tungsten filament lamp L_1 concealed in a housing. The luminance of L_1 was varied by means of filters and a diaphragm. The stereoptor was attached to a disc which could be turned 180 deg so as to provide the eight-bar positions incorporated in the test. The disc was behind a white screen 20 in. high and 18 in. wide, in the center of which the stereoptor was seen through an opening. In front of the screen and on each side were 2 lamps enclosed in cylindrical housings which provide a uniform illumination of the screen. The luminance was varied by placing matched neutral filters in front of L_2 and L_3. In order that the stereoptor could be placed at various distances from the observer the components of the depth gauge were assembled on a carriage which ran on metal tracks on a heavy wooden plank. Mounted behind the white screen the black front surface of the Verhoeff stereoptor was completely covered so that the three bars were seen against a homogeneous white surround. By these means the transilluminating light from L_1 and the frontal illumination from L_2 and L_3 could be made equal in luminance and color.

To study the effect of tinted windshield glass on depth perception an observer was seated at the end of the optical track on which the stereoptor was mounted, his head being stabilized on a chin rest. The stereoptor was placed at 100 cm and the eight positions shown. If correctly identified, the distance was increased until the spatial relationships of the three bars was just perceptible. If stereopsis was poor and the distance of 100 cm too great for correct identification of bar positions the stereoptor was brought nearer until the distance was found at which depth could be perceived correctly.

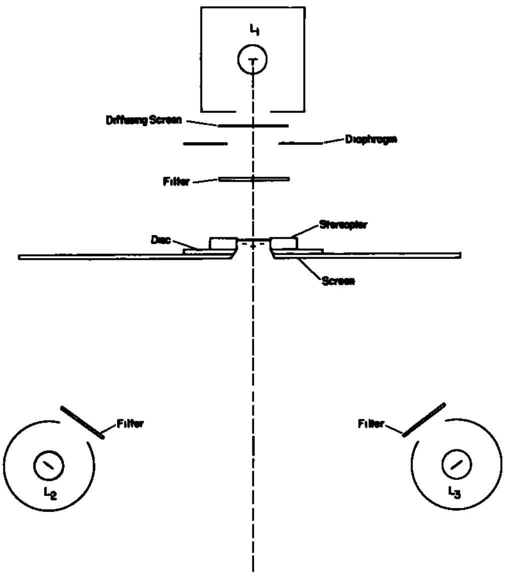

Figure 5. Diagram of arrangement of Verhoeff Stereoptor for depth perception tests.

Twenty observers were tested. The majority had no difficulties in perceiving depth at 100 cm, some recognized depth at 150 cm, and one giving a correct score at 200 cm. For observers for whom the distance of 100 cm was too great, the distance was decreased to 75 or to 50 cm. After the critical distance had been found for each individual without a filter, the determinations were repeated with the tinted windshield glass in the path of vision.

The results of these tests showed consistently that stereopsis was reduced from 12.5 to 37.5 percent when the depth target was viewed through the tinted glass. To specify the relative positions of the bars in all eight presentations correctly the stereoptor had to be moved closer.

Inasmuch as the tinted windshield absorbs 30 percent of light while the luminance of transillumination of the stereoptor and of the surrounding screen were equally reduced and rendered bluish-green, it was necessary to test stereopsis when the luminance was reduced by filters placed in front of the light source. Reduction of luminance with tinted windshield glass, neutral filters, or Cruxite B had the same effect as when tinted windshield glass was placed into the path of view. Subjective observations do not indicate a preference for one or the other type of filter. Some observers stated that the bars appeared sharper with the neutral filters, others preferred the bluish-green tint of the windshield glass.

When the over-all luminance of the depth target and the screen was reduced from 50 to 5 and 0.5 footlamberts, depth acuity for some observers decreased. In others the change in luminance had no effect. For some subjects the stereoptor needed to be brought 10 to 15 cm closer before the bar positions were identified correctly. When the stereoptor was viewed under reduced illumination through clear windshield glass, tinted windshield glass, or neutral filters placed in front of the light sources, depth acuity was reduced by amounts corresponding to those found at the high luminance level.

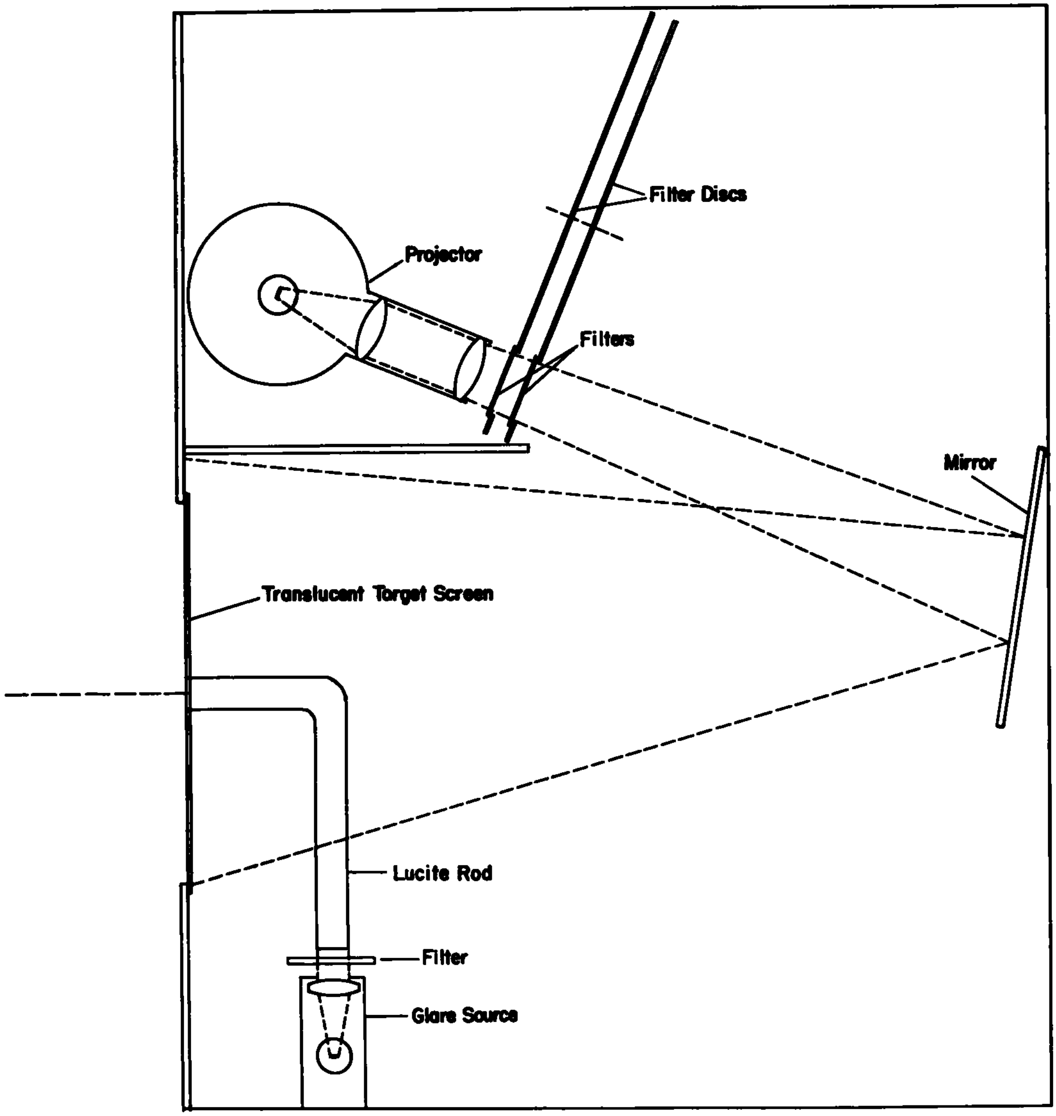

Figure 6. Diagram of instrument for measuring the effect of glare on visibility in the vicinity of a glare source.

In some observers depth perception was tested also with yellow filters of the Noviol C type. This filter reduced luminance about 12 percent. The results obtained with Noviol were compared with those obtained when no filter, when tinted windshield glass were used, and when luminance was reduced by neutral or tinted windshield glass filters placed in front of the light sources. Yellow filters worn in the form of aviation-type goggles had no noticeable influence on depth perception.

The Effects of Tinted Windshield Glass on Perception as a Function of Glare

Claims have been made that colored filters provide relief from glare. Because tinted windshields are one variety of color, filter tests were made to determine their effect on perception as a function of glare. To conduct this study a glare meter was constructed and is shown in Figure 6. This instrument provided a glare source of high luminance, and presented targets in the form of Landolt rings at various distances and directions from the source.

The glare source consisted of a Spencer microscope lamp, the light was collimated and passed through a clear plastic rod of 1-in. diameter. The plastic rod was bent 90 deg so that its front end appeared in the 1-in. center hole of a translucent screen on which the Landolt rings were displayed. The full luminance of the glare source as measured from the eye position of the observer was 3240 millilamberts. To control glare, absorptive filters could be interposed between the glare source and the plastic rod. The plastic rod was encased in cardboard tubing to prevent stray light from falling on the target screen.

The target screen was illuminated by a small, well-shielded projector located behind the front wall of the instrument. The light from the projector passed through openings cut near the edge of two discs in front of which were mounted neutral density filters. One series of filters provided transmissions of 10, 20, 30, 40, 50, 60, 70, 80, and 90 percent. The other series provided transmissions of $1/10$, $1/100$, $1/1,000$, and $1/10,000$. By combining 2 filters the luminance of the target screen could be varied in 10 percent steps over a wide range.

The light passing through the filter discs was reflected by a mirror in order to illuminate the target screen evenly. Because the encased plastic rod was in the light path, a shadow was cast on the screen downward from the center. Hence, no Landolt rings were visible on the vertical radius below the glare source. However, targets were visible along the radii at 0, 45, 90, 135, 180, 225, and 315 deg. On each radius were 3 Landolt rings at different distances from the center, forming 3 circles of symbols around the glare source.

The screen was viewed from a fixed distance of 230 cm, while the head of the observer was so adjusted on a chin rest that the eyes were at the same level as the glare source. As seen from this position the angular separation was 1.25 deg between glare source and the inner circle of rings, between glare source and the middle circle of rings it was 2.25 deg, and between glare source and the outer circle of rings it was 3.25 deg.

The tests were performed in a darkroom. When the glare source was turned on and the target screen only barely illuminated, the targets were invisible. By changing the filters in front of the projector to lesser densities, a luminance level was found at which the Landolt rings of the outer circle and the gaps became just perceptible. As the screen luminance was further increased the threshold for seeing the gaps in the rings of the middle circle was found; finally, a further increase in luminance revealed the thresholds for seeing the gaps in the Landolt rings of the inner circle. By these means luminance values for seeing targets of fixed size at fixed angular distances from a glare source were determined. The values obtained for the differentials in luminance were indicative of an observer's perceptual capability in the presence of glare. For instance, if the luminance of the glare source, or that of the target screen was altered by placing absorptive filters in front of the glare source, or in front of the eyes, it was possible to determine whether such a change reduced the differential between glare and target screen luminance, and thus, reduce the disturbing effect of glare.

Thirty-one observers, all college students, participated in the glare tests. The threshold luminance of the target screen at which the gaps in the Landolt rings of the outer, the middle and the inner circle were visible was determined successively (a) when there was no filter in front of the glare source nor in front of the observer's eye, (b) when the eyes of the observer were not shielded and the luminance of the glare source was reduced by tinted windshield glass, (c) when a tinted windshield was in front of the observer and no filter was in front of the glare source, and (d) when the tinted windshield was in front of the observer and the glare source was shielded by tinted windshield glass.

Condition (a) corresponded to a night driving situation in which no tinted windshield was used, and condition (c) to the situation in which a tinted windshield was used. Under condition (b) the driver's vision would not be handicapped by a tinted filter, but the glare from headlights would be reduced by a filter in front of the source. Under condition (d) a tinted windshield would be in front of the driver's eyes while glare would not be reduced. Results of these tests are given in Table 6.

When the luminance values of the target screen for detection of the gaps in the Lan-

TABLE 6

Test Condition	No Filter in Front of Eyes		Tinted Windshield in Front of Eyes	
	Threshold Luminances (millilamberts)			
	(a) No Filter in Front of Glare	(b) Filter in Front of Glare	(c) No Filter in Front of Glare	(d) Filter in Front of Glare
Outer circle	0.082	0.050	0.082	0.050
Middle circle	0.094	0.082	0.094	0.082
Inner circle	0.181	0.095	0.162	0.121

dolt rings of the three circles under condition (a) was the standard, it was seen that when the luminance of the glare source was reduced by a tinted windshield glass that the critical thresholds were lower in accordance with the luminance reduction of the glare, (b). When a tinted windshield was in front of the observer the luminance of the glare source and of the target screen were both reduced, (c). Except in close proximity to the glare source the over-all reduction of luminance did not change the threshold values found under condition, (a). Finally, when the target screen was viewed through a tinted windshield when a filter of the same type was in front of the glare source, (d), the threshold luminances were smaller than in (a), but not essentially different from those found under condition (b).

There is little variation in the results among the 31 observers tested so that the example presented in Table 6 may be regarded as typical for the group. Only in subjects of advanced age (70 years and over) an increase in target screen luminance in excess of 1 log unit is needed for recognition of the targets under the various conditions (Table 7).

TABLE 7

Test Condition	Threshold Luminances (millilamberts)			
	(a)	(b)	(c)	(d)
Outer circle	0.586	0.181	0.586	0.586
Middle circle	1.011	0.311	0.011	1.011
Inner circle	1.116	1.011	1.481	1.481

If the reduction of glare by a tinted windshield was helpful in rendering targets more visible in the vicinity of a glare source, then a significant difference in threshold luminance should be obtained between conditions (a) and (c), and in no case was a significant change indicated. The effect of a tinted windshield in front of the glare source alone was always easily recognized. Smaller target screen luminances were required when a tinted windshield was in the path of vision and the glare source itself was dimmed by means of a tinted filter.. This suggests that the glare-reducing effect of a tinted windshield was lost by the absorption of light from the targets. An advantage was gained only when the glare luminance was reduced in the absence of a tinted windshield.

The recognition of targets in the vicinity of a glare source required the same ratio of glare luminance/target luminance, both when the eyes were not shielded by an absorptive filter and when they were shielded by tinted windshield glass. The beneficial effects claimed for tinted windshields in coping with headlight glare were not substantiated by tests under controlled conditions.

When the tinted windshield glass was replaced by ophthalmic Cruxite B in the glare tests, the results were essentially identical with those obtained with the tinted windshield. The observer's subjective impression is that the Lamdolt rings and gaps appear sharper at threshold with Cruxite B filter than with the tinted windshield glass, but in no case is there a reduction in threshold luminance.

DISCUSSION

In studies on the effect of tinted windshield glass on dark adaptation, recovery from light shock, visual acuity, depth perception, and visibility in the presence of glare, it was shown that a reduction of visual efficiency occurred with a tinted windshield in proportion to the absorption of radiant energy.

When filters of approximately the same density but with different transmission characteristics were used, the reduction in visual function was the same as with tinted windshield glass. This indicated that it was the loss of luminance rather than spectral selectivity which was responsible for reduction in visual function.

Glare must be regarded as an entoptic phenomenon into which enter such factors as diffuse transmission of light through the iris and sclera; flares, produced by multiple reflections at the different refracting surfaces; specular reflection from the front surface of the retina; halation produced by reflection at the pigment epithelium, choroid, and sclera; light reflection through the vitreous from one part of the retina to another; fluorescence of the lens; and scatter by the ocular media (24, 25, 26). Effects of glare may be somewhat mitigated by the exclusion of short-wave radiation from the glare source. This suggests a reason for claims that yellow or amber filters are advantageous in coping with glare.

When a glare source is viewed while the ambient illumination is sufficiently high, the ill effects of glare are not experienced in their full extent. The glare effect in creases as the contrast between glare source and surround becomes greater. Also the glare effect is lessened with large glare sources since glare is inversely proportional to the area of the source. For this reason it has been suggested that the size of headlights ought to be increased (5).

Another factor contributing to the annoyance of glare in automobile driving consists in the dispersion of light within the windshield. With an absolutely clear and homogeneous medium between the eyes and a glare source, the image of the glare source is sharp, and flares and halations are reduced. The surface film of small particles on the windshield undoubtedly adds to the unpleasant effects of glare. It would therefore be desirable to develop and apply adequate techniques for the elimination of surface film and fogging of windshields.

Because the purpose of tinted windshields is twofold, namely (1) the screening of radiant heat, and (2) glare reduction, the essential question is whether a tinted windshield is the proper and only possible solution of this complex problem. Whether heat absorption by tinted glass is of any real value is questionable since the dark colors of automobile bodies will absorb far more heat than that which is excluded by the heat-absorbing glass. It also should be realized that the heat absorbing characteristic of glass does not depend on dark tints.

The reduction of daytime glare by 30 percent through the windshield does not necessarily eliminate the need for sunglasses. To be effective sunglasses should have at least 80 percent absorption as well as a spectral transmission which will allow good color rendition (27). The percentage absorption of tinted windshield glass is far too small to remove the need of sunglasses under daylight conditions. The combination of sunglasses of various colors and densities with tinted windshields may yield very undesirable filter combinations for visual comfort (5). Not to be overlooked is the fact that high density sunglasses can easily be removed at dusk, and a clear windshield would interfere considerably less with visual perception in mesopic and scotopic vision at dusk and at night.

SUMMARY

Dark adaptation, recovery from light shock, visual acuity, depth perception and visibility under glare conditions were studied when the targets were seen through tinted

windshield glass. The results were compared with those obtained when no filters or filters of different absorptive properties were used.

The tinted windshield glass used in these tests was an absorptive filter of light bluish-green tint with a maximum transmission near 500 millimicrons. The transmission of this type of glass is approximately 70 percent.

Thresholds were about 0.15 log units higher in dark adaptation tests when tinted windshield glass was used in front of the testlight compared with the data obtained when no filter was used. The higher threshold corresponded to the reduction in test-field luminance caused by the filter.

Recovery time after light shock was 1.2 to 1.4 times longer when the test target was obscured by tinted windshield glass than when no filter was placed in front of the test target. The increase in recovery time was proportional to the loss in luminance.

When Landolt rings of small size differences were used as targets, visual acuity was less when a tinted windshield was interposed between the observer and the target than when no filter was used. Besides, the lower luminance prismatic effects produced by two curved heavy laminated sheets of glass were responsible for reduced visual acuity.

Tests with a Verhoeff stereoptor showed a 25 percent reduction in depth perception when a tinted windshield was placed in the path of vision than when no filter was involved.

When thresholds are determined at which targets at fixed angular distances from a glare source become visible, it was found that the ratios of glare-luminance/target-luminance were the same whether or not the glare source and target screen were shielded by tinted windshield glass or by an absorptive filter.

The results of these tests in no way indicated any advantage in the use of tinted windshields.

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Dark Adaptation as a Function of Age and Tinted Windshield Glass

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● THIS STUDY was designed to measure the relative effects of light-absorbing, clear, and tinted windshield glass on the terminal levels of dark adaptation in a large sample of subjects who varied widely in age. The penalty age imposes on dark adaptation (1, 3, 4, 19, 28) is universal, but only recently has the extensive range of individual differences in dark adaptation as a function of age been estimated (18) with reasonable confidence. If the natural physiological processes of aging reduce perceptual-motor efficiency then any conditions that artificially and unnecessarily interfere with sensory-response functions should be avoided. Previous studies have shown that tinted windshield glass is just such an artifice. Although little is known about the relative effects of tinted filters on the dark adaptation efficiency of persons in different age groups, there is reason to believe that the adverse effect increases with age.

Because there is a direct functional connection between the physiology of the dark adaptation process and night vision, and a direct statistical connection between levels of luminance on which night vision depends and the frequency of fatal and non-fatal vehicle accidents, the relevance of studying individual differences in the population is clear.

The relationship of changes in luminance to the frequency of vehicular accidents is strongly suggested by the following evidence. Studies have shown that when the probability of accident exposure was held constant that nighttime fatalities were three times greater than daytime fatalities. One study (31) conducted in Detroit showed that 75 percent of all night accidents occurred on about 100 mi of streets through which flowed nearly 15 percent of all night traffic. The illumination was raised by a factor of three, and over a two-year period the number of nighttime accidents was reduced to approximately 26 percent of the total number in the city. A similar procedure (31) in Hartford, Connecticut, involved doubling the illumination. There, the accident rate was halved. Parallel results were achieved in Atlanta (25), and in Kansas City (32). The evidence from these investigations was the same; that is, when street and highway illumination was improved, nighttime accidents were reduced.

Because several relationships within the dark adaptation process itself are important for the understanding of the problem, the restrictions on vision determined by low levels of illumination will be explored in detail.

The adaptation of vision to low levels of illumination is a complex phenomenon that takes place in two distinct though overlapping phases. Cone vision depends on relatively high levels of illumination that range between 16,000 ml, the upper limit of retinal tolerance, and 0.01 ml, the lower limit of cone efficiency. Cone vision degenerates rapidly below 0.01 ml, the cone-rod transition point, and is replaced by the much less efficient rod cell vision, the threshold of which is approximately 0.000001 ml. Both cone and rod vision are represented by successive decay curves. The first phase is relatively short and nearly reaches its asymptote in about 4 to 6 min. The second phase requires 20 min or more. Interposed between the two is the junction of the two curves where both cone and rod vision are not fully efficient, cone vision having been reduced nearly to zero sensitivity when the retina is deprived of light, while rod vision is still in the early stages of development.

The most efficient degree of visual acuity, color perception, and depth perception depends on cone vision. Rod vision, capable of mediating only gross form in certain stages of its development, is most insensitive to color, and is inferior in three-dimensional vision.

The rate at which the eye becomes adapted to low luminances is extremely important. Rate of adaptation is a function of several conditions common to daily human experience. Thus, dark adaptation and therefore, night vision, is dependent on duration, intensity, and wave length of the light band to which the individual has been exposed prior to the initiation of the process. In turn, these vary during the day, time of year, and with the geographic region. It is also known that adaptation varies adversely with anoxia (20), hypoglycemia (21), and CO concentration (22).

Adaptation to low levels of illumination requires a relatively long time, while only a fraction of a second exposure to moderately high luminance is sufficient to destroy dark adaptation. This is an unfavorable characteristic in those instances where the individual must continue to function with precision under low illumination.

It is clear that interference with the rate and degree of adaptation must reduce visual efficiency, especially when interference occurs at levels of luminance involving rod adaptation, and therefore, night vision. It has been shown (27) that much of the time night driving takes place under low luminance levels that range from 0.0028 ml to 3.176 ft lamberts. It can be seen that 0.0028 ml is less than the lower limit suggested as typical of cone vision. Thus, some driving takes place under levels of illumination that are inadequate for cone vision.

Nevertheless, the benefits that have been said to be derived from lowering illumination through the use of tinted windshield glass are (a) reduction of interior temperature of vehicles and the protection of occupants from exposure to infrared rays of solar energy, (b) relief from glare, (c) more rapid recovery from "light shock," and (d) improvement of visibility, presumably visual acuity. Evidence supporting these assertions is related only to the infrared light-absorbing effect of filters. No data have been found to support the remaining claims. The evidence against these alleged benefits follows.

The conflict between thermal discomfort and impediments to vision is more apparent than real, because engineering problems associated with filtering infrared rays and the development of vehicular air conditioning are not actually so critical. Furthermore, it is doubtful whether tinted windshield glass in vehicles can be justified on this basis partly because the dark color of many vehicles cancels out the possible temperature reduction by glass filters. Direct exposure to infrared light can be avoided in other ways, for instance, by the modification of vehicle design and through the use of appropriate clothing.

The effects of filters on light transmission, glare, "light shock," visual acuity, color rendition, and stereopsis will be considered next.

Any laminated filter reduces radiant energy that would otherwise reach the retina by (a) surface reflection, (b) limitations imposed by the transmission characteristics of the glass, and (c) the light-absorbing characteristics of colored laminating substances. Experimental data obtained by McFarland and Wolf (23) indicate that a Noviol C filter having higher transmission in red-yellow than a popular brand of bluish-green windshield influences the course of dark adaptation in almost the same way. The total transmission factor of the Noviol C filter differed by no more than 4 percent from the windshield filter. This indicates that it is luminance loss, not surface reflection, nor selective frequency absorption of the tinted laminating material which is responsible for the decrement introduced into dark adaptation.

Glare must be regarded as an entoptic phenomenon dependent on such factors as (a) the diffusion of light transmitted through media such as the iris and sclera, (b) flares, produced by multiple reflections from different refracting surfaces, (c) specular reflections from the front surface of the retina, (d) halation produced by reflections from the pigmented epithelium, choroid coat, and sclera, (e) light reflections through the vitreous humor from one part of the retina to another, (f) fluorescence of lenses, and (g) scatter by the ocular media.

Glare has three major parameters: (a) it is inversely proportional to the area of the light source, (b) increases as the ratio between source and surround increases, and (c) varies with visual angle. It is apparent that a filter interposed between the eyes of the observer and the light source and its surround decreases the total amount of light available for seeing, but it does not reduce the area of the source, visual angle nor, the ratio between source and surround. Thus, the fundamental conditions from which glare is derived remain unchanged.

Light "shock" occurs when light is presented tachistoscopically. It will be recalled that dark adaptation can be destroyed in a fraction of a second even though it requires a relatively long time to develop. Rate of recovery, then, is exceedingly important, especially where the individual must see under levels of illumination that are not constant, and where the fluctuation in intensity is great as well as rapid.

Any filter will reduce the intensity of glare and light shock. However, the same degree of absorption that reduces light intensity also reduces visibility of the background. It has been demonstrated (23) experimentally that when tinted glass is placed in front of the light source and also in front of test targets, that there is no relief from glare and no material gain in recovery time relative to the reduction of luminance. Neither is it a matter of "coming out even" because the reduction of total luminance results in an absolute degree of reduction of visual acuity or visual discrimination. Thus, there is a margin of over-all loss, depending on the transmission factor of the filter, all else being equal.

Tinted filters reduce acuity in varying amounts depending on the filters (6, 8, 10, 11, 14, 15, 24) distort color rendition (16, 17), and reduce depth perception (23). Conditions of visibility between 25 and 200 ft (8, 24) from the viewer have been found to be adversely influenced by tinted filters. However, little is known concerning the relationship of perception under conditions of lowered illumination as a function of age and tinted filters.

METHOD

Subjects

There was a total of 240 male subjects drawn from YMCA youth groups, college-age students, university faculty, taxi drivers, unemployed persons obtained through a USES Agency, and men living either at home, or living in private institutions for the aged. Thirty subjects were drawn from each decade ranging from the teen-age level through the age of 89 yr. All subjects were paid for their services. After the data were obtained more than one-half the subjects in each decade were then offered and given a complete optometric examination free of charge. The optometric data will be described in a separate publication.

Apparatus

The instrument used throughout this study was a modified Hecht-Schlaer Adaptometer (12). From time to time the apparatus was housed in a dark room in each of three cities principally to accommodate aged persons for whom traveling was inconvenient.

Procedure

The subject (S) was seated in the experimental room. His left eye was covered by a patch, and his head was held steady in a standard head-chin rest. Vision was uncorrected. The lights in the dark room were turned off, and after a lapse of approximately 1 min the retina of the right eye was bleached for 3 min by exposure to a standard 1600-millilambert (ml) evenly diffused incandescent light. At the end of the pretest phase the fixation point was presented 7 deg right of the test field. The violet test light stimulus was exposed tachistoscopically. The duration of each test flash was $1/5$ sec. All the data were obtained by one technician (David Ward).

The first observation was made approximately within the first 40 sec after the termination of the pre-exposure bleaching light. Then, beginning with the second observation, one test was made every minute for the first 10 min, and every 2 min for the next 6 min, every 3 min for the following 24 min, and finally, every minute for the last 10 min. Beginning with the 41st min, a filter cut from the center of a standard clear glass windshield (CWG) was interposed between the test patch and S's eyes. On the 46th min this filter was interchanged for a second filter cut from the center of a popular brand of tinted windshield glass. Particular care was taken to obtain the sample filter from the eye level of a wide range of subjects. There were 32 observations made during 50 min of dark adaptation time, 5 of which were made with a clear windshield glass filter, filter A, and 5 of which were made with a tinted windshield glass filter, filter B.

The transmission factor of filter A was approximately 90 percent. Maximum transmission values found for samples of tinted windshield glass ranged between 65 and 69 percent. The actual value of filter B used in this study was approximately 70 percent as indicated by the Macbeth illuminometer. Figure 1 shows the percentage transmission curve of filter B.

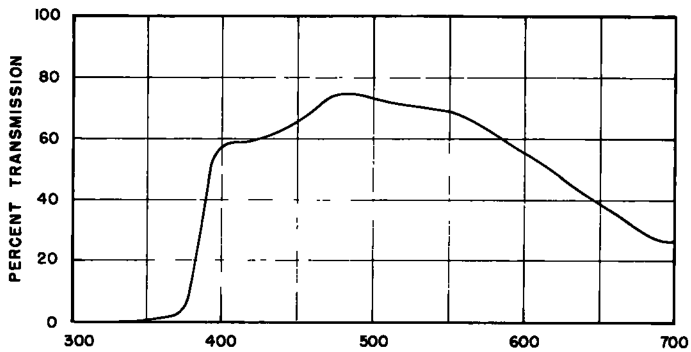

Figure 1.

RESULTS

Figure 2 shows that the family of mean dark adaptation curves rises in an orderly manner as a function of age. With the exception of the reversal of the cone curve elevations for the 16-19 and 20-29 year old groups, no other reversal is visible. This slight overlap is not sustained and it does not reverse the order of terminal points of the mean curves as a function of age.

Figure 2 demonstrates that the effects of age occur immediately since the initial mean scores are separated. It can be seen that with the passage of time the absolute differences among the mean curves increase. Therefore, the full effect of age on the course of adaptation is most clearly revealed when the curves approach their respective asymptotes.

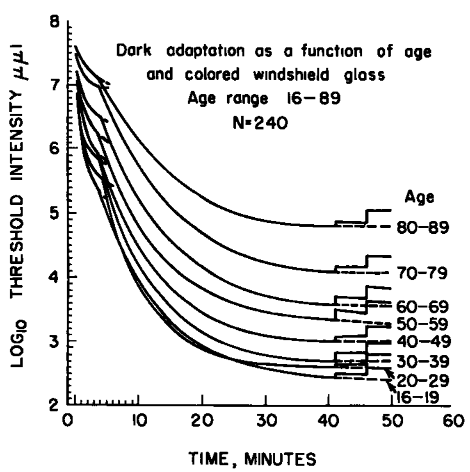

Figure 2.

Figure 2 shows that the first terrace-like rise in the curves begins at the 41st min, the time when filter A was interposed between the S's eye and the test light. The magnitude of the rise represents the average increase required in the intensity of the testlight before the Ss could just see the stimulus, and therefore the functional effects of the 90 percent transmission factor of filter A. The introduction of filter B at the 46th min was followed by a second rise at the ends of the curves.

In Table 1 columns B, C, and D give the log values at the 40th min, 41st min after the introduction of the clear glass filter, and after the introduction of the tinted filter at the 46th min. Columns E, F and G give the anti-log values of columns

TABLE 1

DARK ADAPTATION AS A FUNCTION OF AGE, TIME AND WINDSHIELD GLASS

Age	Luminance									
	Log10			uul					% Luminance Increase	
A	B 40thMin No Glass	C 41st Min Clear Glass	D 46th Min Tinted Glass	E 40th Min No Glass	F-E Diff CG-NG	F 41st Min Clear Glass	G-F Diff TG-CG	G 46th Min Tinted Glass	H No Glass to Clear Glass	I Clear Glass to Tinted Glass
16-19	2.427	2.446	2.571	267.3	12	279.3	93.1	372.4	4.48	33.33
20-29	2.602	2.632	2.777	399.9	28.6	428.5	169.9	598.4	7.15	39.64
30-39	2.694	2.789	2.952	494.3	120.9	615.2	280.2	895.4	24.45	45.54
40-49	3.016	3.043	3.204	1037.5	66.6	1104.1	495.4	1599.5	6.41	44.86
50-59	3.346	3.408	3.600	2218.2	340.4	2558.6	1422.5	3981.1	15.34	55.59
60-69	3.642	3.653	3.813	4385.3	112.5	4497.8	2003.5	6501.3	2.56	44.54
70-79	4.104	4.142	4.306	12705.7	1161.8	13867.5	6362.5	20230.0	9.14	45.88
80-89	4.806	4.847	5.030	63973.3	6333.2	70306.5	36846.0	107052.5	9.89	52.40

B, C, and D. It can be seen in the difference columns F-E and G-F that both the clear glass filter and the tinted glass filter lead to an increase in the demand for light for all age groups. However, as age increased the relative demand for light increased at a geometric rate. Thus, the light decrement for elderly persons was far greater than the light decrement for younger persons. Columns H and I give relative percent change in the demand for light as a function of filter A and B, and age.

The range of mean increase in demand for light associated with filter A was 12 μμl for age 16-19 to 6333.2μμl for age 80-89. Tinted windshield glass was associated with a similar mean increase in demand for light of the order of 93.1 μμl for age 16-19 to 36846.0 μμl for age 80-89.

An elaborate statistical analysis of the results was not considered appropriate because the effect of both filter A and filter B on the degree of dark adaptation of Ss within the various age groups was so obvious. When filter A was introduced during the time interval 41-45 min, 6 Ss indicated a decrease in demand for light, 7 Ss failed to change their demand, and 227 subjects demanded an increase in the brightness of the test patch. When filter B was introduced in the interval 46-50 min, one subject decreased his demand for light, and 239 Ss demanded an increase in the brightness of the patch.

The complete data are given in Table 2.

TABLE 2

CHANGE IN DARK ADAPTATION LEVEL FOLLOWING THE INTRODUCTION OF CLEAR WINDSHIELD GLASS AND FOLLOWING TINTED WINDSHIELD GLASS

	Number of Ss Changing Demand for Light After Introduction of Filter A			Number of Persons Changing Demand for Light After Introduction of Filter B		
Age	Decrease	Unchanged	Increase	Decrease	Unchanged	Increase
16-19	1	1	28	1	0	29
20-29	1	0	29	0	0	30
30-39	3	1	26	0	0	30
40-49	0	0	30	0	0	30
50-59	0	2	28	0	0	30
60-69	0	2	28	0	0	30
70-79	1	0	29	0	0	30
80-89	0	1	29	0	0	30
Sum	6	7	227	1	0	239

Because the probability of a change in the demand for light would be one-third in favor of decreasing illumination, one-third in favor of increasing illumination, and one-third favoring no change, the hypothesis of chance may be tested as shown in Table 3. X^2, 405.205, and .P, 0.001 show that the chance hypotheses could not be maintained. Therefore the increase in the demand for light in the presence of filter A cannot be considered a chance effect.

Since 239 subjects of the total sample of 240 Ss demanded an increase in light following the introduction of tinted windshield, the influence of tinted windshield glass appears to be unequivocal.

TABLE 3

NO GLASS VERSUS CLEAR GLASS

Chi Square Test for Chance			
	Decrease	No Change	Increase
Frequency of observed changes in demand for light	6	7	227
Frequency of expected changes in demand for light	80	80	80
Chi square	405.2050		
df	2		
P	Exceeds 0.001 level of confidence		

DISCUSSION

The present data show that dark adaptation efficiency drops sharply as age increases. As a matter of fact, at the 40th min of adaptation subjects in the oldest group required 239 times more light to just notice the test stimulus than persons in the youngest group. Tinted filters decreased the efficiency for both groups.

The statistical treatment and Figure 2 show clearly that when the viewer was presented with the tinted windshield filter that the amount of light necessary to just see the test patch increased. Functionally this was equal to a regression in time to some former, less adequate, level of adaptation. For the youngest and most efficient Ss, the filter, in effect, reinstated the lower degree of efficiency present at the 30th min of adaptation. Because maximum dark adaptation is nearly reached after ½ hr the youngest subjects were not seriously penalized. However, the older subjects, who were many times less sensitive than the youngest persons, regressed still further on the timecontinuumto a level characteristic of the 23 min of adaptation. This was equivalent to the threshold manifested by the youngest group after only 5 min of adaptation. Comparatively, then, the oldest subjects were not only penalized by age, but were further penalized by the tinted filter to a relatively greater extent than were the youngest subjects. Stated in another way: the eldest subjects who viewed the test patch through the tinted filter required 50 min to achieve a degree of dark adaptation achieved by the youngest subjects without any filter after only 5 min. Or stated in still another way: after 5 min of dark adaptation the night vision of the younger subjects on the average was equivalent to the maximum threshold expected of subjects 80-89 years of age who viewed the test patch through tinted windshield glass.

The evidence from this study and other research clearly indicates that filters of all types including sections of tinted windshields interfere with every major visual function. There is no evidence to support the assertion that tinted windshields aid vehicle drivers in any way. Nevertheless, between 1950 and the present time millions of land vehicles have been equipped with different types of windshield glass that reduce illumination coming to the eye of the operator from 30 (23) to 28 percent (6). Coincidently, a 30 percent reduction in transmission is the lower limit permitted by the American Standards Safety Code (2), a criterion difficult to justify because it fails to take into consideration individual differences or the variation in individual tasks performed by persons at reduced levels of illumination.

A 30 percent reduction in luminance may not present difficulties as long as there is enough illumination to maintain cone vision if there is no serious distortion of images, interference with depth perception, or false rendering of color. But tinted windshields are permanent installations, and therefore do not allow vehicle operators a choice of filter with maximum transmission when the level of illumination in the driving environment falls below the amount necessary to maintain cone vision. As indicated previously, road illumination is often less than enough to sustain cone cell sensitivity.

What then is the relationship of these findings to the problems of vehicle control? It has already been shown that the frequency of accidents is proportionally greater at night than during the day. In addition it has been demonstrated in four different cities that there was a statistical correlation between reduction of fatal and non-fatal accidents and increases in road and street illumination. No data seem to be available showing that when road, street, and highway illumination is increased that accidents also increase. The data favor the hypothesis that the correlation between accident reduction and increasing illumination is not accidental.

It can be seen that there is a relationship between variation in rate of adaptation not only among persons of the same age but as a function of age as well. For instance, illumination in the night driving is not constant. It fluctuates in intensity from relatively high levels, 3.1716 ft lamberts, to relatively low levels, 0.0028 millilamberts. But it does so intermittently, and in an unpredictable manner at a rate that cannot be matched by the dark adaptation process of even the most efficient visual apparatus. The low levels of illumination are often not high enough to sustain cone vision. This is indicated by the 0.0028 ml shown above. Thus, the vehicle operator must depend part of the time on rod cell vision, usually of the incompletely dark adapted eye, or otherwise on the relative levels of partial dark adaptation characteristic of the intersection between cone and rod vision. It is clear that age brings deterioration of the initial capacity, and that filters artifically deprive the viewer of a considerable degree of his remaining sensitivity. Vehicle operators are forced to depend on something less than the full sensory command over their driving environment.

Vehicle operators must function under the dynamic conditions of traffic movement which at varying rates demand accurate perception of movement and velocity. This perceptual capacity varies among individuals to a marked degree. Individual differences as high as 40 percent (7, 34, 35) have been found. And because the perception of movement and velocity varies as a function of cone vision and rod vision, it is directly related to age and to degrees of illumination which determine cone and rod sensitivity. This means that the rate of movement of a vehicle will not appear to be the same under high and low luminance levels. Unnecessary reduction of available light will not assist the operator to function more adequately. For instance, it would be expected that if tinted windshield glass merely changed the appearance of the stimulus world of the driver that he would adapt to novelty quickly. But this is not the main effect: at certain distances stimuli that would ordinarily be seen through clear glass cannot be seen at all through tinted windshield glass.

The perception of distance, movement, and velocity is growing in importance with every increment of increased speed added to the flow of modern traffic. For instance, when the limitations imposed on vision by tinted windshield glass are integrated with the data on mean braking distance it has been demonstrated (8) that operators who use tinted windshield glass should reduce their general speed by a factor of about 30 percent. But it has been found that in the last 19 yr, average traffic speed has increased by about 5 mph, and that the passing time of the more powerful vehicles has decreased by approximately 5 percent. Evidence does not show that tinted windshield glass has resulted in lower speed on the highway.

More interesting was the discovery that even on highways where the passing sight distances ranged from 1,800 to 3,300 ft some vehicles completed their pass when an oncoming vehicle was less than 200 ft away. When it is realized that two vehicles approaching one another at the rate of 50 mph will meet in slightly less than 200 ft in 1.4 sec, it will also be recognized that margins of safety on highways become slight indeed. Reducing illumination by 30 percent in this situation at night could not be expected to improve visual perception on which safety depends.

Still more arresting was the finding that though vehicle speed has increased slightly, and passing time (26) reduced by a small percentage, the left lane road distance required to pass another car has increased by about 19 percent. This was found to be true on roadways where the geometry of the seeing and passing distance of the track had not changed in 20 yr.

It has been shown that tinted windshield glass results in the reduction of visual efficiency even at distances less than 200 ft. Therefore, not only does tinted glass interfere with vision, it does so in a man-machine-environmental situation complicated by conditions of marginal safety.

Visual efficiency is fundamental to the precise and reliable control of vehicles under these circumstances. In demonstrable instances these margins are being reduced by such factors as increasing traffic congestion, and increasing demand for more passing space in fixed sight distance regions. Thus, when the limitations imposed on vision by tinted windshield are integrated with the data on mean braking distance it has been demonstrated (8) that operators using filters should reduce their general speed by about 30 percent. But vehicle speed has not been reduced on the average. It has been increased by at least an average of 5 mph. The relevance of the perception of movement and velocity to highway traffic problems of many types is clear.

Inasmuchas it has been demonstrated that tinted windshield glass does not aid, but distinctly hinders visual efficiency at low levels of illumination, then the advocates (5, 6, 9) of increasing highway illumination and the advocates of tinted windshield glass are diametrically opposed. Actually the introduction of TWG has cancelled out much of the effort of agencies working to increase illumination. To compensate for the limiting effects of tinted windshield glass, illumination of streets, roads, and highways should be increased by the same amount, preferably more. To do this, artificial illumination would have to be further raised by 30 percent or more merely to maintain the advances made by highway illumination engineers in the last few years.

CONCLUSIONS

1. Both clear and tinted windshield glass reduce the amount of light that reaches the retina of the vehicle driver's eye.
2. Tinted windshield glass transmits less light than clear windshield glass, where the transmission factor of clear windshield glass is about 90 percent, and the transmission factor of tinted windshield glass ranges from 55 to 70 percent.
3. Some areas of tinted windshield transmit less light than is permitted by the American Standard Safety Code. The lower limit allowed by this code is 70 percent transmission.
4. Dark adaptation is a function of age.
5. Clear windshield glass interposed between the testlight and the eye of the subject at terminal levels of dark adaptation is followed by a greater demand for light to just see the test stimulus, and therefore a rise in the dark adaptation curve.
6. Tinted windshield glass interposed between the testlight and the eye of the subject at terminal levels of dark adaptation is followed by a demand for light to just see the test stimulus that exceeds in magnitude the demand caused by clear windshield glass.
7. Both clear and tinted windshield glass are impediments to vision under low levels of illumination for persons ranging in age from 16 through 89 yr.

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The Association Between Retinal Sensitivity And the Glare Problem

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● ONE OF THE more frustrating problems in the consideration of the effect of glare from headlights is the difficulty involved in obtaining effective measurements during the relatively short duration of the passage of two vehicles. It has occurred to us that the discomfort and reduced visibility during headlight glare may be an adaptation problem instead of a brightness problem. This opinion has been substantiated by recent investigations of retinal sensitivity during photopic adaptation.

The luminance on the road, in the headlamp beam, is fairly high. That of the background is low. As an oncoming car approaches, from this low luminance background area, the background suddenly increases by a large factor. The rate of this increase may be more rapid than the eye as a whole (retina and pupil) can tolerate by adaptation. Consequently visual perception suffers and visibility is temporarily but dangerously reduced. The phenomenon of discomfort must be associated with the adaptation level because there is no discomfort when lighted headlamps approach during daylight.

Two vehicles moving at 50 mph, approach each other at about 160 ft per sec. If the glare is assumed to be debilitating at 1,000 ft, the glare will persist for 6 sec, until they have passed each other. Assuming that the background is nearly dark, say of luminance of less than 1 foot-candle, and that the illuminated pavement can be as bright as 15 foot-candles, what happens to retinal sensitivity during this sudden shift of background, when the approaching headlamps become annoying?

Retinal sensitivity can be assayed by the measurement of the critical fusion frequency of an alternating light stimulus (1). The extent of the variation between individuals and the association of reduced sensitivity with increasing age was described to the Highway Research Board in 1959 (2). It has been found that this reduced sensitivity is associated with a delay in shifting visual perception from low to higher levels of ambient illumination. The delay may be for a few seconds, or it may last nearly a minute. The lower retinal sensitivities are associated with greater delay to a degree that far exceeds chance, and retinal sensitivity may therefore contribute to the difficulties in night visibility under conditions of glare from the headlamps of an approaching vehicle.

In order to understand the authors' method of assessing retinal sensitivity it is first necessary to consider the phenomenological aspects of flicker, because this method is greatly different from standard or previous procedures. Usually, a large lighted area is alternated mechanically or electronically between blackness and brightness, at various ratios of light and dark. As the rate of alternation is increased, the overt perception of black and white changes to a rather random series of irregular flashes, and then, at sufficiently rapid rate, to steadiness. The change towards steadiness is not abrupt, as is often reported, but follows a normal probability function if the steps are small enough.

In this set up, the level of a large background is maintained at a steady luminance, just matching the average of the alternating stimulus. But the stimulus does not alternate between darkness and brightness, it alternates between two brightnesses, one 5 percent above and the other 5 percent below the luminance of the background, at equal intervals. The background is 50 deg in diameter, the stimulus is 1 deg, or less than the foveal area. The subject maintains foveal fixation on this spot. As the rate of alternation approaches the "critical" or threshold range, perception of the changes due to the alternating stimuli tend to fade out. At speeds above this rate, the spot itself becomes uniform, and merges into the background. During the threshold range, the spot seems to scintillate. That is, there appear to be random smaller flashes or shadows within the small alternating area. In fact, the behavior of perception seems closely analogous to the behavior of the random scintillation found in a phosphor exposed to a radiation field at low intensity. For this reason the authors prefer to describe the stimulus as alternating and the perception as scintillating, in order to avoid the semantic error of using the term "flicker" for both stimulus and perception.

Within the threshold range, the probability of a report of scintillation follows the normal probability curve of liminal measurements, varying, as alternation rate increases, from 100 percent or certainty of visual perception, to 0 percent or certainty of failure of visual perception. If the stimulus is described in milliseconds of duration of one-half cycle, instead of rate, there is a direct linear relationship between the standard deviation of the probability of seeing curve and the logarithm of the stimulus time, shorter times being associated with lower chance of perception.

In presenting the stimuli in this threshold range, it is essential that they be given in a random order. That is, the subject must not be able to anticipate his response. Although this procedure is followed assiduously in all psychological laboratories when measuring thresholds, the fact of its necessity has not extended sufficiently outside of the laboratory. Consequently the medical literature of threshold measurements for the so-called "flicker" phenomenon nearly always shows that this precaution has been neglected, resulting in many failures in this application of repetitive stimuli to the estimation of retinal sensitivity (1). In those experiments where the subject controls the stimulus rate, this error becomes maximal.

Different individuals will show different stimulus times for the 50 percent probability of seeing, or "50 percent limen." Thus a group of subjects can be graded with respect to their scintillation thresholds as an index of retinal sensitivity to a low contrast repetitive stimulus.

The experiment using this technique, which is being described in this report, included the following phases:

1. Estimate of scintillation threshold at 50 cd/m^2 (approximately 15 foot-candles).
2. A period of adaptation to dim light, at 0.3 cd/m^2 (about 0.09 foot-candles) for 5 min.
3. A reassessment of scintillation threshold at 50 cd/m^2, starting near the upper end of the liminal range.

In this procedure, it is frequently noticed that after the adaptation period the subject cannot see at all the stimulus he previously responded to with high probability. When this happens the stimulus is continued until he does respond. This delay may be too short to measure, but may require as much as ½ min for adaptation to the brightness of the background. The modal value of this delay, with the 39 subjects studied, was 5 sec. The subject was not blinded, he merely suffered a reduction of sensitivity during this period. It is believed that this is actually a glare phenomenon, and that as such, it is subject to accurate measurement.

To relate the delay period, or glare period if it may be so described, to retinal sensitivity, the data have been arranged in the double trichotomy given in Table 1. Here the actual cases are given and compared to the theoretical distribution of the same frequencies, had there been no causal relationship between sensitivity and glare. Testing this trichotomy against the null hypothesis shows $X^2 = 22.89$, with 9 deg of freedom. From this it is concluded that the data indicate 0.3 percent probability that there is no relationship between recovery from glare and retinal sensitivity.

Examination of the relative association between glare recovery and retinal sensitivity (Fig. 1) tells us that all cases of good retinal sensitivity showed fast recovery from glare, and that the majority of the cases of poor retinal sensitivity showed poor recovery from the glare.

The previous report (2) predicted that night visibility might be depressed in cases of poor retinal sensitivity, and that older persons showed such poorer sensitivity. The present report permits sharper prediction that one of the forms of decreased performance to be expected in poor retinal sensitivity will be a reduction of the capacity to overcome the effects of glare, such as occur with approaching vehicles.

Obviously more specific research is required, in which the luminances involved more nearly match those typical of night driving conditions. Such a study could serve to forewarn both elderly drivers and younger ones who have driven all day in bright

TABLE 1

DOUBLE TRICHOTOMY OF RELATIONSHIP BETWEEN SECONDS OF "GLARE" DELAY AND ARBITRARY SCORE OF RETINAL SENSITIVITY. NUMBERS IN PARENTHESES REPRESENT NULL DISTRIBUTION.

	Retinal Sensitivity			
Glare Delay	Poor 19-25	Median 26-34	Good 35-51	
Fast 0-4 sec.	3 (7.4)	7 (6.9)	8 (3.7)	18
Median 5-7 sec.	6 (5.7)	8 (5.4)	0 (2.9)	14
Slow 8-25 sec.	7 (2.9)	0 (2.7)	0 (1.4)	7
	16	15	8	39

Null hypothesis: $X^2 = 22.89$
$n' = 9$
$p = 0.003$

sunlight, of the degree of risk above average that they are exposed to when meeting headlamps at night. However, it would be naive to assume that elderly or exposed drivers would have more accidents, they will only suffer more discomfort. When it is realized that driving is a series of accident preventions, the more experienced or more careful driver will be more successful in anticipating and avoiding accidents. The value of a specific study on glare and sensitivity would lie in focussing attention on the danger, and with proper public education, could serve to reduce one of the many hazards involving night visibility.

ACKNOWLEDGMENTS

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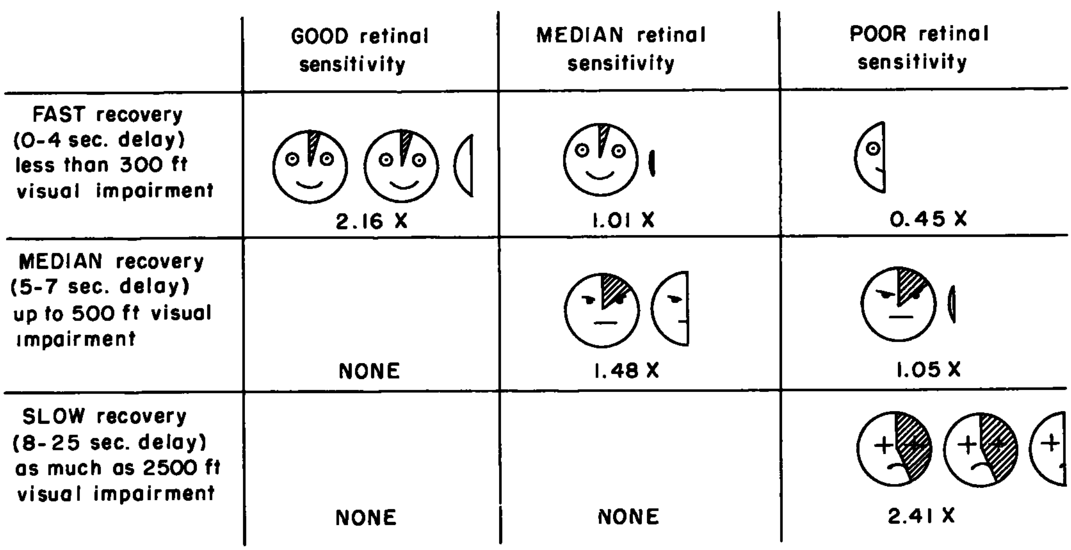

Figure 1. Relationship between actual count and pure chance prediction for glare recovery and retinal sensitivity.

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Some Factors Affecting Driver Efficiency At Night

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Combining the results of certain published researches yielding background information on human reactions brings out certain relationships of importance in traffic design, operation and safety. Some of these affect night driving efficiency. Increased task difficulty leads to longer perception-judgment-response times. At night, driver response time may be slowed an additional amount by reduced visibility.

Data on time for dilation and constriction of the pupil of the eye in adapting to light and to dark indicates that the "dark hole" effect in entering a tunnel can be eliminated by design taking account of the human reaction. It also explains accident experience reported in crossing certain highly illuminated thoroughfares and suggests remedial measures. Reduced sensitivity and a change of relative sensitivity to colors may lead to driver errors. These characteristics of the human eye should be given proper consideration in highway design and traffic engineering activities to improve operation and reduce hazards.

Fatigue results in reduced human efficiency and, for most drivers, probably will be greater at night. Studies in industry indicate that moving bright sources in the periphery of vision tend to induce fatigue. They may be also a factor in inducing sleep. An experimental study of drowsiness in driving showed an increasing frequency of eye closure leading up to actual drowsing behind the wheel. Turnpike and other studies of one car accidents seem to indicate a high proportion of sleep accidents between midnight and 6:00 a.m.

It is suggested that discomfort glare may be of great importance as a fatigue and drowsiness inducing factor and that the threshold for discomfort glare may be lower under sleep deprived and fatigued conditions of the driver.

Drivers must realize that critical phases of the driver's task often are even more critical under night driving conditions. Proper consideration of eye characteristics in design of lighting, signing and marking of highways can help to reduce hazards from the various factors discussed.

● CONSIDERABLE INFORMATION is available from research in the human factor sciences which can be put together to contribute to better understanding and solutions of various highway problems. An attempt to do this was made for certain areas of behavior some time ago (1). From this and other studies, this paper points out some factors affecting highway efficiency at night. Many factors affect driver efficiency in daylight as well as at night, but some of them are more likely to occur at night or may be of greater influence under night conditions.

PERCEPTION, JUDGMENT AND RESPONSE TIME IN REDUCED VISIBILITY

Combining the results of various studies of perception, judgment and response time measurement shows clearly that perception-judgment-and-response time increases with the complexity and difficulty of the task, that is, the number of component stimuli and responses. Times required for these human reactions in driving range from less than 0.5 sec to 3 or more sec depending on the complexity of judgment involved (1).

Superimposed on this response time increase as a result of task complexity is another increase due to task difficulty from lower illumination or other conditions leading to poorer visibility. Figures 1 and 2 show results of two different studies illustrating this increase of response time as task difficulty posed by poorer visibility conditions increased. In both cases, the whole curve showing the effect of complexity is

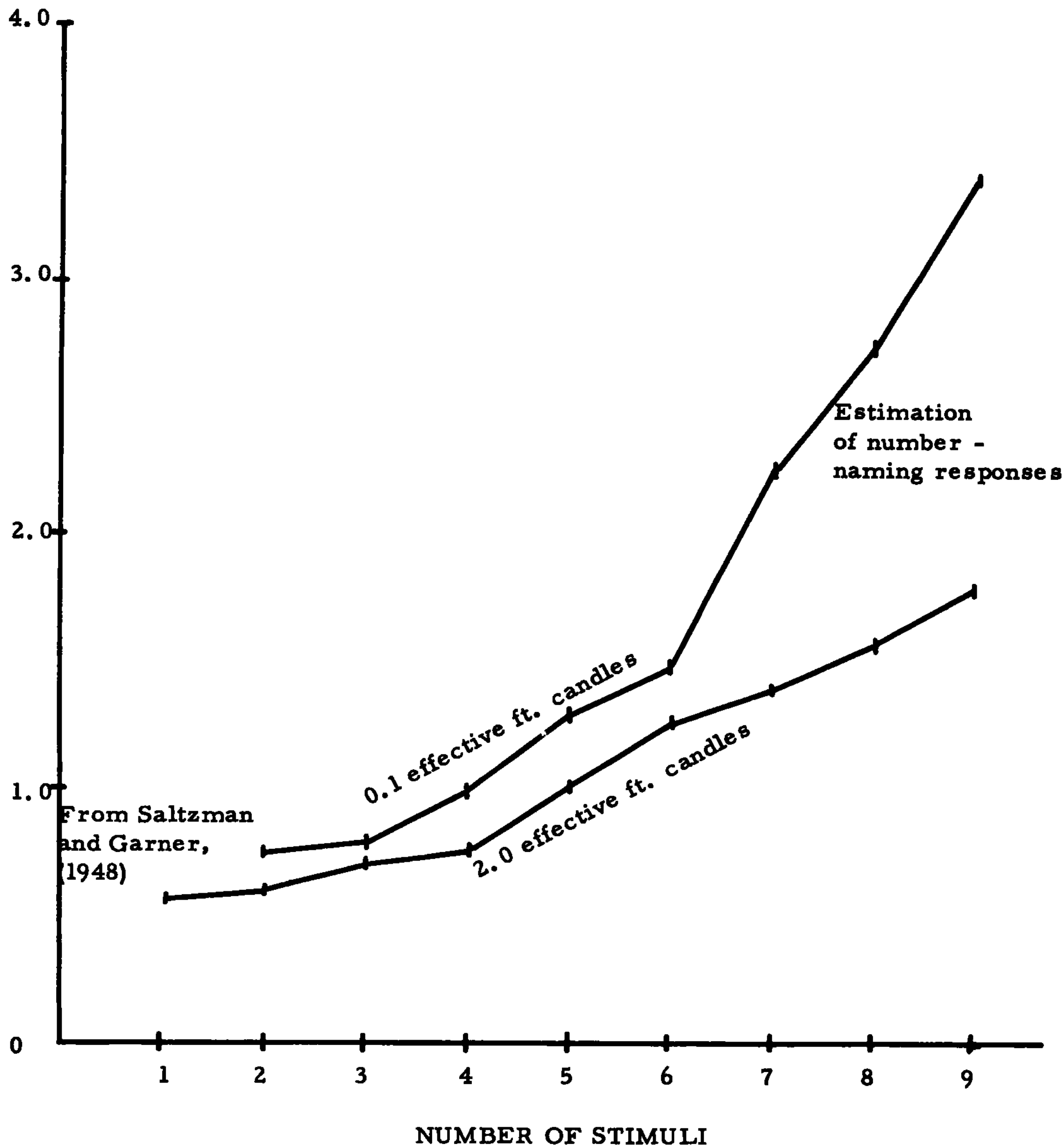


Figure 1. Increase of response time with increased difficulty of perceptual task; estimating number of circles and dots during short presentation (From (1), p. 15).

transposed upwards under lower illumination and visibility. Figure 1 resulted from a laboratory study whereas Figure 2 represents results from outdoor, full-scale experimental simulation of a judgment required in driving.

Thus it is seen that the decreased visibility (often characteristic of night driving)

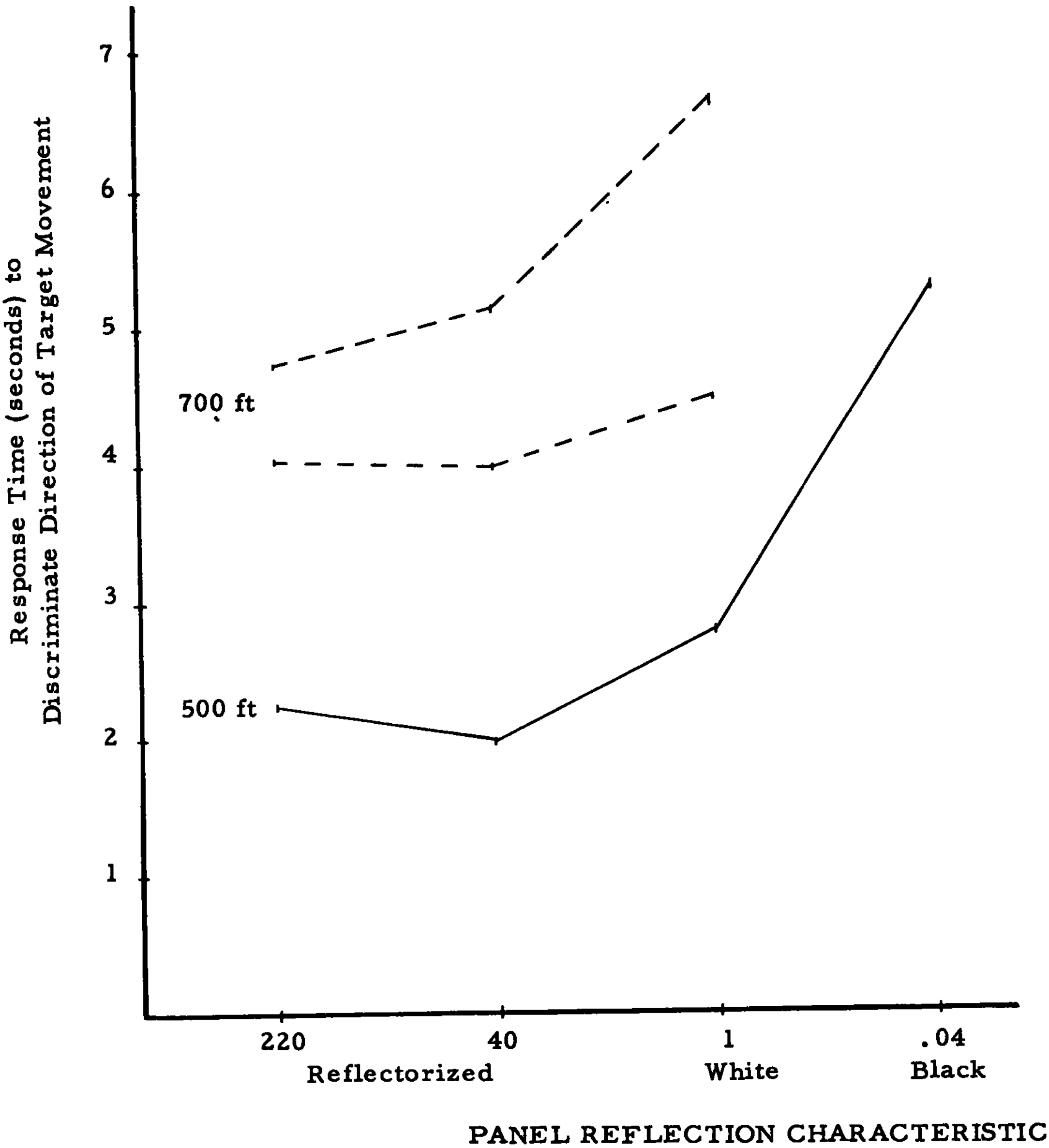
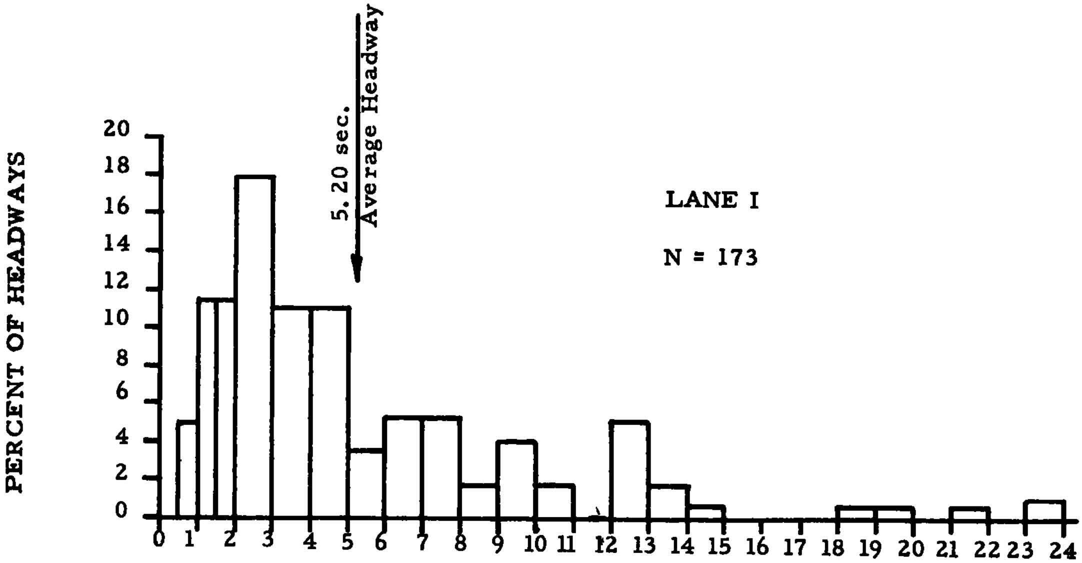


Figure 2. Increase of perception-response time when target distance is greater and illumination lower; judging direction of relative motion of panel on rear of truck, relative target speed ± 5 mph (From (10)).



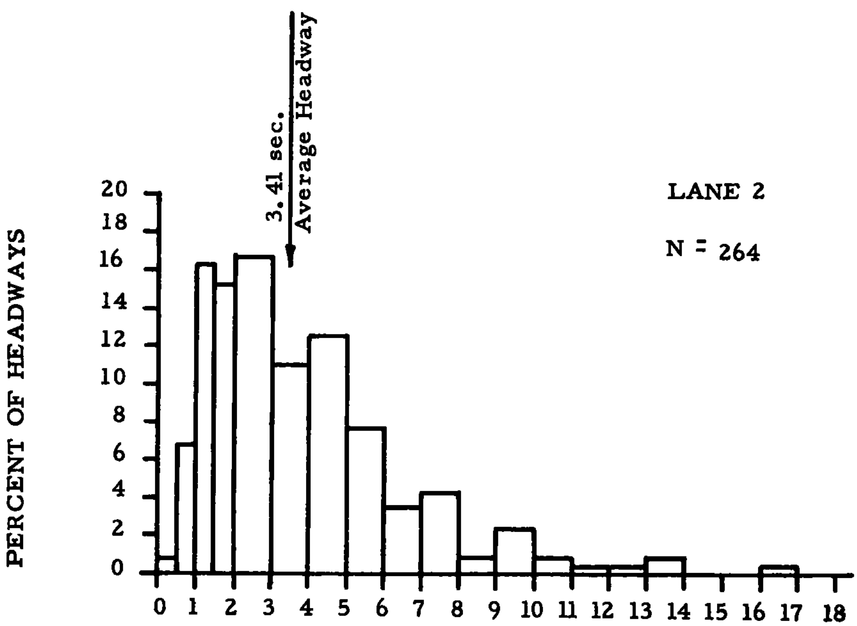


Figure 3. Distribution of individual time headways at night, Ford Expressway, Detroit; 7:15 to 7:30 p.m., Feb. 14, 1958, lighted.

will tend to decrease efficiency in this process of perception-judgment-and-response in terms of response time. Errors also may be expected to increase.

IS THIS AMOUNT OF SLOWING CRITICAL?

Increases of response times to the above extent may be very critical. In a recent paper (2) it was pointed out that in modern traffic on high-speed highways in daylight many drivers are led to operate at time spacing between vehicles as low as 0.25 sec quite commonly. A similar situation was found in records of night driving made in Detroit (3). Figure 3 shows an example of such headways measured after dark on a lighted urban expressway. Time headways under 1.5 sec were less frequent than in daylight but still constituted from 16 to 23 percent of the cases.

As many as 23 percent of time spacings were under 1.2 sec in lane 2 and about 7 percent were under 0.7 sec. Center to center spacings of 0.5 to 1.0 sec occurred in some 5 to 7 percent of the cases and almost one percent were under 0.5 sec. To determine time between vehicles, the length of the vehicle must be subtracted. This represents from ¼ to ⅓ sec at 50 and 40 mph. Thus these time spacings in nighttime traffic were from 0.25 to 0.70 sec; that is, at or below minimum perception-response time values. Time headways below 1.5 sec represented spacings below 1.2 sec approximately.

Therefore, increasing the time for perception-judgment-and-response to 1, 2 or 3 sec is of great importance both for safe operation and for effective highway capacity as well.

On rural highways, if several cars are traveling together in platoons, time headways may be of similar magnitude. If traffic is lighter on open high-speed highways, time headways may be longer and driver response somewhat less critical. However,

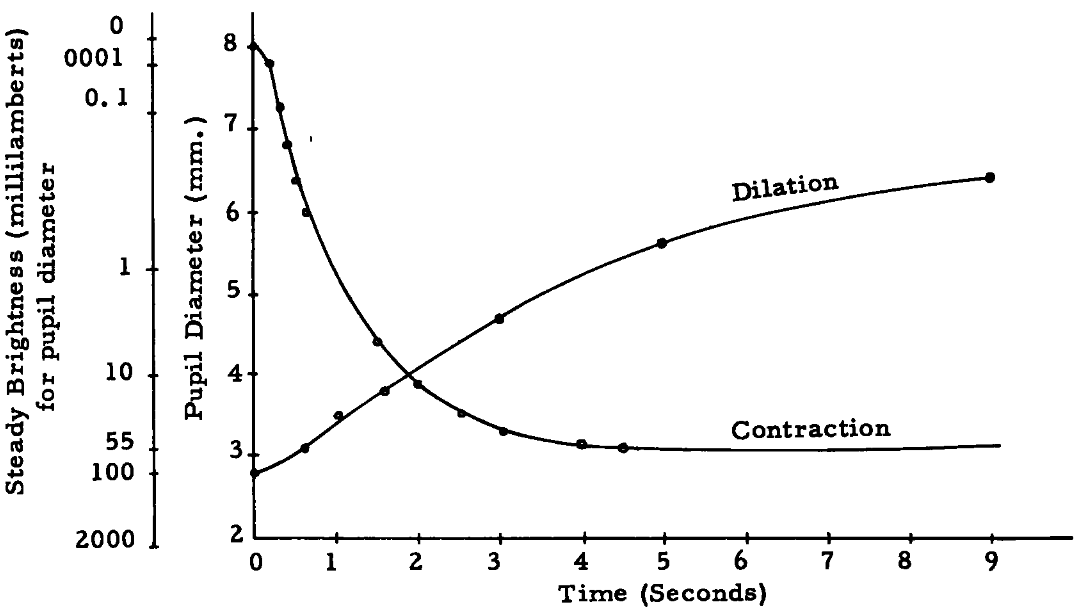


Figure 4. Pupillary contraction and dilation (From (1), Fig. 11).

at intersections or interchanges, or whenever there is passing or bunching of vehicles, response times still will be critical.

Or, if the drivers assume a greater time spacing because of poorer visibility, there may be a backing up effect at that particular point which will affect the interchange capacity. Even then, slower perception-judgment-and-response time may result in greater hazards as vehicles enter from side roads or ramps.

PUPILLARY RESPONSE TIMES AND VISIBILITY

Effects of time required for pupillary dilation when entering the dark and pupillary contraction when emerging into higher illumination are now compared. Data from several well-known studies of pupil diameter changes (Fig. 4) show that the dilation response is considerably slower than the contraction to light (1).

The slower rate of dilation may lead to an almost continuous lowered visibility for dark objects in passing a succession of headlights or street lights. The eye will be going through a series of fluctuations in pupil size almost continuously under such circumstances.

For seeing in moderately low brightness, the retina adapts relatively rapidly as

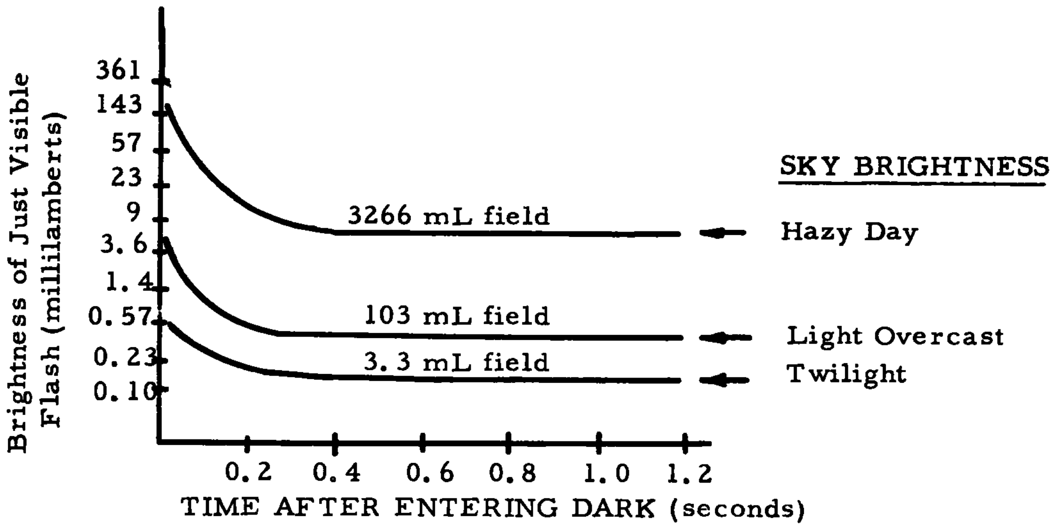


Figure 5. Visual sensitivity to brief flashes of light very shortly after entering the dark from various field brightnesses with constant small pupil opening (See (1), Fig. 12).

compared to the pupil. Figure 5 shows that when the pupil size is artificially held constant the eye reaches its new threshold of sensitivity in a little over 0.2 sec when entering the dark from various field brightnesses. Other studies, of course, show that the length of exposure to a brighter field and the degree to which dark adaptation must be carried, affect such measurements greatly. However, where lower illumination levels are moderate and where intensities vary rapidly, as in streets and highways, Figures 4 and 5 together show that the response of the pupil will control visibility because the retina cannot adapt until the pupil allows more or less light to enter the eye.

ACCIDENT FACTOR AT BRIGHTLY LIGHTED INTERSECTION

Referring again to Figure 4, note that contraction in going from a field brightness of one millilambert to one of 50 millilamberts takes place in about 1.5 sec. In contrast, dilation to adapt to the reverse change (from 50 ml to 1 ml) requires some 3.5 sec.

Therefore, as a driver approaches an intensely lighted intersection his pupils will contract by the time he has reached it because he is seeing the brightly lighted area as he approaches. Thus his visual efficiency will be maintained. However, if there is a relatively sharp cut-off of the light, he will go suddenly into the dark again. The pupils will not have dilated to the 1 millilambert condition for another 3 or 4 sec and his visual efficiency will be much reduced.

The brightness for each pupil diameter is shown beside the pupil diameter scale in Figure 4. Because the light transmitted is proportional to area of the pupil, in the preceding example, there will be roughly a 3:1 reduction in the effective brightness of objects and dark objects may drop below the visual threshold. This is undoubtedly a factor in accidents when crossing brightly lighted streets and highways where a driver hits a pedestrian or other dark object beyond the lighted area. A gradual reduction of illumination should be provided on side streets to avoid reduced visual sensitivity before the eye has dilated again.

Although this effect is well-known to most of those in technical fields dealing with visibility, it is not always known to those in traffic engineering and highway design. Questions raised as to the cause of accidents in going from brightly lighted to dark areas suggest that this result of characteristics of the eye may be of practical interest to traffic engineers.

TIME VALUES IMPORTANT FOR TUNNEL APPLICATIONS

This same principle relates to the entrance to tunnels. The effect is well-known and illumination intensity is usually increased at the mouth of the tunnel for daylight conditions. In such applications pupillary response times are fundamental and should not be overlooked.

From the curves it can be seen that by gradual reduction of daylight before reaching the entrance of the tunnel at a rate to allow for pupil dilation time it would be possible to reduce or eliminate the effect of plunging into the dark. Such a plunge is still found in some tunnels in spite of increased artificial illumination in the entrance. At night, the problem is met at the exit of the tunnel in going from a lighted tunnel into darkness. Here, approach illumination usually is provided by luminaires outside the tunnel. How-

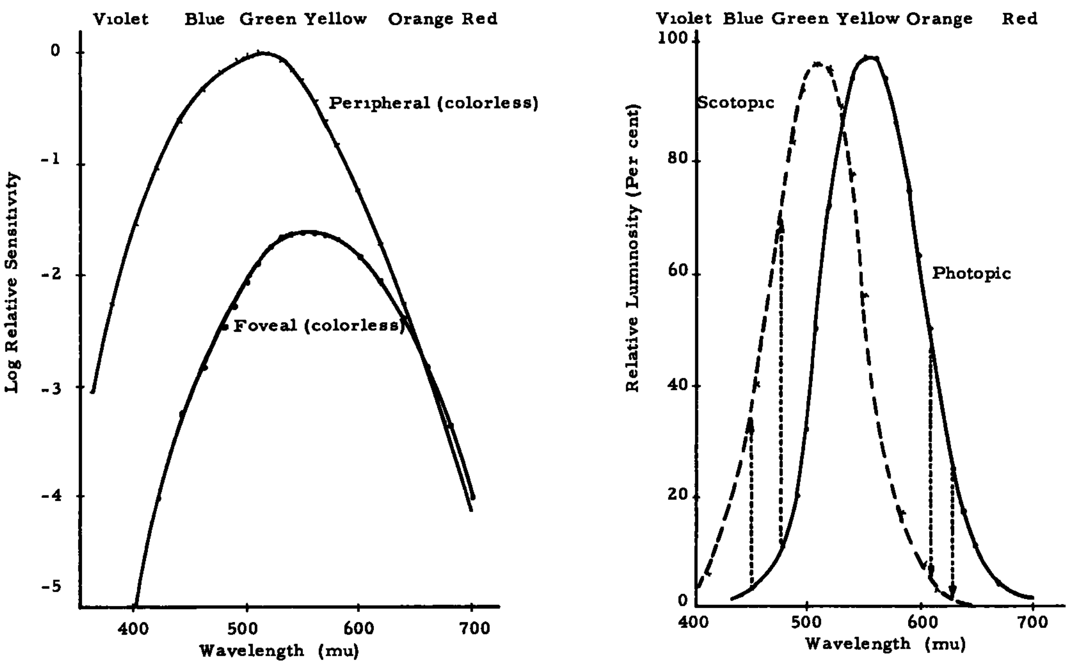


Figure 6. (Left) Reciprocals of least relative energy to produce a sensation of light (See (1), Fig. 11a). (Right) Relative luminosity of colored stimuli under daylight (photopic) and night (scotopic) illumination levels (See (1), Fig. 11b).

ever, unless carefully designed, gradual reduction of intensity is provided at the end of the lighted section, a period of several seconds of reduced visual sensitivity may yet occur in leaving the lighted approach section. Hence, an unlighted vehicle parked at such a location may be visible to a person standing near it but not to an emerging driver.

REDUCTION AND CHANGE OF COLOR SENSITIVITY

Change from photopic vision in high illumination to mesopic and scotopic or vision under lower illumination conditions at night involves complex mechanisms on which much research has investigated the many and complicated interrelationships. For practical purposes of the traffic engineer, however, it may be said that in general there is a marked loss of sensitivity to most color stimuli and a change in relative sensitivity to the different colors.

Figure 6 (left) shows the relative sensitivity for both foveal and peripheral vision. It is well-known that under high illumination and brightness conditions foveal vision is most acute and is most used in seeing. Under low illumination peripheral vision is more sensitive.

In Figure 6 (right) relative luminosity shows the relative effectiveness of light of different wave lengths as stimuli under the two extreme conditions of seeing. It shows that the greatest sensitivity moves from the light yellow region over toward the greenish. Furthermore, dark red is very much reduced in stimulus effectiveness under low illumination conditions and blue wave lengths have gained effectiveness relatively.

Thus in terms of driver efficiency, it may be said that at nighttime under low illumination, sensitivity to the red end of the spectrum becomes much less efficient and sensitivity to the blue end trends to become more efficient relatively. At intermediate levels of illumination, both mechanisms of the eye may combine to give intermediate visual sensitivities.

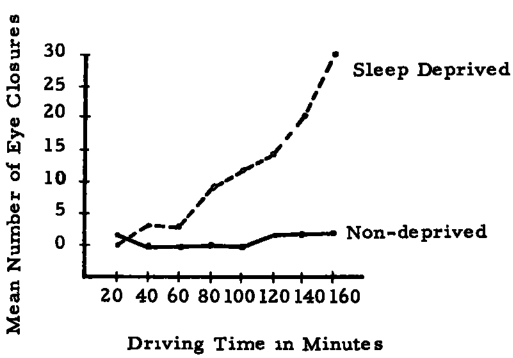


Figure 7. Comparison of deprived and non-deprived groups on eye closure (From (7), Fig. 4).

COLOR CONSTANCY AND DRIVER ERRORS

Under low luminance conditions where colors in the red end and blue end of the spectrum have almost passed below threshold of a driver's sensitivity, a well-known psychological effect called color constancy may cause errors in driver judgment. Under these conditions, a driver may detect a visual stimulus but not the color characteristic. He then unconsciously reads into it a color he associates with an object or which he anticipates, and this may prove to be an erroneous one. This effect can be demonstrated experimentally in the psychological laboratory with ease.

Because of this reduced efficiency in detecting color stimuli, especially of the extreme red and violet ends of the spectrum, problems are introduced when these colors are used for low luminance traffic indications. An unreflectorized sign background or highway marking of a dark red or dark blue color, therefore, may be interpreted as another color which the driver erroneously expects. Also, this means that the traffic engineer who is familiar with the color of the sign or the marking cannot judge validly its effect on a motorist who is not acquainted with this particular marking. Tests of such signs with appropriate control of conditions must be made using subjects unfamiliar with the signs being tested to obtain representative results.

VISUAL FACTORS AND PHYSICAL FATIGUE AT NIGHT

The effects which are generally known as fatigue are generally familiar. Again, without going into the details of a complex field, it is noted that certain effects are quickly reversible and therefore are usually classified as subjective or "psychological" fatigue. Other effects are more long-continued and are of a more physiological nature. Reduction of efficiency of human reactions has been one index for measuring fatigue and studying its causes. A very extensive study of fatigue from driving was carried on by the U.S. Public Health Service several years ago (4). More recently, fatigue has been shown to affect pilot responses not in keenness of visual discrimination ability but in alertness and speed of corrective action (for example, see studies by Bartlett and by Macworth discussed by Chapanis, Garner and Morgan (5)).

There is greater likelihood of decreased driver efficiency from fatigue at night. A driver who arranges his schedule to work at night does not necessarily start out with any reduced efficiency from fatigue, but the majority of drivers have carried activities during the day and, therefore, the probability of fatigue effects at night will be higher. Furthermore, visual factors have been shown to be of importance in inducing fatigue. Reduced efficiency and accuracy of responses and reduced alertness as reflected in judgments and responses to stimulus situations are characteristic of fatigue effects.

GLARE, FATIGUE AND SLEEP

Studies of industrial work conditions have brought out the importance of brightness contrasts and of bright sources of light in the periphery of vision as fatigue inducing factors (6). They are especially fatiguing if continually changing or moving (relative to the eye). Light from overhead luminaires or from passing headlights would, therefore, be expected to be fatigue and sleep inducing influences on the highway in addition to its direct effects in reducing visibility. The tendency of the eye to turn reflexly toward the bright source is probably part of the mechanism leading to physiological fatigue, and the blinking and eye closure may be regarded as protective reactions.

An experimental study produced drowsiness behind the wheel (7) in less than 3 hr of driving even during daylight conditions. Among the reactions observed and recorded, drifting, speed changes, eye blinks and eye closures showed similar increasing trends during the trip. Sleep deprived subjects showed more eye blinks during the driving period than the same subjects under normal schedules. It was significant that for both groups blinks increased during the time of the drive. For the sleep deprived, actual eye closures began to appear and became uncontrollable, resulting in drowsing in nine out of ten cases in less than 3 hr of driving. Obviously, there was 100 percent loss of efficiency at those times (Figs. 7 and 8).

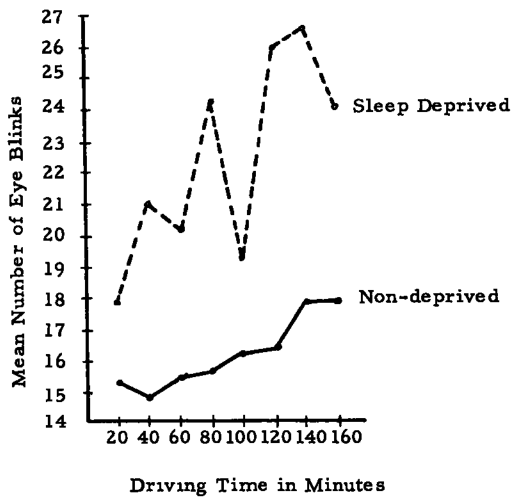


Figure 8. Comparison of sleep deprived and non-deprived groups on eye blinks; average values for five subjects, two 2-min samples each 20-min period, (From (7) Fig. 5).

DROWSINESS AND ACCIDENTS

A number of accident studies on turnpikes and state highways have indicated a higher proportion of one-car accidents (and possible sleep accidents) between midnight and the early morning hours (8). The effects of sleep deprivation shown during daylight driving in the drowsiness study would be even more likely to occur during night driving because of sleep habits of the vast majority of people.

Furthermore, the probability that people going on vacations may work late on preceding days in order to start after work would lead to a higher probability of sleep deprived drivers during night driving.

IMPORTANCE OF DISCOMFORT GLARE REDUCTION

Under sleep deprived and/or fatigued conditions, it is suggested that discomfort glare may be of even greater importance than under other conditions. Recent studies have made important contributions toward the measurement and study of discomfort glare (9) leading toward its reduction through design and other approaches. It is suggested that under the sleep deprived and/or fatigue conditions, the discomfort threshold may be lower and the effect on the driver even more important than when he is in a more normal or average state.

Under such sleep deprived conditions, observations and personal experience show that oncoming headlights and glaring overhead illumination may tend to increase the drowsiness effects experienced by the driver.

Under such circumstances of borderline drowsiness, the driver may be expected to be definitely slowed and less accurate in his judgments and responses even beyond the range discussed previously. The hazard presented by such driving is obvious.

CONCLUSIONS

It has been shown that increasing the complexity and difficulty of the driver's task can increase the time required for perception-judgment-and-response by a factor of two, three or more. Thus, under daylight conditions a complex and more difficult response may require 3 or more sec as contrasted with 0.2 to 0.75 sec for the simpler responses. In night driving, reduced visibility can be expected to increase this slowing of perception-judgment-and-response. Such increases may be critical in relation to time headways in night traffic on high-volume highways and under certain conditions in low volumes.

Pupillary response time may be a factor in some accidents. Changes in color sensitivity due to low illumination may cause driver errors. Proper consideration of these characteristics of the eye in highway design, lighting and traffic engineering can reduce critical situations which may present hazards.

Drivers must be informed and must come to realize that night driving is a somewhat more difficult task, that sleep deprivation makes this worse and that they must, therefore, avoid driving under sleep deprived conditions.

Finally, it is of vital importance that all lighting, signing and marking be designed with the characteristics of the eye taken into consideration and with a view to reducing fatigue and drowsiness inducing effects as much as possible. Discomfort glare may be of great importance here.

In these ways, driving efficiency impairment at night may be at least to some degree reduced.

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An Experimental Low-Cost Lighting System For Important Highways in Rural Areas

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● IN THE United Kingdom, fixed lighting is at present restricted almost entirely to urban areas. There are two main reasons for this. First, it has not yet been proved that the high cost of group A lighting, as provided on urban traffic routes (see Appendix A), is justified in rural areas (see Appendix B). Second, the present administrative arrangements make it difficult to finance lighting schemes in rural areas (see Appendix C).

Group A lighting is intended to be of a sufficiently high standard to enable drivers to see pedestrians and other unlit objects on the road without having to use headlight beams, either driving beams or meeting beams. Possibly a lower standard of lighting would suffice on rural highways where there are few pedestrians and lower traffic flows. The Road Research Laboratory of the Department of Scientific and Industrial Research is therefore studying the effectiveness of a possible low-cost lighting system for use on the more important rural highways.

THE PROBLEM AND A POSSIBLE SOLUTION

Seeing on unlighted highways is not a serious problem until opposing traffic is met. Then, unless the highway is divided and has either a wide median or some form of anti-glare screen, seeing distances are necessarily short, for, if both drivers use driving beams, the range of vision is limited by glare, and if both drivers switch to correctly aimed meeting beams, the range of vision is limited by the reduction in the illumination on objects ahead.

A possible solution to the problem is suggested by the fact that unlit objects are sometimes detected as dark silhouettes seen against a bright patch formed on the pavement surface by the headlights of approaching vehicles. Possibly a long-spaced system of luminaires can be used to provide the long-range warning of unlit objects on the highway which drivers travelling on meeting beams lack.

A TRIAL INSTALLATION

Preliminary tests were carried out by switching off some of the luminaires in a full group A system. These showed that, provided a cut-off light distribution (Fig. 1) is used, glare from the luminaires can be negligible and, provided drivers use their meeting beams to fill in the first dark patch ahead of them, the bright-dark fluctuation can be quite tolerable. A trial installation was erected on a ½-mi stretch of the Colnbrook By-pass, a three-lane undivided highway 30-33 ft wide which forms part of the truck road A. 4 about 18 mi to the west of London. Details of the installation are given in Table 1 and a photograph of its appearance at night is given in Figure 2.

Although the spacing of 270 ft is three times the normal spacing for cut-off luminaires at a mounting height of 25 ft, the figure of a pedestrian, well beyond the range of meeting beams, can be seen silhouetted against several bright bands. An object 200 ft ahead of the driver of a normal automobile need only be about 2 ft high to cover one complete unit of the brightness pattern (that is, one bright band plus one dark band). Because of the extreme simplicity of the brightness pattern, it is relatively easy to see where it is broken by the silhouette of such an object.

This transverse brightness pattern is obtained by using a cut-off light distribution instead of the more usual non-cut-off medium-angle or high-angle distributions (Fig. 1). Central suspension is used to insure that the bright patches stretch across the full width of the pavement, though no doubt a satisfactory appearance could be obtained with side-mounted lanterns if they were 35 ft or more in height. The appearance on a wet night depends to a considerable extent on the pavement surface texture but, as is the case here, if the pavement has a medium surface texture that does not readily flood (1), a satisfactory appearance is obtained even while light rain is falling.

Another important reason for the selection of a cut-off light distribution is that, with a long-spaced system, it appears to be necessary to reduce glare to a minimum. With long-spaced non-cut-off systems, maximum disability glare appears to arise when the driver wishes to scan a dark area ahead. With the cut-off system the driver's eyes are screened from the maximum beam intensities by the roof of his vehicle.

The luminaires chosen have a diffusing bowl, the effect of which is to allow sufficient light to be emitted at high angles to give guidance to drivers in conditions of poor visibility. Although this means that a complete cut-off is not obtained, the glare is so small as to be almost imperceptible.

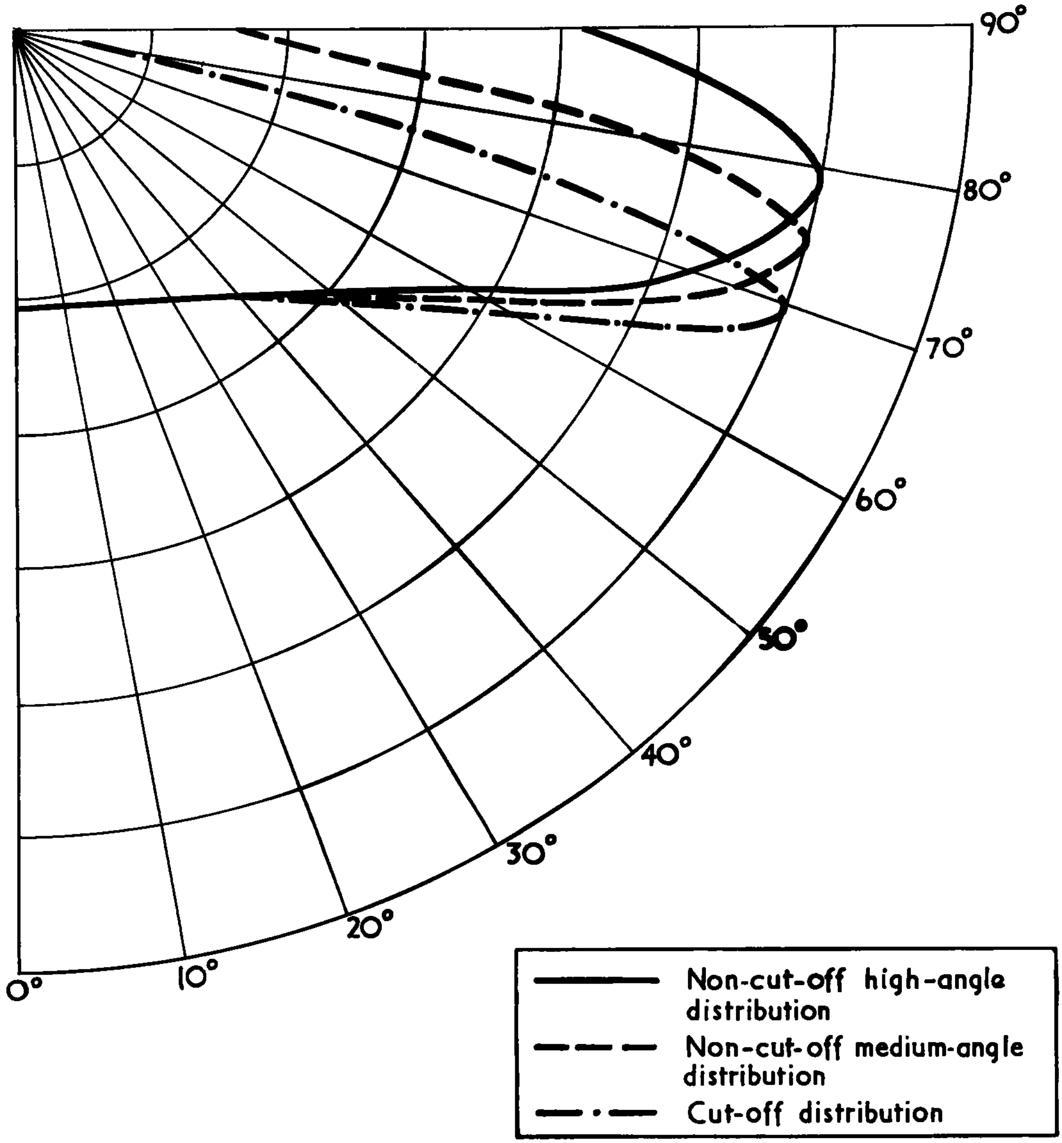

Figure 1. Typical vertical light distributions as used for group A lighting in the United Kingdom (polar curves of intensity in vertical planes parallel to the direction of the road).

TABLE 1

DETAILS OF TRIAL INSTALLATION

Length: ½ mi (approx.).	No. of points: 10.
Spacing: 270 ft.	Height: 25 ft.
Arrangement: Central suspension.	Lamp: 400-watt horizontal mercury lamp.
Luminaire: Enclosed reflector-type with slightly diffusing glass bowl.	Date of switch-on: 14th Nov. 1956.
Distribution: Cut-off.	

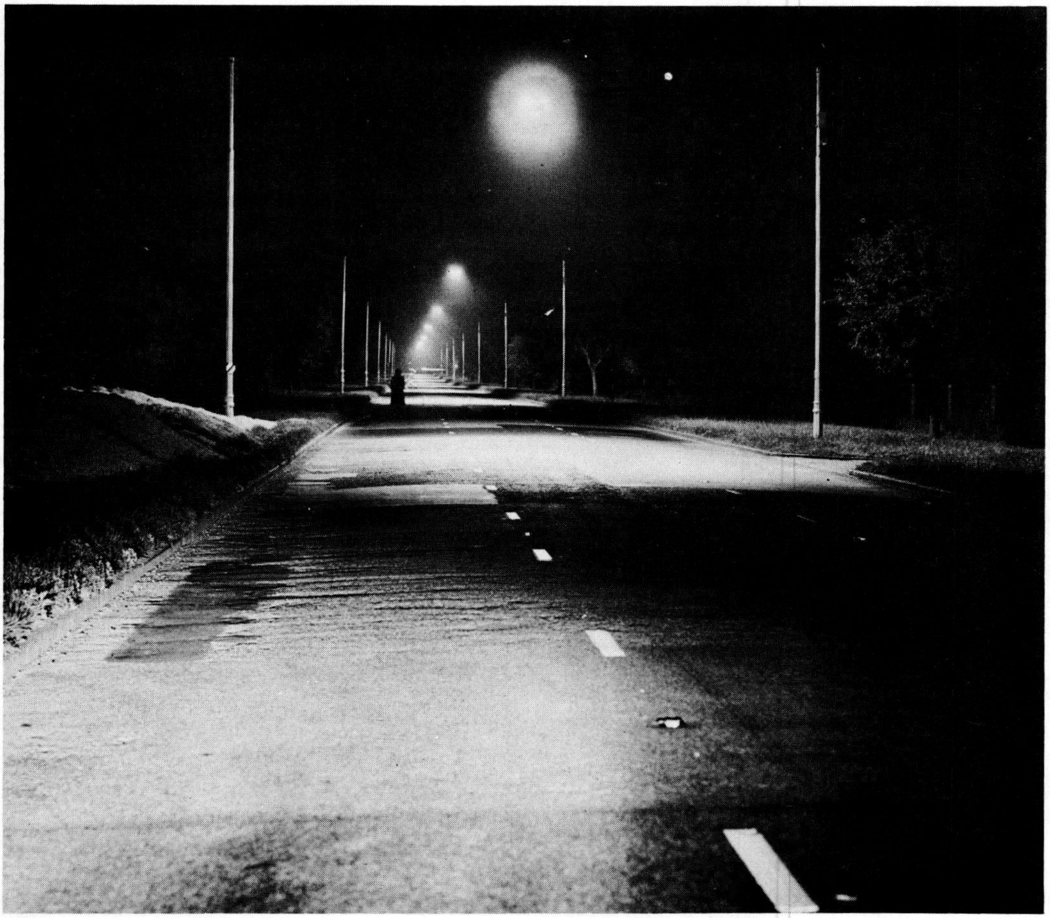

Figure 2. Appearance of the experimental long-spaced lighting system as seen by a driver using his meeting beam (note how the figure, well ahead of the driver's beams, is silhouetted against several bright bands).

The cost of this long-spaced system, relative to that of a conventional group A staggered non-cut-off system using 400-watt mercury lamps at a height of 25 ft and a spacing of 120 ft, depends on many factors, including how far electricity supplies have to be brought. Generally, the total cost of the long-spaced system over an effective life of 15 years will be in the region of one-half that of the group A system.

The trial system has been in operation for three years, and its effectiveness has been studied in various ways. The results of these investigations will now be reviewed individually. In discussing these results it is necessary to treat westward-bound and eastward-bound vehicles separately, since the former are travelling from an unlighted stretch of road into the long-spaced lighting and the latter from full group A lighting into the long-spaced lighting.

SYSTEMS OF VEHICLE LIGHT USED

Illuminated signs are posted at each end of the experimental system recommending drivers entering the system to use meeting beams. It will be seen from Table 2 that, in spite of these signs, most drivers use only parking lights—as is commonly done in the United Kingdom in full group A lighting.

TABLE 2

PERCENTAGES OF DRIVERS USING ONLY PARKING LIGHTS IN THE EXPERIMENTAL LIGHTING SYSTEM (ALL VEHICLES TOGETHER)

Eastbound drivers (entering from a well-lighted zone)	68 percent
Westbound drivers (entering from an unlighted zone)	53 percent

It is possible that these signs are not large enough to command a driver's attention. However, it is interesting to note that, when a sample of 189 drivers who use the road were interviewed, only 42 percent said they drove on parking lights. Possibly some drivers who see the signs prefer to ignore the advice but are unwilling to admit to so doing.

SPEEDS OF CARS

Speeds of cars were measured with radar speedmeters on clear dry nights at corresponding times before and after the switch-on of the experimental lighting. The observed mean speeds are given in Table 3.

TABLE 3

MEAN SPEEDS OF CARS (MPH)

	Before	After
Eastbound drivers (entering from a well-lighted zone)	42.3	42.8
Westbound drivers (entering from an unlighted zone)	43.0	44.4

The observed increase of 1.4 mph in the mean speed of cars entering from the unlighted zones is statistically significant at the 5 percent level, but the observed increase of 0.5 mph in the mean speed of automobiles entering from the well-lighted zone is not statistically significant.

OPINIONS OF DRIVERS

Two separate surveys were carried out by trained interviewers to find out the opinions of drivers who had used the Colnbrook By-pass at night. In the first survey, 186 drivers were asked the question: "What do you think of this form of lighting?". In the second survey, 189 drivers were asked the question: "Which system do you prefer, the long-spaced lighting or no lighting at all?". The replies received are classified in Tables 4 (a) and (b), respectively.

In the first survey, the question was posed in a way that may have resulted in drivers comparing the long-spaced lighting with full group A lighting, and it is therefore rather remarkable that as many as 55 percent should express unqualified approval.

TABLE 4

OPINIONS OF DRIVERS

(a) Replies to the question "What do you think of this form of lighting?"		(b) Replies to the question "Which system do you prefer, the long-spaced lighting or no lighting at all?"	
Unqualified approval	55 percent	Long-spaced lighting	70 percent
Unqualified disapproval	22 percent	No lighting	16 percent
Mixed response	23 percent	Other answers, usually including some adverse criticism of the lighting	14 percent

In the second survey, the drivers were specifically asked to compare conditions in the long-spaced lighting with conditions on unlighted roads. Only 16 percent favored no lighting at all, though a further 14 percent thought that the lighting was not as good as it should be.

ACCIDENTS

Table 5 shows the total numbers of accidents (all types together) that have taken place during the hours of darkness, in comparable periods before and after the installation of the lighting, for both the experimentally lighted sections and a control section. The control section is to the east of the experimental section and remained unlighted during the period under consideration. The control section is straight and about ¾-mi long and is similar to the experimental section except that it contains some entrances to industrial premises, a garage, a hotel, and a cafe, whereas the experimental section has entrances only to fields, estates, etc.

TABLE 5

ACCIDENTS DURING THE HOURS OF DARKNESS IN THE EXPERIMENTAL AND CENTRAL SECTIONS

	Experimental Section	Control Section (unlit)
3 years before (1953-56)	8	12
3 years after (1956-59)	4	22

It will be noticed that the number of night accidents on the experimental section has apparently fallen by one-half, whereas the number on the control section has apparently almost doubled. However, owing to the small number involved, these differences could have arisen by chance. An increase in the number of night accidents was to be expected in the control section, because the number of accidents in darkness is estimated to have increased by about 20 percent in the country as a whole, but there is no obvious reason why the increase should be as large as that found.

DISCUSSION

As the results of this preliminary experiment are promising, the lighting has since been extended by nearly 1 mi (including the control section previously unlighted). It is hoped that within a few years it will be possible to reach a definite conclusion on the effect of such long-spaced lighting on safety.

SUMMARY

This paper describes a trial installation of a low-cost system of lighting designed for the more important rural highways, roads that are at present generally unlighted. Most drivers find the lighting helpful and there is some evidence that it reduces the number of night accidents. The trial installation has therefore been extended from ½ mi to 1½ mi in length in order to obtain more reliable evidence.

ACKNOWLEDGMENTS

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Appendix A

THE LIGHTING OF TRAFFIC ROUTES

On urban traffic routes in the United Kingdom, group A lighting, as defined in the British Standard Code of Practice on Street Lighting, CP1004: Part I: 1952, is used.

The mounting height of the luminaires is 25 ft. Usually a staggered arrangement of luminaires is used at a spacing of about 120 ft for pavements up to 44 ft in width. On wide pavements opposite arrangements are used, and on divided highways separate systems of luminaires are provided for the two directions of traffic.

Usually non-cut-off vertical light distributions are employed (Fig. 1). When a cut-off distribution is employed, the spacing is dropped to 90-100 ft.

The light sources employed are mainly single 140-watt sodium lamps, 250- or 400-watt mercury lamps or three 80-watt tubular fluorescent lamps.

The annual cost of such lighting (including capital amortization and all running costs) is from £ 750 per mile upwards.

Appendix B

THE EFFECT OF FIXED LIGHTING ON ACCIDENTS

From studies made at 64 sites on traffic routes in urban areas in the United Kingdom, it has been estimated (2) that bringing the lighting up to group A standard, as specified in the British Standard Code of Practice, caused a reduction of 30 percent in the number of injury accidents during the hours of darkness (about 45 percent for accidents in which a pedestrian is injured and 23 percent for other accidents). The cost to the nation of these improvements appears to be more than recovered in the form of savings due to the reduction in the number of accidents at night.

The justification for full group A lighting on rural highways is less clear-cut because (a) there are generally fewer night accidents per mile to be eliminated than on urban traffic routes; and (b) a lower proportion of accidents involves pedestrians. However, it must be remembered that the reduction in the accident rates quoted previously were obtained by improvements to the lighting; greater reductions would be expected to follow the introduction of full group A lighting on highways hitherto unlighted. Moreover, monetary savings due to reductions in the number of accidents are not the only benefits derived from highway lighting. There is also the reduction in human suffering following the elimination of accidents, the more comfortable seeing conditions at night, etc.

The question of whether full group A lighting is justified on the United Kingdom rural highways is likely to remain open until extensive trials have been made.

Appendix C

ARRANGEMENTS FOR FINANCING HIGHWAY LIGHTING IN THE UNITED KINGDOM

Legislation towards the provision of street lighting in the United Kingdom is permissive; in only a few cases are local authorites under an obligation to provide lighting.

In many cases, the authority that has power to provide lighting on a rural highway in a Parish Council, which is quite unable to accept the financial burden, and which, in any case, does not feel that it should be called on to provide lighting for road users, most of whom are merely passing through the area. On trunk roads, the Ministry of Transport makes a 50 percent grant towards the installation and running costs of lighting, but even this is not enough to alter the situation.

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Effectiveness of Holland Tunnel Transitional Lighting During the Winter Months

ALAN T. GONSETH, Research Technician, The Port of New York Authority

The Port of New York Authority has previously conducted experiments in conjunction with the installation of mercury-vapor transitional lights in the Holland Tunnel.

The experiments were run during periods of maximum annoyance due to sun glare, which exists for about one hour per day at most, when the sun is between 5 degrees north to 5 degrees south of due east. The tunnel approach ramp is in a due east direction.

Sun position data show that the sun is above the horizon in that position only during the period of March 21 to September 21. Allowing for rainy and cloudy days during that period, it is estimated that this occurs only about 120 days per year.

The study reported in this paper was conducted to determine if the flow of traffic is affected during the winter months when the tunnel entrance ramp is shaded by local industrial buildings. If not, possibly a decorative facade constructed over the portal could shade the entrance in summer as well as in winter and thereby reduce, if not eliminate, the need for extensive transitional lighting all year long.

Once the vehicle operator passes under a tunnel portal the decided reduction in light intensity causes a speed reduction until his eyes have adjusted to the change. Transitional lighting, of course, has improved this operational feature considerably. New facilities are being equipped with flared portals and variable transitional light sources controlled by photoelectric cells. However, on existing tunnels and underpasses it would be almost impossible in many cases to flare the portals, and costly indeed to revise the facility lighting system to adapt an automatically controlled variable light source. With this in mind it was thought that it might prove easier and more economical to reduce the light intensity outside rather than increase it inside the tunnel.

●AN EARLY morning driver approaching the Holland Tunnel on Twelfth Street in Jersey City, New Jersey in the interim from early spring to mid-fall is confronted with a low-lying, but brilliant sun which is directly within his line of sight and his line of travel. The pupils of the driver's eyes automatically adjust to this extreme light condition. However, when the vehicle eventually reaches the tunnel and passes under the portal, the driver is met by a decided reduction in light intensity. Once again the pupil of the driver's eye must adjust to this reversed drastic change. The fulfillment of this eye adjustment requires a certain time increment during which the driver's ability to see is reduced. (It has been proven medically, but most everyone realizes from personal experience, that it takes the pupil of the eye slightly longer to adjust when subjected to a change from light to dark as opposed to a change from dark to light (1). Throughout this period of adjustment it has been noted, and it only stands to reason, that the driver would immediately decelerate his vehicle until his vision returned to a reasonably trustworthy degree.

Temporary blindness of this type not only creates conditions for accidents, but could also reduce the capacity of the tunnel lanes because of slower entering speeds and irregular flow. However, it has been indicated by the Illuminating Engineering Society that:

1. A change in brightness having a maximum ratio of 15 to 1 would not be difficult for the driver's eye to adjust to for speeds greater than 30 mph and would not cause temporary loss of vision(1).
2. The normal eye is able to adapt to this brightness change within the space of 2 to 3 sec.
3. Subsequent studies and research may justify modifying this advised 15 to 1 (outside to inside) ratio to, say, 20 or 30 to 1; especially in instances of slower entering speeds (1).
4. A normal eye doubles size in approximately 10 sec when required to suddenly adapt from extremely high to low brightness levels.

However, certain recent findings point to the possibility of adopting somewhat shorter eye adjustment times in the neighborhood of 2 sec for greater intensity differentials than 15 to 1(2).

EXISTING TUNNEL LIGHTING

The basic Holland Tunnel lighting is done by continuous-burning 150-watt filament lamps in flush-type luminaires on 20-ft linear and opposite spacing, as they were installed at the junction of the side wall and ceiling in 1927. The light intensity on the roadway ranges from 1.5 to 2.0 foot-candles and cannot be varied. Several methods of transitional lighting were investigated and tried in an attempt to create a smooth transition of lighting intensity between daylight and the basic tunnel lighting.

At one time supplementary daytime entrance lighting only utilized 200-watt incandescent lamps spaced on 10-ft centers for approximately the first 300 ft and on 15-ft centers for the next 200 ft after which regular 20-ft spacing applied for the next 1,000 ft. Sometime thereafter in order to increase the transitional light intensity, floodlights were provided in the ceiling, for a distance of approximately 150 ft, spaced at 15-ft intervals. A total of 44 floodlights were installed, of which 12 were 1,000 watts, 8 were 750 watts, 16 were 500 watts, and 8 were 300 watts. Still later, Simes fluorescent fixtures were installed along the left wall for a distance of approximately 220 ft, replacing the 200-watt incandescent lamp. Finally, in the latter part of 1957, a series of 400-watt reflector-type mercury-vapor lamps were installed, on 10-ft centers for approximately 110 ft and are now used in place of the floodlights and fluorescent fixtures. They provide uniform wall coverage at a 45-ft-candle level.

STATEMENT OF PROBLEM

During the mornings of the winter months, the sun does not affect the driver as much as it does in the summer months. The sun remains low, but swings to the south enroute to setting in the west instead of following a direct east-west line as is the case in the summer (Fig. 1). The people travelling east on Twelfth Street in Jersey City are still faced with the sun, but when they have proceeded beyond the Holland Tunnel toll booths, the roadway is shaded by local industrial buildings (Fig. 2).

The 1,000 ft or so of shaded roadway allows the driver's eyes to adjust, somewhat like a stage in transitional lighting, and in turn, reduces the ratio of outside to inside brightness considerably. It was thought that because the shaded roadway leading to the tunnel portal had reduced the light differential between the outside and inside that perhaps it reduced it to such a degree that if the mercury-vapor lamps were not used, then possibly the ratio would not increase beyond the 15 to 1 maximum ratio suggested by the Illuminating Engineering Society. If this is true, then there should be no significant difference in the speeds of vehicles in the transitional zone immediately within the tunnel portal with the transitional lights on or with them off.

APPROACH TO THE SOLUTION

The purpose of this report was to determine if the mercury-vapor transitional lights had any significant effect on traffic entering the eastbound tube of the Holland Tunnel during the winter months. To do this required the collection of speeds and headways just outside the tunnel portal and just inside the tunnel portal during heavy, free-flowing

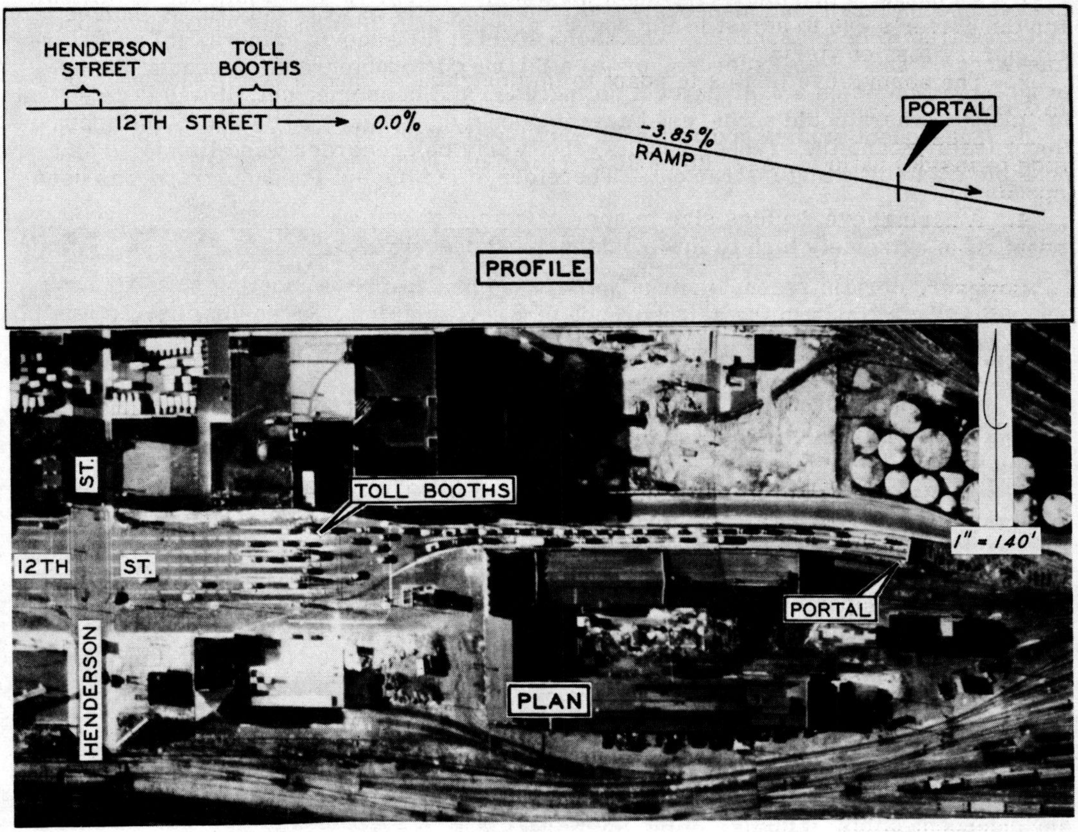


Figure 1. Plan and profile of tunnel approach.

volumes and during lower, free-flowing volumes. Good weather conditions were needed to fulfill the necessary requirements. A before-and-after study could quickly be assimilated by turning the transitional lights, which are on a separate circuit, on and off at will. In addition, no lane changing by vehicles is permitted on the approach or within the tunnel which is advantageous for this study. Following is a description of the use of the equipment that was decided on to be used and how the data was analyzed and interpreted to logically draw conclusions and recommendations.

METHOD OF STUDY

Site Description

The Holland Tunnel south tube is 8,371 ft long and carries two lanes of eastbound traffic from Jersey City, New Jersey to New York City on a 20-ft dark asphaltic concrete pavement. The bare concrete ceiling is 13 ft over the roadway and allows 12 ½ ft for operating headroom. The walls of the tube are covered with white tiles which are highly reflective and delineate the tunnel outline. For all intents and purposes, the roadway on either side of the portal of the south tube in the study area is a tangent section on a 3.85 percent downgrade. This one tube carries approximately 27,000 to 30,000 vehicles daily and has a composition of traffic having up to 50 percent commercial vehicles which are kept primarily in the right-hand or "slow" lane.

Instrumentation

Several methods could be used to collect speed and headway data, ranging from a movie camera to a count done manually at key stations. However, it was necessary to have speeds taken instantaneously and, therefore, there were only three choices that appeared to be reasonable. The choices were: (a) a movie camera, (b) an Esterline-Angus Twenty Pen Recorder, or (c) a Simplex Productograph. Because the approach roadway is on a 3.85 percent downgrade, and in an open cut, it was decided that the movie camera could not be used advantageously. Because of the bulk, the operational features and the graphed results, the twenty pen recorder was eliminated as a possible data collecting instrument. Therefore, the Simplex Productograph was used.

Figure 2. Shadowed entrance ramp.

This device is essentially a time clock which prints time to a tenth of a second plus a six letter code on standard adding machine tape. Hours, minutes and seconds are printed in figures, and tenths of a second are printed by a vernier scale. The productograph can be activated by either a road tube or a manual switch. Because of the problem caused by the laying of road tubes, and also their unknown psychological effect on drivers, it was deemed best to use micro-switches to activate the Simplex Productograph Recorder. A Macbeth Illuminometer had been previously used to determine the light intensity on the walls inside the tunnel with the transitional lights on and with them off. The Illuminometer was to be used on the day of the study to determine the light intensity outside the tunnel.

Basic Assumptions

Brief speed checks taken in the left-hand or "fast" lane at random indicated an approximate 25-mph vehicle entering speed. It was decided that only one lane of traffic could be checked adequately and inasmuch as the left lane has higher speeds it was felt that the transitional lighting would affect its traffic more, therefore, it was chosen as the

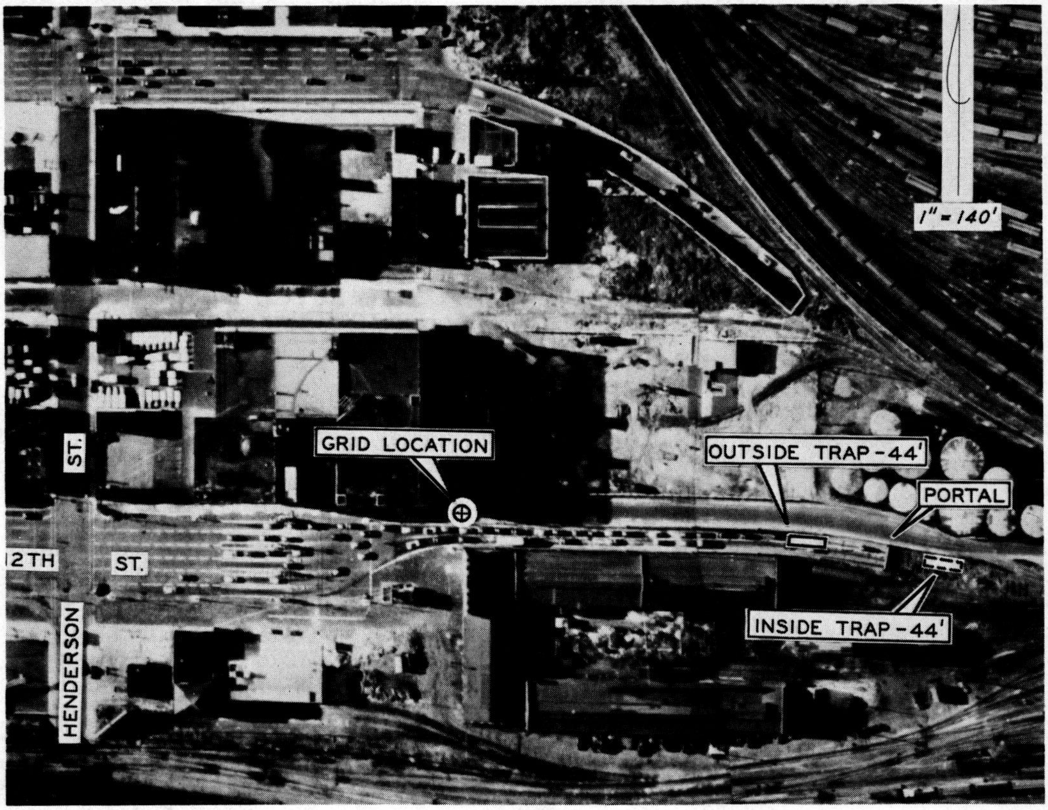


Figure 3. Speed measuring zone and grid locations.

study lane. It was assumed that a PIEV (Perception-Intellection-Emotion-Volition) time (3) of 1 sec for the driver to react to the light differential from the time when he passed beneath the portal until he applied the brakes was included in the average eye adjustment value of 2.5 sec. This would indicate that the average motorist would begin deceleration when he is 1 sec beyond the portal and start accelerating again 2.5 sec beyond the tunnel portal. Converting these times to distances by using the average 25-mph entering speed shows that deceleration could be anticipated to start about 37 ft inside the tunnel with acceleration beginning at about 82 ft beyond the portal (assuming the driver's deceleration slowed him to an average of 20 mph during the last 1.5-sec adjustment period). Therefore it was decided that a 44-ft speed measuring zone would be placed in a position starting 40 ft inside the tunnel. The position of the other speed measuring zone was completely arbitrary, but for convenience sake, it was placed in a position starting 124 ft outside the tunnel (Fig. 3).

Inclement weather caused several postponements of the study date. Finally, the data was taken on the morning of December 31, 1958. Investigation of New Years Eve traffic data of past years taken at the Holland Tunnel indicated that the A.M. peak-hour traffic was normal for a weekday and only the P.M. peak hour was affected by the occasion of New Years Eve. The transitional lights were turned off for 15 min and then on for 15 min throughout the morning study period.

Conventions

Throughout the remainder of this report, the following definitions and conventions will be used:

Speed Measuring Zone. — A 44-ft section of pavement where a time was recorded for each entering and exiting vehicle.

Outside Speed Measuring Zone. — The zone that is set up outside the tunnel portal (Zone 1).

Inside Speed Measuring Zone. — The zone that is set up within the tunnel (Zone 2).

Headway. — The time differential between the front bumper of a vehicle entering a speed measuring zone and the front bumper of the preceding vehicle.

High Volume Study. — The comparable study done between 9:30 A.M. and 10:07 A.M.

Low Volume Study. — The comparable study done between 11:00 A.M. and 11:30 A.M.

Lights On. — 400-watt mercury-vapor transitional lights are on.

Lights Off. — 400-watt mercury-vapor transitional lights are off.

ANALYSIS OF DATA

Comparable Studies

During the collection of the data, the recording tape was marked when the flow of vehicles was restricted by breakdowns within the tunnel, or by shock waves (4) (accordian effect) as caused by bottleneck conditions. Therefore, the only data that was accepted was that of free-flowing vehicles.

Each vehicle's speed was recorded and classified along with its headway for both the inside and the outside speed measuring zone. Because the data was taken for a 15-min period with the lights being on and then a 15-min period with the lights being off, it was assumed that the vehicles had exactly the same stream characteristics except for the effect of the transitional lights. The only usable data during the high-volume study period with the transitional lights on was from 9:31 A.M. to 9:39 A.M., when 166 vehicles were recorded. A comparable volume was recorded when the transitional lights were out from 9:56 A.M. to 10:07 A.M. The comparable periods of lighter volume with the transitional lights on and off were 11:00 A.M. to 11:17 ½ A.M. and 11:17½ to 11:30 A.M., respectively.

Statistical Analyses

Velocities. — The mean ($\bar{X}$) velocities for both the "lights on" and "lights off" phases of both the high-volume and low-volume studies were calculated. Next the standard deviation (a measure of scatter) for the speed was calculated by the use of the formula:

$$s = \sqrt{\frac{(X-\bar{X})^2}{N-1}} \tag{1}$$

in which

s = standard deviation
X = individual measured value
$\bar{X}$ = mean value
N = sample size

These calculated values are given in Table 1.

Before starting the analysis a check was made to see if the sample sizes were large enough to be dependable, by the use of the formula:

$$N = \left[Z_{(1-\alpha/2)} \frac{s}{d} \right]^2 \tag{2}$$

in which

s = standard deviation
d = tolerance
$1-\alpha/2$ = % confidence
N = sample size needed
Z = confidence limits

TABLE 1

SPEED DATA

Time A.M.	Transitional Lights	No. of Veh.	Outside Speed Measuring Zone Mean Speed (mph)	Outside Speed Measuring Zone Std. Dev. (mph)	Inside Speed Measuring Zone Mean Speed (mph)	Inside Speed Measuring Zone Std. Dev. (mph)
9:31-9:39	On	166	21.9	4.8	25.0	5.0
9:56-10:07	Off	176	22.4	5.3	24.3	4.5
11:00-11:17½	On	232	23.4	3.7	29.0	4.6
11:17½-11:30	Off	174	23.6	4.2	29.4	4.8

For example, if the outside speed measuring zone, during the high-volume period, when the lights were on, it was desirable to be 99 percent sure that the population mean was within -0.5 mph of the estimated mean, a required sample size would be:

$$N = \left[2.576 \frac{(4.8)}{1.0} \right]^2 = (12.36)^2 = 153$$

This is less than the 163 recorded, therefore, the sample size is adequate. The remaining sample sizes were checked and the results are given in Table 2.

TABLE 2

SAMPLE SIZE

Time A.M.	Outside Speed Measuring Zone Recorded Sample	Outside Speed Measuring Zone Required Sample	Inside Speed Measuring Zone Recorded Sample	Inside Speed Measuring Zone Required Sample
9:31 to 9:39	166	153	166	165
9:56 to 10:07	176	175	176	134
11:00 to 11:17½	232	91	232	151
11:17½ to 11:30	174	117	174	153

Because the standard deviation is the square root of the variance, it is possible to obtain the variance for the different conditions. The variance can be used in testing statistically whether two estimates of variability are significantly different (5). One such procedure is the statistic F given by the formula:

$$F = \frac{s_1^2}{s_2^2} \tag{3}$$

which has a sampling distribution called the F distribution. There are two sample variances involved and two sets of degrees of freedom. This test is to determine if the variances of two comparable variables are significantly different. Assuming a 95 percent confidence limit, the F ratio limit of acceptability is 1.35. If the ratio is between 1.00 and 1.35, it indicates that it cannot be proved that the two variables are significantly different. For instance, the F ratio for the variance of the inside speed measuring zone was calculated for the high-volume comparison as follows:

S_1 = variance of the speeds in the inside speed measuring zone with the lights on.
S_2 = variance of the speeds in the inside speed measuring zone with the lights off.

$$F = \frac{S_1}{S_2} = \frac{(5.0)^2}{(4.5)^2} = 1.23$$

$$1.23 < 1.35$$

Therefore, with 95 percent confidence it can be said that the two estimates of variances cannot be proved significantly different.

The same procedure was used to compare the "lights on — lights off" velocity variances of the three other conditions. In all cases the ratios were less than 1.35 and, therefore, there was no significant differences with the results given in Table 3.

Because there was no significant difference in the velocity variances, they can safely be assumed as equal in each case.

Now that the variances are considered to be equal, it is possible to test to see if the means are equal. This can be done by setting up the hypothesis that the means are equal, knowing that the variances are equal. The procedure for this is outlined and explained by Dixon and Massey (5, p. 121) and is as follows:

Step (1) Hypothesize that the means are equal:

$$\mu 1 = \mu 2$$

Step (2) Assume an α, or rejection limit. Say 0.05 (for 95 percent confidence)
Step (3) Select the statistic t, which is given by the formula:

$$t = \frac{\overline{X}_1 \quad \overline{X}_2}{Sp\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}} \qquad (4)$$

in which

S_p = pooled variance
$\overline{X}_1$ = larger mean speed
$\overline{X}_2$ = lower mean speed
N_1 = sample size
N_2 = sample size

Step (4) The rejection limits set up with the selection of $\alpha = 0.05$ and statistic t are:

$$1.658 > \text{ or } < -1.658$$

Step (5) Solve: All the variables in equation 4 are known except the pooled variance (S_p) which can be obtained by the following formula for which all the appropriate values are known:

$$S_p^2 = \frac{(N-1)S_1^2+(N-1)S_2^2}{N_1 + N_2 - 2}$$

For example, if the speeds in the inside speed measuring zone during the high-volume comparable period are put through this process, it is found:

$$S_p = \frac{(166-1)\ (5.0)^2 + (176-1)\ (4.5)^2}{166 + 176 - 2}$$

$$S_p^2 = \frac{4125 + 3544}{340}$$

$$S_p^2 = 22.56$$

$$\therefore S_p = 4.75$$

Now substituting in the "t" formula it is found that:

$$t = \frac{25.0 - 24.3}{4.75 \sqrt{\frac{1}{166} + \frac{1}{176}}}$$

$$t = 0.43$$

Inasmuch as 0.43 < 1.658 and 0.43 > -1.658 it cannot be proved that the two mean speeds are significantly different.

The same process was used on the other comparisons and the results are given in Table 3.

TABLE 3

ACCEPTANCE TABLE

		High Volume Comparison		High Volume Comparison	
	Acceptable Range	Outside Zone	Inside Zone	Outside Zone	Inside Zone
F ratio	1.00 to 1.35	1.22	1.23	1.29	1.09
S_p	-	5.04	4.75	3.92	4.69
t value	-1.66 to 1.66	0.289	0.430	0.161	0.270

Headways. — The headway data cannot be analyzed in a similar manner because they form a skewed distribution and not a normal distribution. The frequency of headways under the various conditions (Figs. 4 and 5) show the skew of the distribution. If headways of 9.0 sec or more are disregarded it can be seen by averaging the remaining values that the differences between the inside and outside speed measuring zone during any one counting period are negligible. It would appear that if the lights had any effect, the headways would be smaller in the inside speed measuring zone when the lights were out. Of course, the headways of vehicles do vary with the volume (Fig. 7). A close inspection indicates that the means of the various groups of headway comparisons decrease as the volume increases (Table 4). Figures 6 and 7 show that the headways follow normal patterns when plotted against speed and volume, respectively.

Brightness

In order to determine the brightness outside the tunnel, readings were taken with a window-frame type of grid containing twelve openings, each 8 in. by 8 in. This grid was located 5 ft away from the observer at the height of an automobile front window. Readings were taken through each opening by means of a Macbeth Illuminometer. (Fig.

8). The grid was placed on the sidewalk of the open cut ramp leading to the tunnel and was positioned perpendicular to the roadway (Fig. 3). Readings were taken through the center of each square of the grid. Certain readings were taken into the open sky with the remainder of the readings being taken on the surrounding features (Fig. 8). The brightness of the sky averaged to about 2,000 foot-lamberts (ft-L) whereas the brightness of the shadowed wall area in front of the tunnel mouth was recorded in the vicinity of 220 ft-L. Taking the 220 ft-L and dividing by a converted 45 foot-candle (ft-C) wall coverage when the lights were out will yield an outside to inside brightness ratio. In this case the 45 ft-C can be considered 33.3 ft-L because at the angle of observation, the reflection factor of the tile wall was 74 percent. Hence, (.74) (45) =

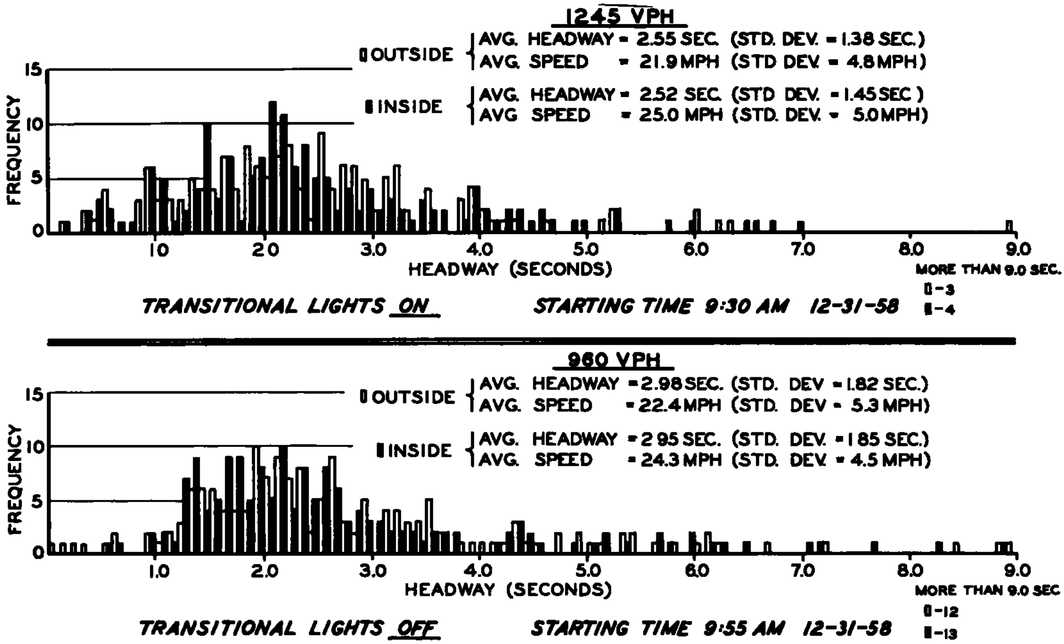


Figure 4. Headway frequency (high volume).

33.3 ft-L. Therefore, the outside to inside brightness ratio is:

$$\frac{220}{33.3} = 6.6:1$$

This is considerably less than 15 to 1.

The wall coverage when the transitional lights are on has an average of about 60 candlepower (c.p.) or 44.4 ft-L. Therefore, its ratio of outside to inside brightness is:

$$\frac{220}{44.4} = 5:1$$

This is also considerably less than 15 to 1 as suggested by the Illuminating Engineering Society.

This more than likely has a strong influence on why the speeds could not be proved significantly different when the lights were on from when they were off.

Limitations

A more comprehensive study of this nature would probably give more convincing re-

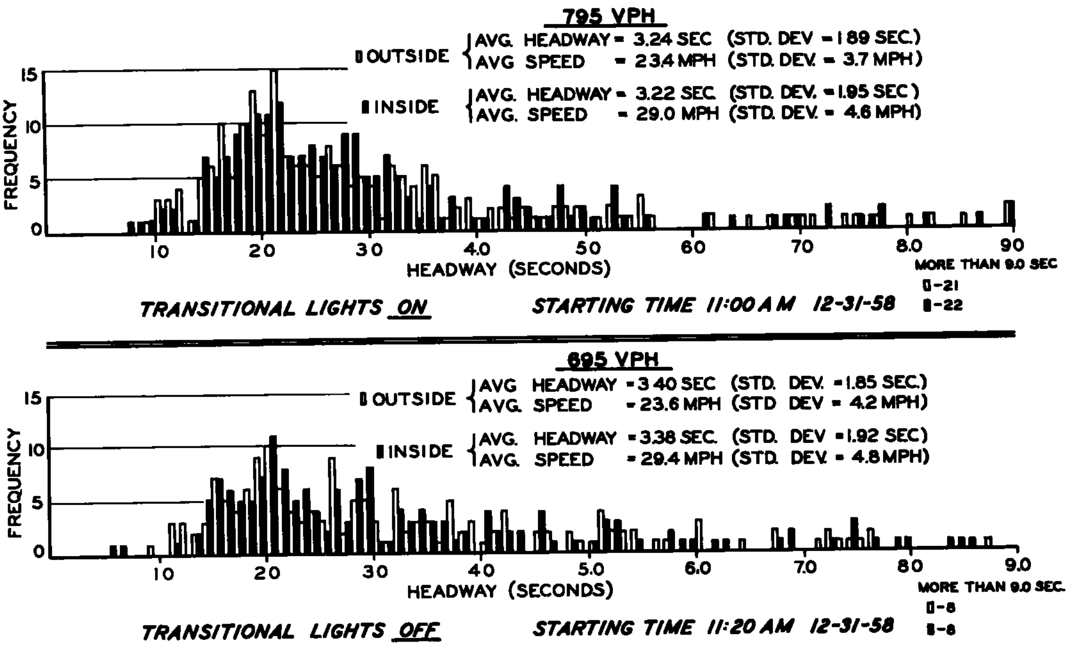


Figure 5. Headway frequency (low volume).

TABLE 4

HEADWAY DATA

Time A. M.	Lights	No. of Veh.	Outside Speed Measuring Zone Mean Headway	Outside Speed Measuring Zone Std. Dev.	Inside Speed Measuring Zone Mean Headway	Inside Speed Measuring Zone Std. Dev.
9:31-9:39	On	163	2.55	1.38	2.52	1.45
9:56-10:07	Off	167	2.98	1.82	2.95	1.85
11:00-11:17½	On	215	3.24	1.89	3.32	1.95
11:17½-11:30	Off	168	3.40	1.85	3.38	1.92

sults. If four or more speed measuring zones could be used with three of them within the tunnel, then it would be possible to determine if the lack of transitional lighting had its effect beyond the point where the one inside speed measuring zone in this study was located. The location of the one inside zone in this study was determined by the selection of a PIEV time and an eye adjustment time. As was previously discussed, there are differences in opinion among authorities in the field as to the absolute values of these time factors, but the one thought to most closely parallel this particular problem was chosen and used.

The manual activation of the micro-switches in connection with the productograph were adequate for the purposes of this study. However, if a more exact study is required as far as speeds and headways are concerned, it is suggested that a concealed ultrasonic detector or photoelectric cell be used.

CONCLUSIONS

Because the ramp leading to the mouth of the Holland Tunnel is in shadow even on the brightest days during the morning peak hours of the winter months, it is found that there is no uncomfortable glare in the driver's eyes. In addition, it was found that the shadows on this open cut ramp create an outside to inside brightness ratio of less than 15:1 whether the transitional lights are on or off. These factors indicate that the transitional lights should have no great degree of influence on the drivers' reaction to entering the tunnel due to a change in light intensity. The conclusion that is of most importance, and which is in full agreement with the foregoing indications, is that the speeds and headways could not be statistically proved as significantly different whether the vehicles entered the tunnel with the transitional lights on or with them off. Therefore, it can be said that the limited work of this study shows that in the winter months, when the ramp leading to the portal of the South Tube of the Holland Tunnel is in shadow on a relatively bright day, the 400-watt mercury-vapor transitional lights have no effect on the entering traffic.

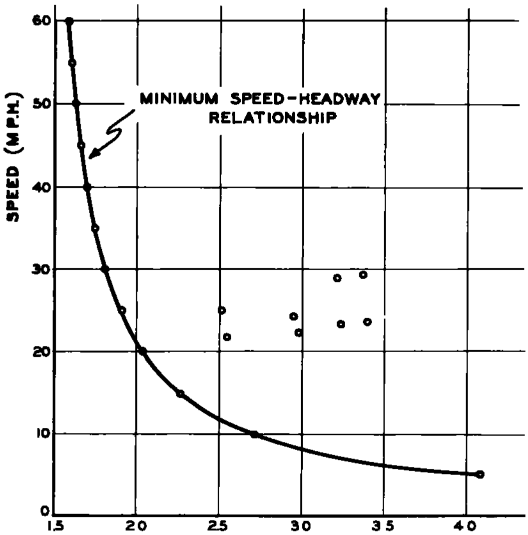


Figure 6. Speed vs headway.

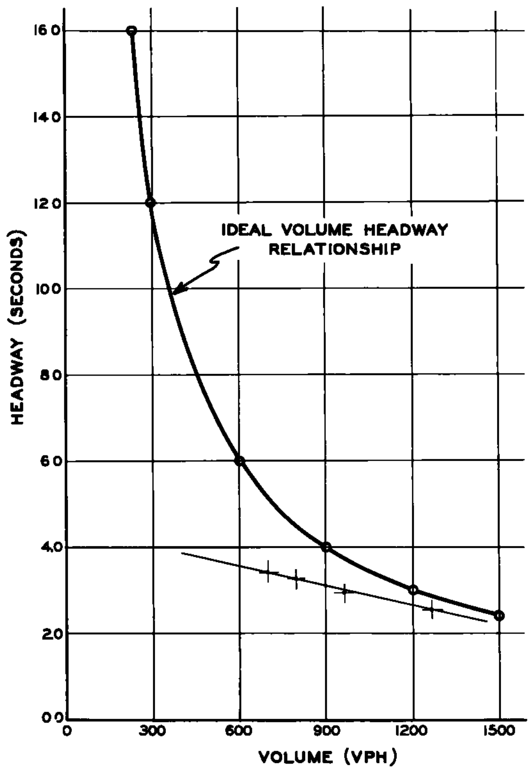
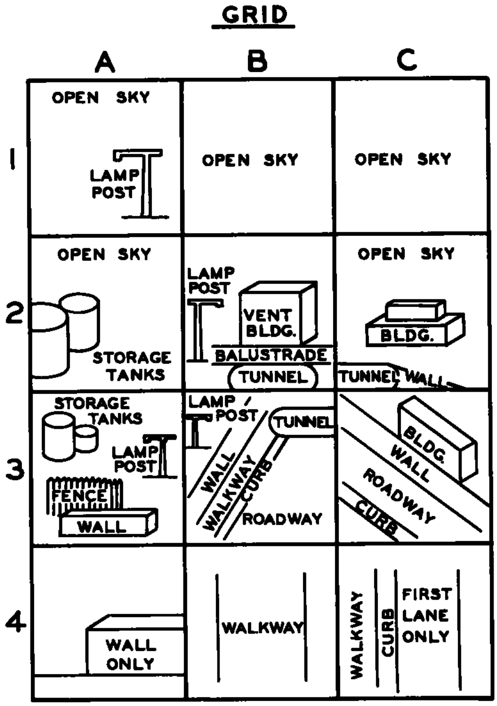


Figure 7. Volume vs headway.

RECOMMENDATIONS

The seriousness of the safety of tunnel users requires that the foregoing conclusions should be considered only as a guide toward a more comprehensive and inclusive research project to determine beyond all doubt that transitional lights have no effect under the stated conditions. If necessary, the outside to inside brightness ratio can be reduced by increased transitional lighting or possibly by shading the approach ramp to the tunnel or underpass. Economics, aesthetics and adaptability to the local surroundings would become the determining factors.



BRIGHTNESS CHART

POSITION ON GRID	BRIGHTNESS (FT. LAM.)
A1	3000
A2	2550
A3	1100
A4	160
B1	3200
B2	206
B3	217
B4	160
C1	3000
C2	121
C3	196
C4	186

Figure 8. Illuminometer grid.

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Some Results of Cooperative Vehicle Lighting Research

THOMAS R. KILGOUR, Chrysler Corporation

● THE FIRST ELECTRIC LAMPS installed on motor vehicles replaced kerosene and acetylene lamps which were troublesome and inconvenient accessories, in the opinion of early motorists, but necessary to provide what was then a maximum of safety for night driving. Perhaps in some cases the amount of illumination was no better with the electric lamps than that which had been provided by the earlier devices, but the greater convenience was an obvious advantage.

Questions of convenience and safety have continued to dominate the automotive lighting problem. Increasing use of motor vehicles at night, greater concentrations of traffic, and the development of lens systems for more efficient lighting have been the principal factors affecting development of automotive lighting equipment in the years since then.

Lighting came to be more than just the provision of marker lamps or even the provision of a beam of light to give the motorist a path to steer. There came problems of controlling glare so other motorists would not be inconvenienced or subjected to hazard. In addition, lighting equipment became a primary source of signalling. First, the stop lamp at the rear of the vehicle came into existence and, in more recent years, turn signal lamps and other variations of signalling devices, both for daytime use and nighttime use.

The technical problems associated with motor vehicle lighting have thus changed substantially. The modern highway systems and new conditions of driving continue to exert influences that will change the technical problems to be dealt with in the future.

Meanwhile, the responsibilities for the performance of lighting equipment also shifted. Initially, the electric lamps were supplied by electrical manufacturers as optional equipment, entirely at the discretion of the motorist himself. Legal requirements early appeared in the laws and regulations of various states, making it necessary to provide a minimum of lighting equipment on every vehicle, so the vehicle manufacturer then had an interest and a responsibility.

As the motor vehicle and its use problems developed in complexity, there were increasing demands for more efficient equipment. The adoption of electrical systems on vehicles soon reached the point where basic lighting was standard equipment, usually considered as an integral part of the vehicle structure and assembly even though the lamp units were still mounted separately on brackets rather than being incorporated into the structure physically.

A great deal of originality was displayed in some of the early lighting equipment, but sometimes with disregard for such practical problems as the glare which annoyed other drivers or the inconvenience of trying to find a source of replacement for some unusual shape of lamp, reflector, lens or other component. Incidentally, it appears that lamp brackets, bases and sockets were among the earliest items of automotive equipment to be standardized on a national level.

Vehicle manufacturers accepted an increasing responsibility for the development and installation of lamps and were well oriented to the complexities of the vehicle lighting problem at the time that state motor vehicle administrators first began to deal on a cooperative and more or less uniform basis with lighting problems in the early 1920's.

For about 15 years this cooperative approach was largely centered in the northeastern section of the country, where the concentration of motor vehicles was greatest. During this period a more national point of view developed to the point where, about 1935, the time was ripe and the circumstances right for a national approach to the problem, both by the manufacturers and the motor vehicle administrators. Here, again, motorists' convenience in terms of ability to get interchangeable parts easily at any time and in any part of the country paralleled the interest in the strictly technical problem of better and more uniform lighting and control of glare.

In 1935 there began a more formal relationship between those who share the responsibility for motor vehicle lighting. A cooperative program was developed which has since sponsored very important research, engineering development and design programs which have contributed vastly to the improvement of lighting and signalling equipment. A first major product of the cooperative effort was the sealed-beam headlighting system and a series of other comparable programs has followed to form a basis for today's active program in this field.

The cooperation on lighting equipment integrates the interest and responsibilities of

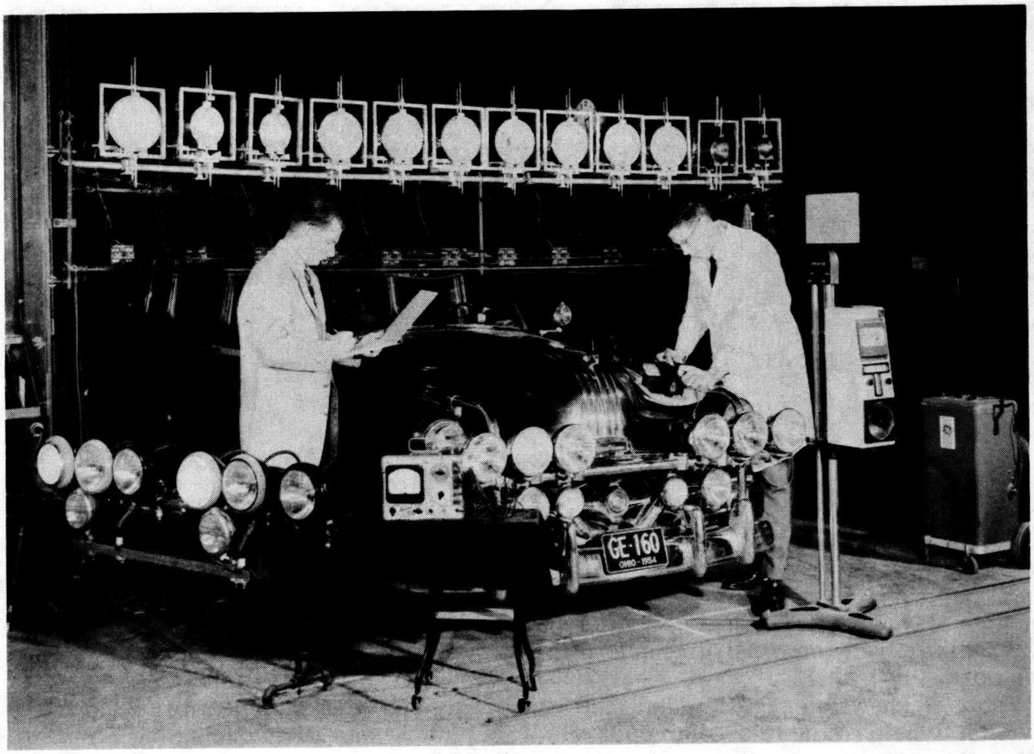


Figure 1. Vehicle lighting laboratory.

the lamp manufacturer, who has the technical capabilities in research, development and production, the vehicle manufacturer, with comparable facilities and responsibilities for the equipment on his product, and the motor vehicle administrators, who by virtue of their state laws and regulations have responsibilities in terms of the public use of lighting equipment.

The basic group that brings about industry coordination of effort, in this formal program, is the Vehicle Lighting Committee of the Automobile Manufacturers Association. This committee is composed of the chief electrical engineers of the various vehicle companies.

Cooperating is the Lamp Manufacturers Subcommittee, a group of leading engineers from the vehicle lamp manufacturers.

These committees have almost unlimited equipment and facilities at their disposal. Numerous laboratories, similar to that shown in Figure 1, are available for lamp development and testing. Several specially equipped lighting test cars, such as those shown in Figure 2, are maintained to allow field observation work. Proving ground facilities are available which have geographic locations that permit tests to be conducted under any weather conditions at any time of year.

For example, the vehicle lighting tests held in 1959 were at Kingman, Ariz., in

March; at Milford, Mich., in May and June; at Cleveland, Ohio, in August; at Detroit in October; and at Phoenix, Ariz., in December. At each location complete testing facilities have been available, together with all required instrumentation, vehicles, shops, equipment and personnel.

The procedures followed in these testing programs have been evolved over a period of more than 20 years. These procedures are constantly being refined to reflect technological advances and changing traffic conditions on the highway.

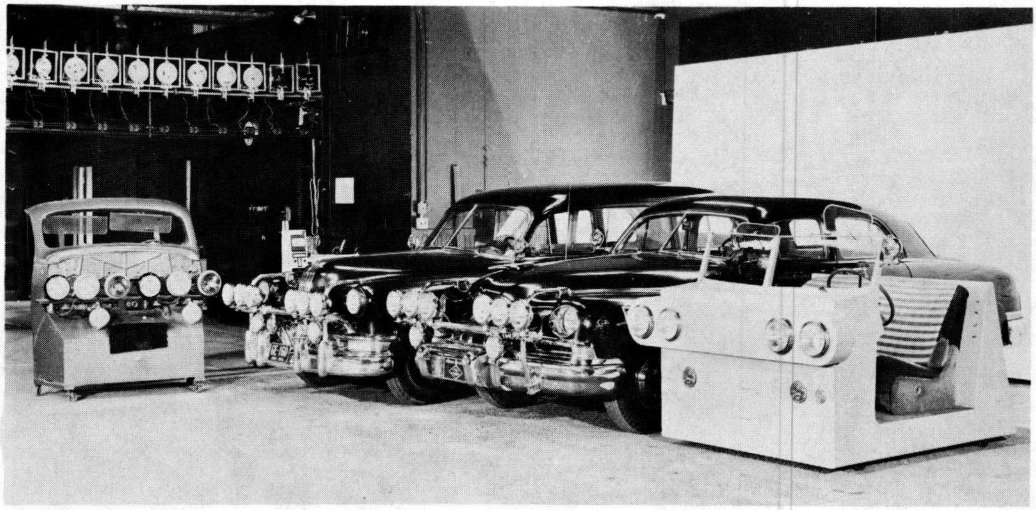


Figure 2. Lighting test cars.

When required, new instrumentation is designed and developed specifically for the test work.

Figure 3 shows an experimental meter currently under development by Guide Lamp Division to help evaluate headlamp glare. This picture was taken during the Kingman tests last spring, at a time when Detroit was experiencing a late snow storm.

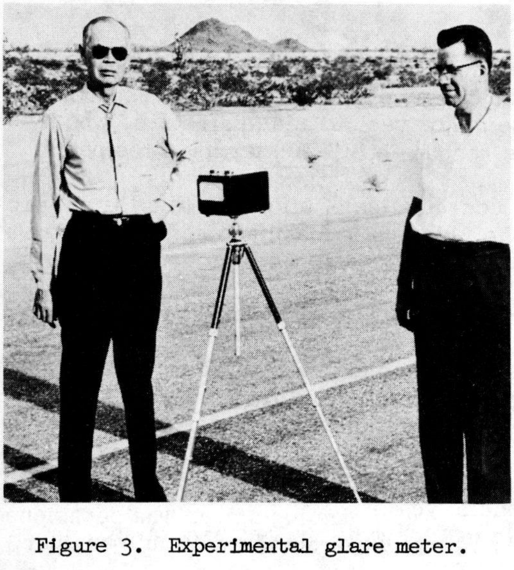


Figure 3. Experimental glare meter.

Another device, designed and built in the laboratory of GMC Truck and Coach Division, was specifically developed for the testing program. This unit allows flashing lights, as turn signals, to be demonstrated under a wide variety of precision flashing rates and filament "on" times.

Of course, the work of industry could not have advanced without the assistance of many other groups, including particularly the Lighting Committee of the Society of Automotive Engineers.

The development and promotion of better vehicle lighting practices are not confined to this country alone. The American industry groups work actively with the committees of the International Electro-Technical Commission, the International Standards Organization and the Economic Commission for Europe.

During the past year the industry has sent delegates to six overseas meetings where vehicle lighting subjects were being discussed.

The foregoing is background information indicating the scope, goals and organizational approach involved in the industry cooperative program. The remainder of this paper outlines the main aspects of the industry's research and testing program in the recent past, covering about the last 18 months.

EQUAL SIGNAL EFFECTIVENESS

In cooperation with members of the SAE Lighting Committee a series of tests were conducted to re-evaluate the candlepower requirement ratios specified for signals of

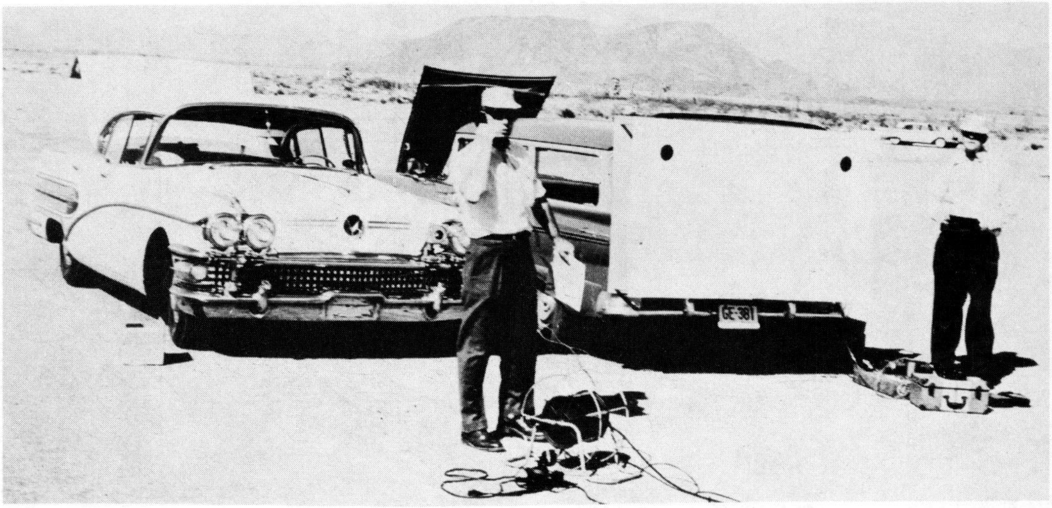


Figure 4. Equal signal effectiveness test setup.

different colors. These tests were conducted both under the more or less average sunshine conditions of Michigan and under the high-intensity sunlight and high-contrast conditions of Arizona. The test arrangement (Fig. 4) consisted of two test lamps set in a background panel which could be either yellow, white or black. Against each of these backgrounds one of the test lamps was at a fixed candlepower of red, while the other was varied through a wide range of candlepower in amber until jury opinion established that both signals had equal effectiveness.

From these tests the following new equal signal effectiveness ratios for different colors of vehicle lamps and signals were established:

Red		Amber		White
1	:	3	:	5

COLOR OF FRONT TURN SIGNALS

Drawing on this new information, tests then were conducted in daylight on amber and white front turn signals mounted on passenger cars. These tests were arranged so that sunlight was shining on the front of the car. Under these conditions it was the consensus of the observers that an amber signal was definitely more visible than white signal of identical candlepower. (Obviously red lights were not compared in this test because red lights to the front of the vehicle are prohibited.)

Comments by the observers indicated that their preference for amber was occasioned by the "masking" of the white signal by sunlight reflections from the vehicle's bumper, headlamp lenses and other areas.

Similar visibility tests were made at night; but to simulate actual driving situations, separate observations were made:

1. From a car located on the right side of the roadway.
2. From a car so situated that the observers were located in the high-intensity portion of the test car's headlamp beams.

Under both of these conditions the observers expressed unanimous preference for an

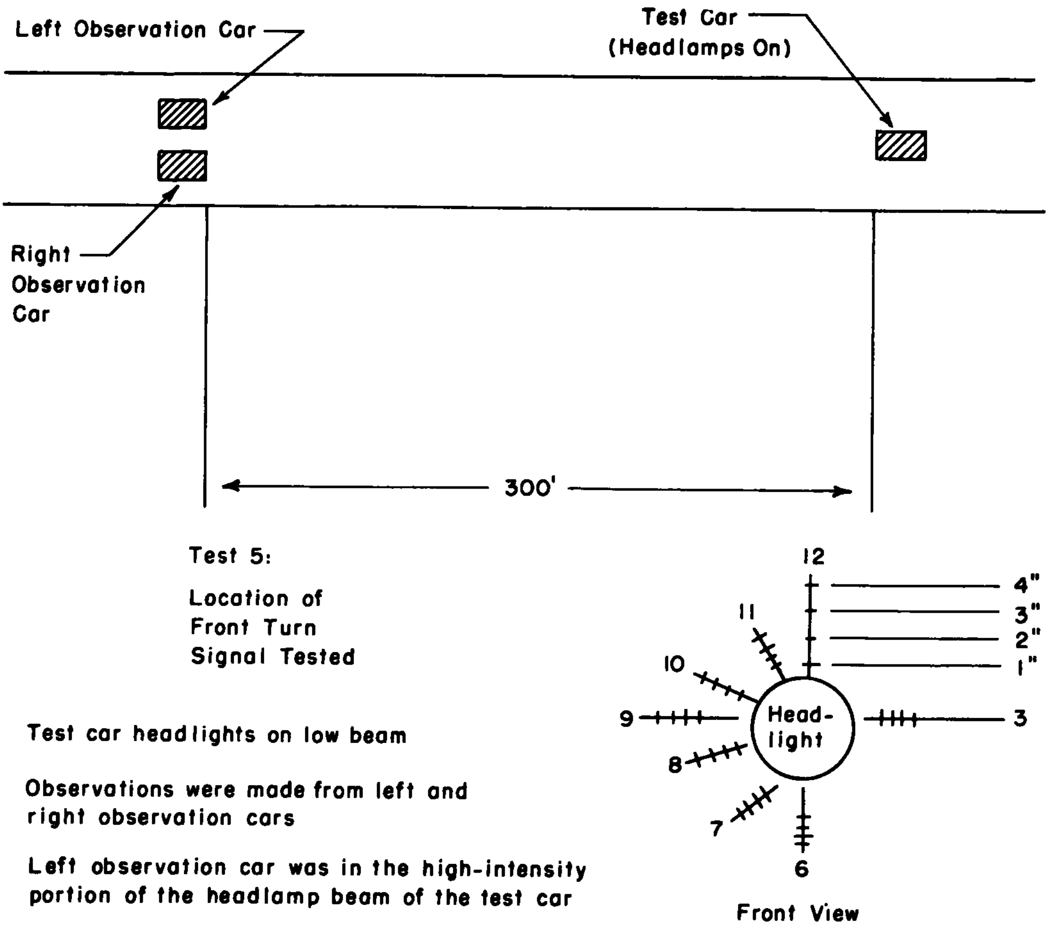


Figure 5. Test setup E used for tests 5 and 19; test site, Military Straightway, General Motors Proving Ground, Milford, Mich.

amber front turn signal as compared to a white signal of equal candlepower. Reports indicated that the amber signal was definitely more visible because it offered more contrast with the illuminated areas of the test car headlamps.

On the basis of the data from these tests a report has been made to motor vehicle administrators with the suggestion that restrictive laws or regulations in several jurisdictions should be amended to permit use of the amber front turn signals, as is permitted in the Uniform Vehicle Code and most state laws.

LOCATION OF FRONT TURN SIGNALS

Another series of tests was conducted to determine the effect of location of the front turn signal with respect to the headlamp.

During these tests the observers were asked to compare the visibility, at night, of front turn signals of various areas when the turn signals were positioned at eight different locations radially around the headlamp, with each location checked at four different spacings away from the headlamp along the radial path.

Figure 5 shows that evaluations were made from two observer locations in order to simulate the actual conditions which a driver might be expected to meet.

From this series of observations it was determined that, to be most clearly visible, a front turn signal should be located at least 4 in. from the nearest edge of a headlamp.

At the completion of the tests the results which had been obtained were referred to the Society of Automotive Engineers. As the result the SAE standard for Turn Signal Units was revised to specify that "The optical axis (filament center) of a Class A and Class B front turn signal lamp should be at least 4 in. from the inside diameter of the retaining ring of the headlamp unit providing the lower beam."

VISIBILITY OF SCHOOL BUS SIGNALS

As a public service the possibility of bringing about improvements in school bus warning signals was investigated.

Tests were conducted in bright sunshine with a jury of lighting engineers as observers.

Numerous lamp intensities were viewed against the characteristic chrome yellow background which is prevalent on school buses. These tests culminated in the following action:

1. SAE intensity specifications for school bus warning lamps were increased by a factor of 3.
2. The recommendation was made to school bus authorities that the area surrounding school bus warning lamps be painted black. The tests showed that this contributes materially to contrast, and thus effectiveness, of these signals.

OTHER ASPECTS OF TURN SIGNAL PERFORMANCE

One of the outcomes of the industry program on turn signals has been expressed in the action of industry representatives on the Uniform Vehicle Code Lighting Sub-committee; under instruction from the AMA Vehicle Lighting Committee and based on test observations they were instrumental in having the minimum visibility distance for turn signals increased in the Code from 100 ft to 300 ft. This change in the Code is expected to require an increase in SAE minimum specification values.

To provide data for the specifications work several field tests have already been run and the data are currently being evaluated.

Another recent test series dealt with the performance requirements for flasher units used in turn signal systems. Information from this series of tests is also currently being evaluated by the SAE Lighting Committee.

REAR LIGHTING OF VEHICLES

In initial stages at the present time is a major testing program to re-evaluate all of the performance requirements of all lamps used on the rear of vehicles. The concept here is to examine lighting and signal characteristics in terms of the now prevailing types of highways and driving situations where the driver of any vehicle has need to know more about the exact positioning and the relative motion of vehicles ahead of him on the roadway. It is hoped that results of these tests can be published in the near future.

7-IN. TYPE 2 SEALED-BEAM HEADLAMPS

Headlighting provides a constant challenge to the designer, the mechanic who aims the lamps and the safety lane inspector. The goal constantly is "improved visibility without increase in glare."

The most recent significant result of industry activity in this area is the 7-in. Type 2 sealed-beam headlamp.

To properly evaluate the value of the 7-in. Type 2, the history of headlighting since the introduction of the sealed beam should be reviewed.

1939. — The sealed-beam headlamp was introduced as the result of combined work by vehicle and lamp manufacturers, through the Automobile Manufacturers Association, in cooperation with the Society of Automotive Engineers and American Association of Motor Vehicle Administrators (AAMVA).

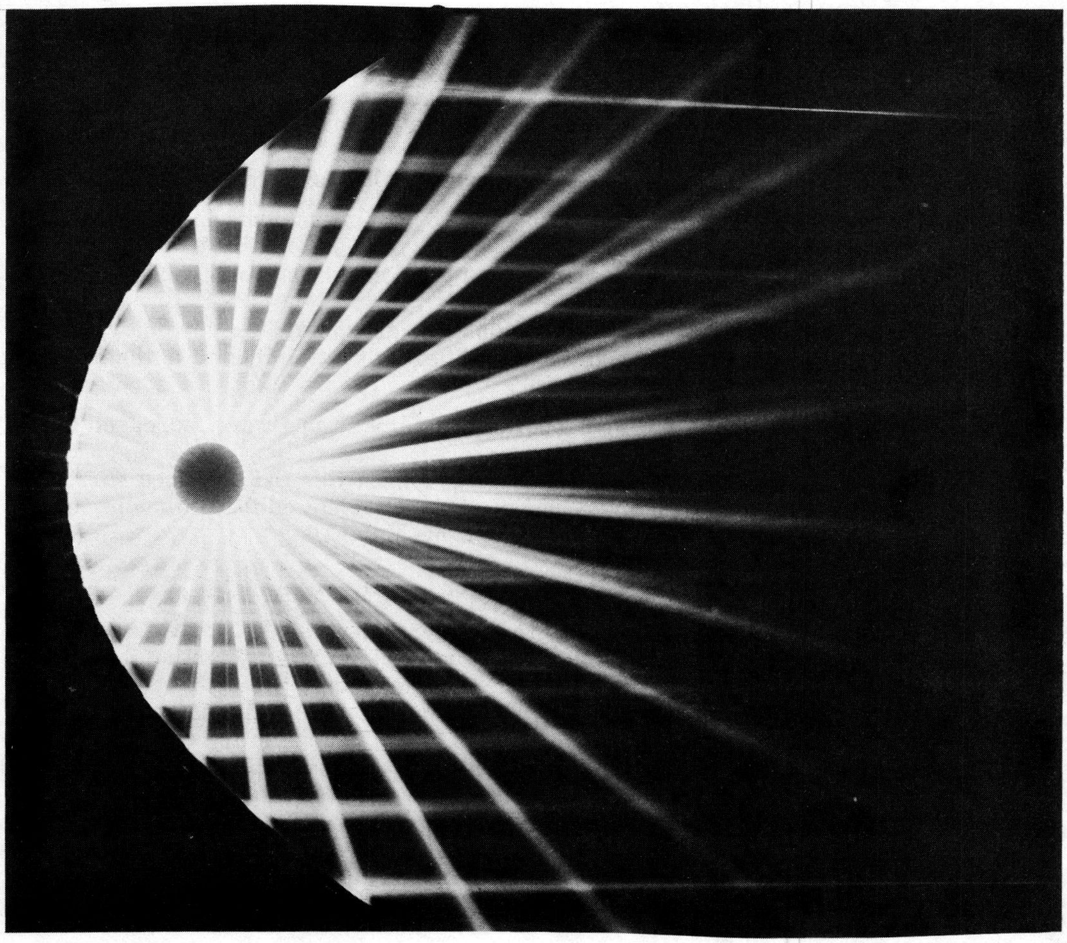


Figure 6. Lamp "A" without fog cap (side view of cut away model).

The lamp construction, interchangeability, dimming switch, upper beam indicator and aiming features made it a noteworthy contribution to night driving safety. Subsequent improvements in the design have come from continuation of this cooperative program.

1955. — In response to AAMVA desires for a better low beam, the improved sealed-beam headlamp was introduced. This sealed-beam unit gave improved visibility in adverse weather.

Improved visibility in adverse weather was the result of the addition of a fog cap. The fog cap is a metal shield which is placed so that it will block off light rays that emanate forward and upward from the low beam filament.

The rays that are intercepted by the reflector become controlled and are transmitted as part of the beam.

The rays that the fog cap now intercepts are those which are not controllable.

Without the fog cap these rays would project forward and upward and would reflect from moisture particles (which constitute fog or rain) back into the driver's eyes causing glare and eye strain. Elimination of this hazard by use of the fog cap is a major contribution. The effectiveness of the fog cap is readily demonstrated (Figs. 6 and 7).

Lamp A does not contain a fog cap. Notice the divergent rays above horizontal.

Lamp B contains a fog cap. Notice the reduction in rays above horizontal.

Use of the fog cap has been so effective that this feature has been incorporated in all subsequent headlamp development.

1956. — A substantial improvement in headlamp aiming techniques was realized with the introduction of aiming pads on sealed beams. Three pads placed on the periphery of the lens established a plane.

The relationship of this plane to the beam pattern is controlled during manufacture. As a result, it is only necessary to "aim the plane." This can be done with a simple tool and the guesswork of visual aim is eliminated.

1956. — The dual headlamp system was introduced on some 1957 cars. This development provided improved upper and lower beam performance. This improvement resulted from increased wattage, improved lens design, and elimination of compromises required in the original 7-in. sealed-beam units.

1959. — A new 7-in. unit, designated as a Type 2 unit, was introduced to provide original equipment and/or service replacement for earlier 7-in. units.

This new unit provides a lower beam comparable in performance to the dual system low beam. This improvement was accomplished without wattage change by placing the lower beam filament on focus and by aiming with the pads.

This unit does not have the upper beam performance of the dual system, but, as mentioned has comparable low beam performance. A reason why upper beam output cannot match the dual system is that generator capacity of older cars would not permit use of higher wattage lamps.

Figure 8 shows graphically the improvements which have been realized in lower beams of 7-in. lamps since 1939.

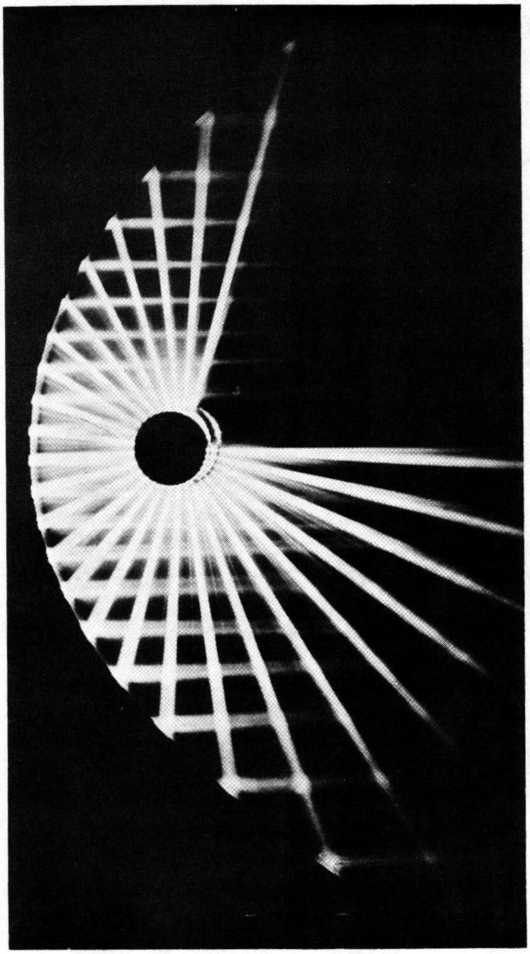


Figure 7. Lamp "B" with fog cap (side view of cut away model).

In addition to the extensive program, the industry lighting group has been active in public service programs to promote good vehicle lighting practices.

Three books on aiming procedures have been prepared, and approximately 100,000 copies of these booklets have been printed. The majority of these have been distributed to dealerships, garages, service stations, law enforcement agencies, inspection stations and others directly concerned with headlamp aiming.

In addition, a team of lighting engineers has visited several states to assist in local headlamp aiming problems. For example, in 1958 officials of one jurisdiction asked for help in setting up a local headlamp aiming inspection program. In response to this request this task force comprised of industry experts gave a presentation on headlamps and how to aim them. On this visit the task force told the headlamp story and headlamp aim story to more than 600 inspectors, officials, gas station attendants, garage and dealer mechanics. As a result of this, the government unit involved now has a successful headlamp aim inspection program.

To assist other jurisdictions in the future, the AMA is planning to create a film to tell the headlamp and headlamp aim stories. It is the hope that this film will contri-

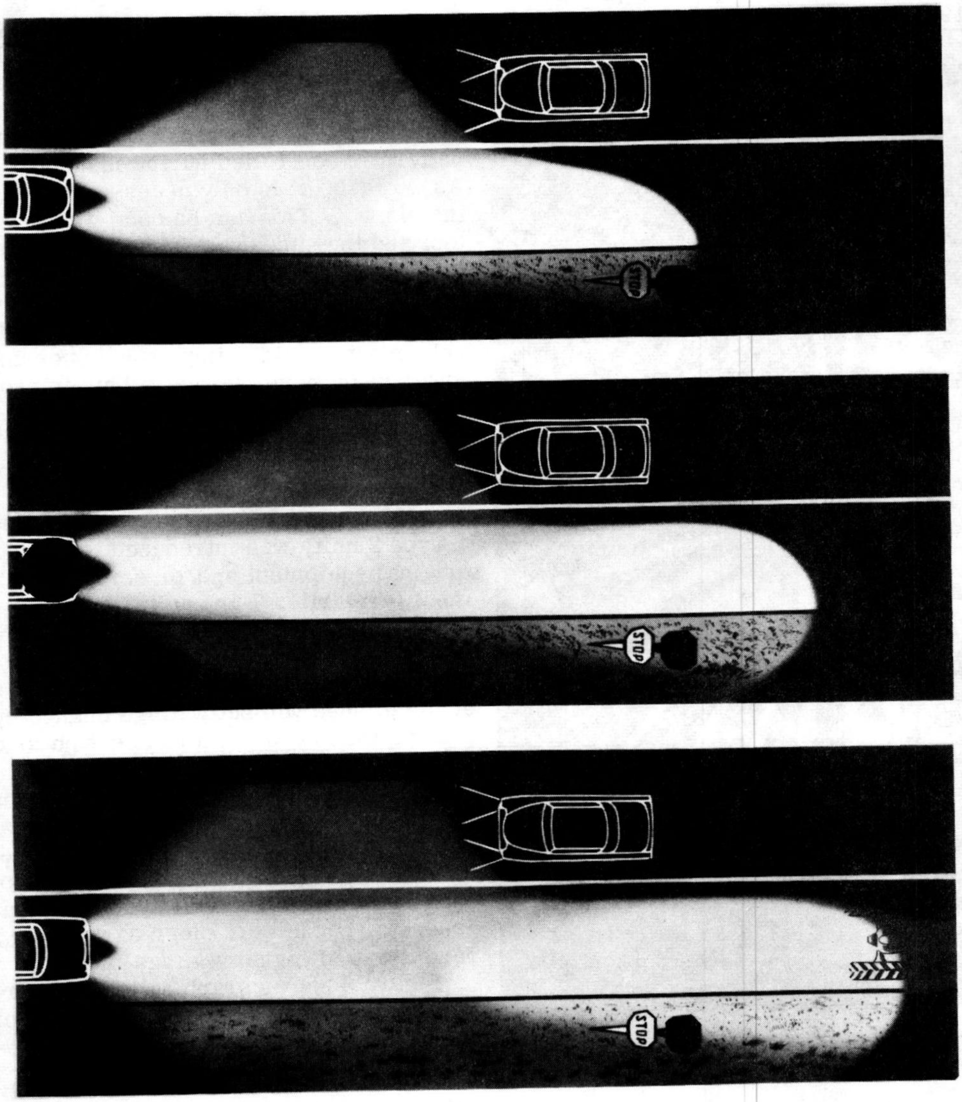


Figure 8. Lower beam improvements, showing: (top) 1939 sealed beam, (center) 1955 improved sealed beam, and 1959 7-in. Type 2 sealed beam.

bute to the establishment of more headlamp aim inspection programs.

It is recognized that headlamp aim inspection is required to insure that maximum visibility with minimum glare is maintained on vehicles. All automotive assembly plants aim headlamps. Enforcement is required to insure that this aim is maintained in the field.

Visual Comfort Evaluations of Roadway Lighting

CHARLES H. REX and J.S. FRANKLIN, Respectively, Roadway Lighting Development Engineer, Advance Engineering; Development Engineer, Photometric Laboratory, Outdoor Lighting Dept., General Electric Co., Hendersonville, N.C.

● THE VISUAL comfort quality of roadway lighting may have implications of greater importance to the over-all public welfare than the benefits of applying comfort principles in prescribing interior lighting. Visual ratings now considered adequate may be considered poor in the future. Added value and increased night use of the multi-billion dollar public investment in streets, highways, autos, trucks, and buses involves seeing comfort as well as visibility. Improved comfort for the motorist is one of the principal objectives in the advanced design of vehicles and roadways.

A recently published report (1) states: "Comfort, convenience, and safety are considerations of importance equal to a consideration of capacity in today's highway planning. This concept of adequate facilities requires modern techniques for handling traffic..."

URGENT NEED FOR RELATIVE VISUAL COMFORT RATINGS

Roadway lighting which makes night driving more pleasant and attractive is being numerically rated (5, 6, 7, 8, 9, 11, 12) in terms of relative visual comfort and relative visibility. These two seeing factors influence motorist opinion, enthusiasm, and demand for the installation and modernization of the lighting.

The Highway Safety Study Report (1) includes comment on the need for evaluation, driver research, and engineering investigation, and analysis of vision problems and driver fatigue. For example (1, 2): "...The Bureau of Public Roads has initiated appropriate cooperative studies with state authorities so that sorely needed new concepts, criteria, and techniques will be developed for determining the true value of continuous lighting on rural highways."

VISUAL BENEFIT RATINGS SHOULD ACCOMPANY RATINGS OF TRAFFIC BENEFIT

In support of such activities (2), plans for research and engineering analysis of the effectiveness of roadway lighting (3, 4), it is essestial that relative ratings be available for both visual comfort and visibility.

If roadway lighting has poor visual ratings, it is obvious that the traffic benefit produced can be expected to be less than that produced by lighting having good visual ratings.

Also of significance are the ratings in terms of relative visual comfort (designated discomfort glare) and relative visibility resulting from studies in other nations, for example: Netherlands (6), Great Britain (7, 8, 9), and West Germany (10).

OUTDOOR FULL-SCALE EVALUATION OF RELATIVE VISUAL COMFORT

This paper presents the use of the Guth evaluator for rating the relative visual comfort of roadway lighting systems. Outdoor, full-scale, field testing is involved as differentiated from ratings based on a previously described computation method (5).

Figure 1 shows relative visual comfort ratings for similar roadway lighting systems derived by two different methods (5, 17).

The evaluator ratings A and B pertain to different driver-observer positions along a roadway lighting system (Fig. 2). The ratings have been derived from a recent selective analysis of data produced by two years of outdoor field testing of a lighting system (13) at Hendersonville, N.C. (Figs. 2 and 3). Observer data selected on the basis of a BCD "population study," involving 50 people, which has been recently conducted in the Photometric Laboratory at Hendersonville, is described later in this paper. The evaluator used was developed by S.K. Guth and J. McNelis of Nela Park (17). The computed ratings are based on use of a method (5) of rating the relative visual comfort of lighting systems which has been presented during the past year (5, 11, 12). In this instance the luminaire spacing is 105 ft staggered. The visual comfort ratings shown in Figure 1 are relative to the motorist-observer sensation which would be at

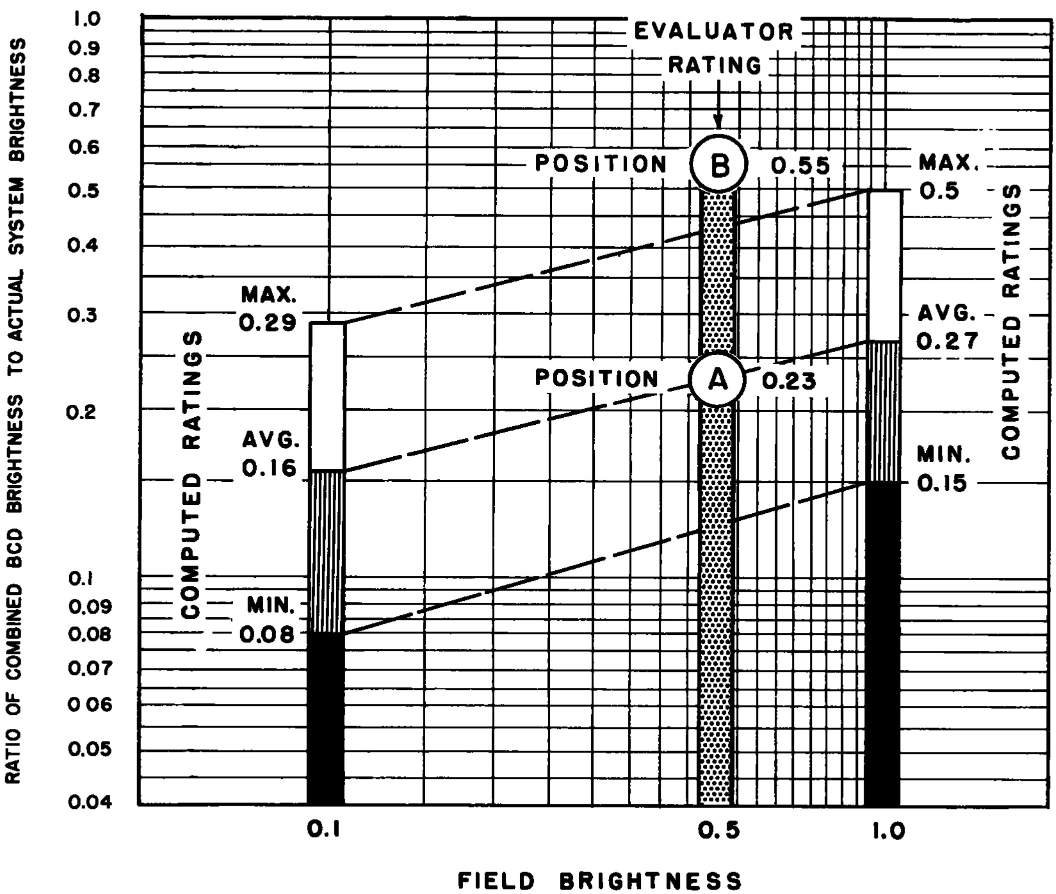


Figure 1. Evaluator relative visual comfort ratings for selected driver-observer at Position A and Position B on the roadway shown in Figure 2 are presented for comparison with computed ratings (5). These ratings for similar roadway lighting systems are of similar magnitude even though different BCD methods are involved. Note increase in computed relative comfort ratings with increase in field brightness.

BCD, the borderline between comfort and discomfort, for the system of luminaires and the lighted roadway (5), or the lighted roadway only (17), as differentiated in Table I and its footnotes.

The evaluator (17) BCD brightness, $\overline{B}_L$, is on the observer's line of sight and excludes the combined brightness of the system luminaires. The computed average combined BCD brightness Avg $\Sigma \overline{B}$, includes the BCD brightness of the luminaires off the driver's line of sight, in representative pole bracket locations. However, there is similarity in the magnitude of the rating ratios produced by the two different methods (5, 17).

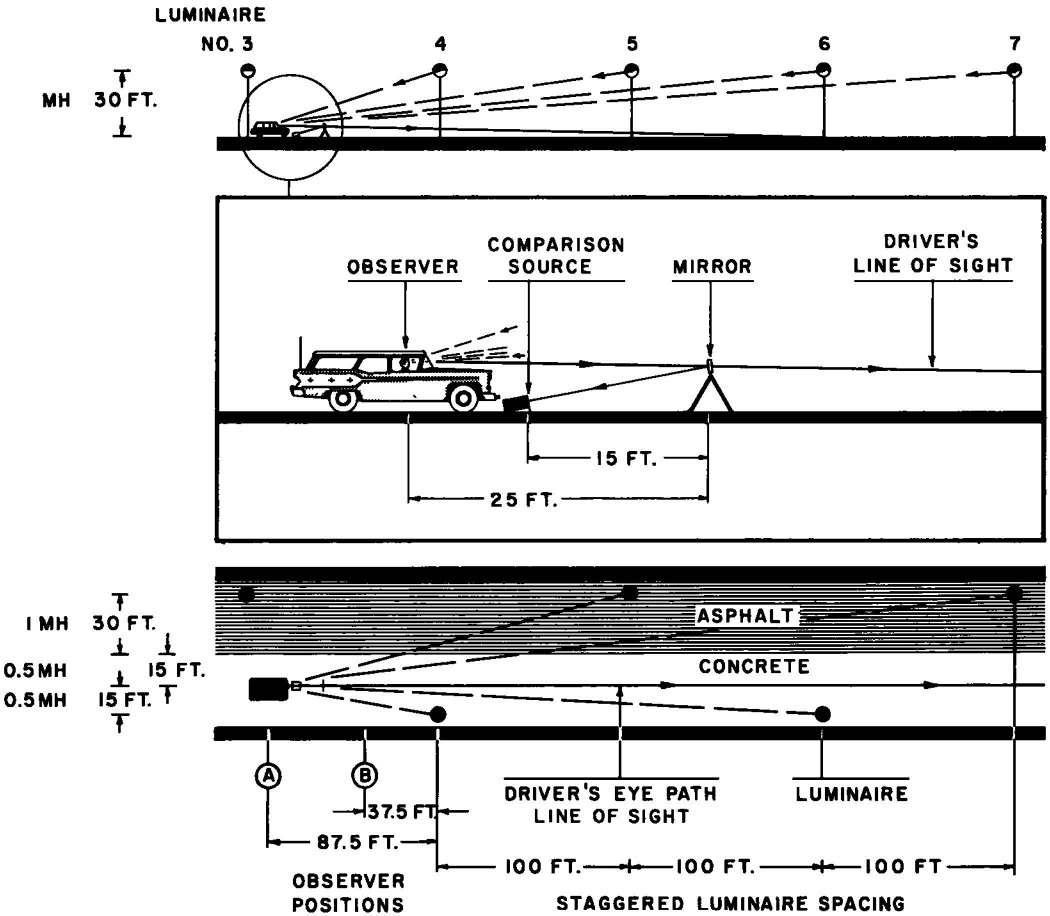


Figure 2. Evaluator observer positions A and B shown with respect to the layout of full-scale roadway lighting system tested. Center inset shows dimensional position of evaluator components; that is, comparison brightness and source, mirror, with respect to observer sitting in a representative automobile.

EVALUATOR RATING METHOD

The evaluator rating at each motorist-observer viewing position is:

$$\text{Evaluator Ratio at each position} = \frac{\Sigma \bar{B}_L}{\Sigma B_c}$$

in which $\Sigma \bar{B}$ is the brightness of a source on the observer's line of sight which is at BCD sensation brightness with respect to the lighted roadway background excluding luminaires (fL) and ΣB is the brightness of a comparison source on observer's line of sight which produces sensation equivalent to the combined brightness of the system of luminaires (fL).

The field brightness in this instance is assumed to be approximately the same as the average pavement brightness along the observer's path, 0.5 footlambert.

The lighting systems for both the evaluator and computed ratings include the same type of standard production luminaires. The luminaires are typical of those which have been installed and are in use in many portions of the United States and Canada. The projected area of the luminaire sources viewed from each observer position is the same as for a type of luminaire which has been widely used for mercury lamps. Equipped with 15,000-lumen multiple-filament lamps, the luminaires are at 30-ft mounting height. The transverse distances are also the same for both systems, as indicated in Figure 2.

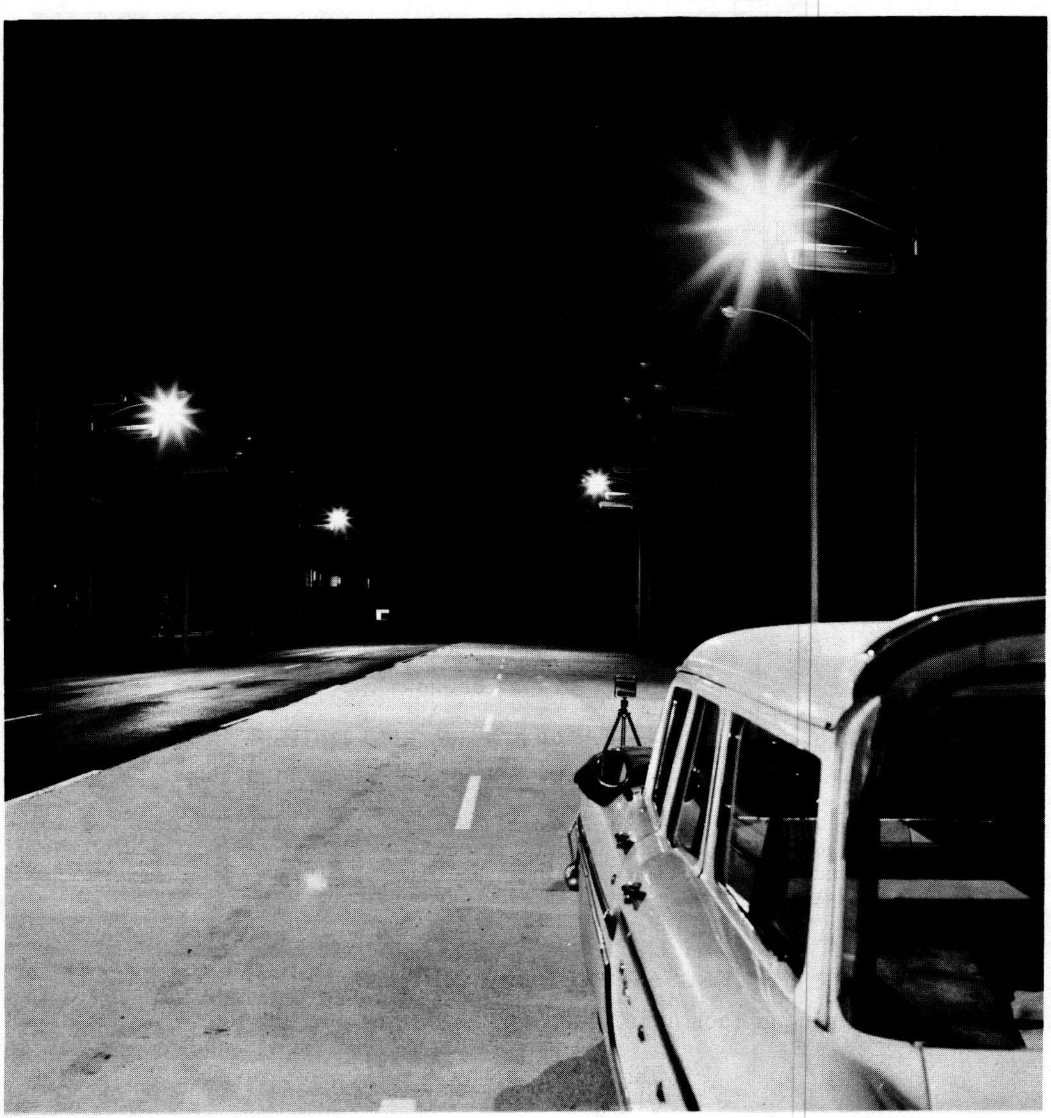


Figure 3. The outdoor laboratory full-scale test roadway at Hendersonville, N.C., the system luminaires, the evaluator mirror in front, and the representative automobile in which the driver-observer is seated while rating relative visual comfort of the lighting system with the aid of the Guth evaluator is shown.

COMPUTED RATING METHOD

The computed rating (5) at each of the several successive motorist-observer viewing positions, and for each field brightness condition is :

$$\text{Computed Ratio at each position} = \frac{\Sigma \bar{B}}{\Sigma \bar{B}}$$

in which $\Sigma \bar{B}$ is the combined brightness of system luminaires which would be at BCD sensation when mounted on the pole brackets with a specified field brightness including that of the pavement (fL) and ΣB is the combined actual brightness of the system luminaires (fL).

A computed rating (designated avg) is the arithmetic average of the ratings (5) over a cycle of 14 observer positions for a longitudinal distance twice the luminaire spacing. Use of the geometric mean of these ratios instead of the arithmetic would change the mean from 0.16 to 0.15 for F = 0.1 footlambert, and from 0.27 to 0.25 for F = 1.0 footlambert. The arithmetic mean or average is being used for computed ratings (5) and geometric mean for evaluator ratings (17).

TABLE 1

EVALUATOR VERSUS COMPUTED METHOD AND RESULTING DIFFERENCE IN DATA FOR SYSTEM OF ROADWAY LIGHTING LUMINAIRES WITH 15,000-LUMEN MULTIPLE-FILAMENT LAMPS (ALL BRIGHTNESS DATA ARE IN FOOTLAMBERTS)

		BCD Brightness		Brightness of System Luminaires		Rating Rates	
Type of Rating	Field Brightness	Avg. ΣB[1] for System of Luminaires Not on Line of Sight	$\bar{B}_L$[2] Excluding Luminaires	Avg. ΣB[3] Actual Luminaires Combined	B_L[4] in Terms of Line of Sight	$\bar{B}_L/B_L$ Line of Sight	Avg. of $(\Sigma\bar{B}/\Sigma B)$
Computed average of ratios for 14 positions	F = 0.1 F = 1.0	3500 5900		24,600 24,600			0.16 0.27
Evaluator Full-scale Test Rating	F = 0.5						
Position A			830		3630	0.23	
Position B			1120		2020	0.55	
Simulator Studies in Photometric Laboratory 1959	F = 0.1 F = 0.5 F = 1.0		417 640[5] 777				

[1]Average combined brightness of system luminaires which would be at BCD sensation when mounted in pole bracket location 30 feet above roadway for two assumed field brightness conditions which include the pavement brightness.
[2]Geometric average of observed brightness of evaluator source which is at BCD sensation on the observer's line of sight toward pavement. Luminaires are excluded. Evaluator source size is 0.000025 steradian.
[3]Average combined actual brightness of lighting system luminaires.
[4]Geometric average brightness of evaluator comparison source on line of sight which produces sensation equivalent to that of the combined effect of lighting system luminaires.
[5]Extrapolation from Figure 11. Source size is 0.000032 steradian.

The computed ratings are shown for two field brightness conditions (5), F = 0.1 footlambert and F = 1.0 footlambert. The field brightness is the average integrated brightness in the driver's field of view including the brightness of the pavement and objects thereon and nearby. The average brightness of the lighted pavement directly in front of the observer is approximately 0.5 footlambert. If, in addition, the integrated brightness of the luminaire sources is included, the over-all field brightness is appreciably increased.

The development of an instrument for the measurement of the combined brightness in the driver's field of view has been actively solicited during the past several years. Fry (28) has developed such a device for an I.E.R.I. project. B.S. Pritchard, of the Ohio State University Institute for Research in Vision, completed the instrumentation for field use. This meter has been used in studies conducted by Blackwell (22). It is hoped that the measured field brightness of the luminaires and pavement for the lighting system shown in Figure 2 will be reported (22) during the 1959 I.E.S. Technical Conference. It is hoped that future footlambert field brightness measurements will be made from the driver's eye position in a typical automobile so as to include conditions such as top of auto windshield cutoff, etc. (5, 11, 12, 14, 16).

The lighting system for the computed ratings spaces the luminaires 105 ft staggered (3.5 MH) instead of the 100 ft staggered arrangement used for evaluator ratings. The multiple of 0.5 MH spacing facilitates computation, using the method presented in detail (5).

The data used for computation was derived from laboratory studies by Putnam-Bower (19) and Putnam-Faucett (20).

The size ω of each luminaire source is computed for the installed pole bracket locations and representative observer viewing positions (5). Expressed in terms of steradians, the size ω is the visual solid angle subtended at the observer's eye position by the projected area of each luminaire source. These data include the driver-observer position at longitudinal distance of 3.0 MH. In this instance, the top of auto windshield cutoff (5) is assumed to occur at longitudinal distance of less than 3.0 MH to correlate with evaluator Position A (Fig. 2).

At the latter position, 87.5 ft in front of luminaire No. 4, on the driver's right, this

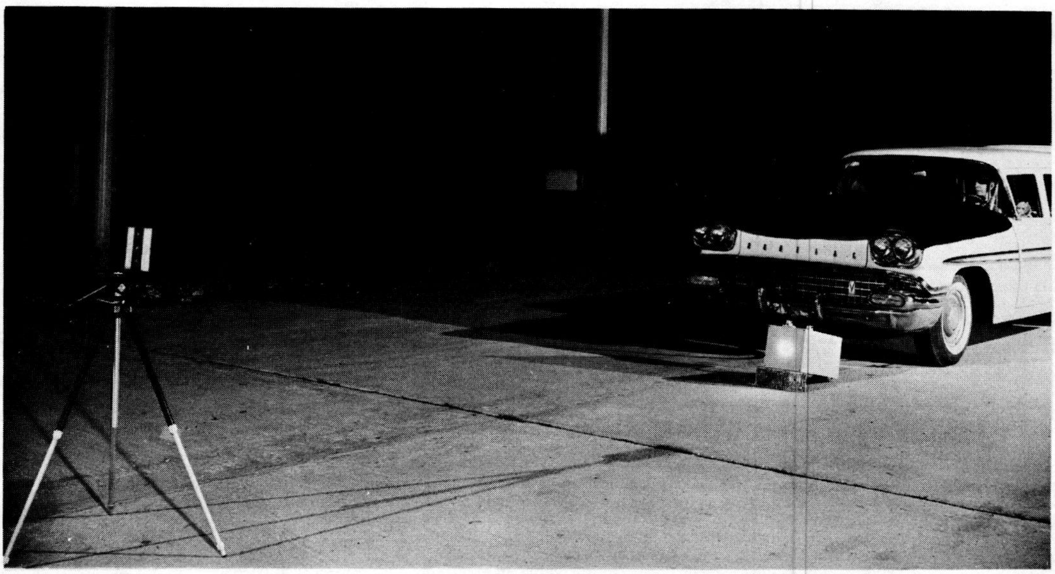


Figure 4. Front oblique view showing test conditions with evaluator BCD or comparison source near front of automobile, mirror at left, and observer in driver position.

source was in full view of all observers. This was at least partially due to the lean-forward posture assumed by the observers in order to use the headrest supported by the auto steering wheel (Fig. 5).

USING THE EVALUATOR FOR RATING ROADWAY LIGHTING

Using the evaluator for rating the visual comfort of roadway lighting has involved setups similar to those shown in Figure 2 to Figure 6, inclusive.

The brightness of the evaluator source is reflected in the small mirror directly in line with the observer's line of sight; that is, toward the middle of the concrete pavement background, about 1 deg below the horizontal.

The brightness of the evaluator source (Fig. 4) is adjusted by the observer, using the variac remote control (Fig. 5). A flashing sequence is used for the evaluator source, 1 sec on, 1 sec off, with a 2-sec break every 10 sec. During the off interval, between each exposure, the evaluator source is lighted to stand-by brightness adjusted to be equivalent to that of the pavement background. The size of the evaluator source is 0.000025 steradian.

BCD EVALUATION

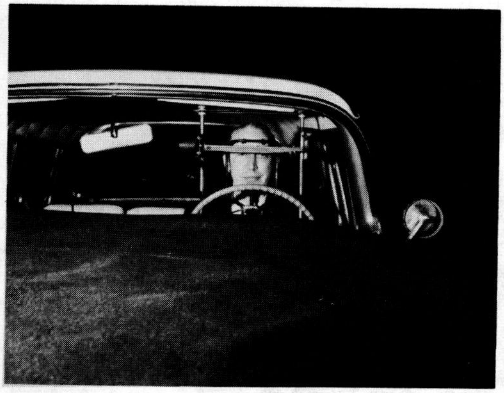
With the movable shield remaining in the down position to shield out the luminaires, as shown in the upper portion of Figure 6, the observer adjusts the brightness, $\bar{B}_L$, of the evaluator source until it is judged to produce the BCD sensation at the borderline between comfort and discomfort. The source brightness reflection is viewed against the field brightness in front of the observer comprising the lighted pavement, some unlighted pavement, roadside, sky areas, and the translucent shield areas as indicated in Figure 3 and the upper portion of Figure 6.

The BCD test results are given in Table I. For observer position A, $\bar{B}_L$ = 830 foot-lamberts on the driver's line of sight.

Figure 5. Observer R.K. Drake shows how the Guth evaluator source brightness is remotely controlled from the driver position in an automobile. During the relative visual comfort rating of a roadway lighting system, the shield portion of the headrest assembly is first down steadily for appraisal of the BCD-brightness on his line of sight with luminaires excluded from view. This is followed by automatic rotation of the shield up and down to alternately expose the observer-driver's eyes to the impact sensation judged to be equivalent to the combined brightness of the system luminaires.

The average pavement brightness along the driver's path is approximately 0.5 foot-lambert. It is believed that these measurements will be consistent with measurements made by B.S. Pritchard, using his 10-mm aperture brightness meter, during studies (22) conducted by H.R. Blackwell and sponsored by I.E.R.I.

Evaluator tests have been made to determine the approximate difference in BCD brightness, $\bar{B}_L$, when the shield is raised to expose the observer's eyes to the steady, combined brightness of the luminaires, in addition to the pavement brightness. This increases the integrated average field brightness. Nine tests by seven observers indicate that, under this condition, the BCD brightness, $\bar{B}_L$, on the observer's line of



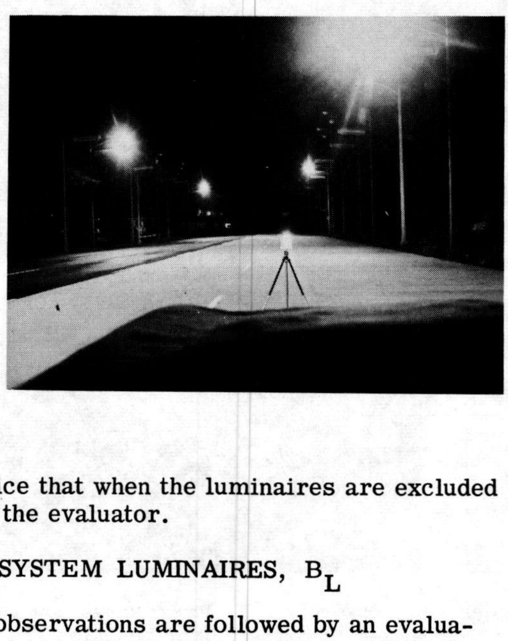


Figure 6. Upper left photo shows observer in test automobile with evaluator headrest shielded in the down position for appraisal of the BCD brightness. The resultant cutoff of luminaires and observer's field of view is shown in the upper right photo. The lower photo shows the driver-observer's view when the shield portion of the evaluator headrest is rotated upward to expose the observer's eyes to the combined brightness of the system luminaires. For evaluation of system luminaire brightness, the upper and lower test conditions are alternated automatically. The observer adjusts the brightness of the comparison source reflected in a mirror on the line of sight for an impact sensation judged to be equivalent to the combined brightness of the luminaires.

sight is increased; that is, of the order of twice that when the luminaires are excluded from view. The latter is customary in using the evaluator.

EVALUATING BRIGHTNESS OF SYSTEM LUMINAIRES, B_L

To complete each evaluator test the BCD observations are followed by an evaluation of the combined brightness of the system luminaires in terms of the equivalent impact sensation brightness of the evaluator comparison source. The shield is rotated upward to expose the brightness of the luminaires to observer view. At this time the comparison source is off, illuminated only to stand-by brightness. Then the shield is lowered to cut off the luminaires without intercepting the aforementioned portion of the field brightness, including the pavement brightness. At this time the evaluator comparison source is turned on.

The alternate exposure of the observer's eyes to the combined brightness of the luminaires followed by the brightness of the comparison source, B_L, is automatic, by a cam which alternately energizes power, to motor operation of the shield, then to the source. The alternate exposures of the system luminaires and the comparison source are of 1-sec duration, separated by 1-sec intervals. Three exposures of each, luminaires, and then comparison source, is followed by a 5-sec period for observer evaluation of the sensations and then re-adjusting the brightness of the comparison source. The observer adjusts the brightness of the comparison source until it produces the same impact sensation (17, 18) or feeling as does the combined brightness of the luminaires.

During the evaluation of both the BCD brightness, $\bar{B}_L$, and luminaire system brightness, B_L, the observers keep their eyes fixated on the comparison source aperture. The observer is allowed as many cycles as desired to make an appraisal. During each test five observations are made of each, the BCD brightness, $\bar{B}_L$, and brightness of the comparison source, B_L, equivalent to that of the luminaires. Comparison of the geometric mean of the brightness appraisals which are both based on observations on the line of sight provides the ratio $\bar{B}_L/B_L$ for the relative comfort rating at each position.

Evaluator data for Position A presented in Figure 1, Figure 2, and Table 1, is based on 240 observations by four observers selected as described later. Each of the six ratings made by each selected observer involved ten observations. The mean BCD brightness, $\bar{B}_L$, is 813 footlamberts. The comparison brightness, B_L, with the system luminaires in view, is 3630. This provides a ratio $\bar{B}_L/B_L$ rating of 0.23. The same rating is obtained by taking the geometric mean of the ratio ratings for each of the four observers. For Position B in Figure 2, the same selected observers were used, but a total of 80 observers and eight ratings are available for the geometric mean.

The selection of observer data on the basis of an average "population study" or BCD brightness evaluation conducted in the laboratory does not necessarily mean that the observers will also make the most authentic evaluator comparison rating for the combined brightness of the system luminaires. However, "population study" provides valuable guidance.

Also of interest in this respect is the fact that the outdoor full-scale evaluator studies at Position A for the same filament lamp lighting system (Fig. 2) have involved 21 observers, including those selected. The 21 observers have made 48 relative comfort ratings, or 480 observations. Based on all of this data comprising a larger number of random observers making an unequal number of tests, the geometric mean relative comfort rating is 0.19. This may be compared with the rating of 0.23 by the four selected observers (Fig. 1).

FEATURES OF EVALUATOR

The evaluator may be used to demonstrate and provide better understanding of the fundamentals involved in improving relative visual comfort. A driver-observer sitting in an automobile readily adjusts the brightness of the flashing comparison source to the BCD, borderline sensation between comfort and discomfort. By changing the lighting, the driver can observe and readily appreciate the fact that the BCD brightness for a roadway lighting system increases with appreciable higher field brightness, including the brightness of the pavement background against which the flashing comparison source is being viewed.

For example, one observer test with the luminaires shielded from view showed an increase in BCD brightness, $\bar{B}_L$, by 4.4:1 when the average foot-candles on the pavement were increased in the ratio of 4.6:1. Inasmuch as the higher level of illumination was obtained with opposite spacing and the lower foot-candle level with the staggered spacing in Figure 2, the pavement brightness did not increase proportionately.

An increase in field brightness improves the relative visual comfort ratio unless accompanied by a corresponding increase in the combined brightness of the system luminaires. The latter may be increased within the limits of the relative comfort ratio without decreasing the relative visual comfort. The evaluator demonstrates that progress involves higher brightness at or near the pavement level with lower brightness up at the luminaire mountings.

Because it provides guidance and aids comprehension of visual comfort principles and ratings for the roadway lighting which makes night driving easy and pleasant for millions of drivers, this evaluator is a very valuable development.

Numerical ratings for the visual comfort quality of roadway lighting are an impelling objective which fully justifies such night work. It is an essential step toward increasing the night use of the public investment in automotive transportation facilities.

INDOOR BCD EVALUATIONS

To provide calibration data on the outside observers, an indoor population study-type exploration of judgments of BCD sensation was made (24). Using a five-sided environmental chamber (Fig. 7), painted flat white on the inside, BCD evaluations were made by means of the Guth evaluator. This meter and its use will not be discussed as it has been described previously and in the literature (17). The test procedure included at least two separate settings for each observer. Each setting consisted of five valid BCD evaluations, at each of three background field brightnesses, with appropriate waiting periods for observer eye adaptation. For example, a minimum 10-min eye adaptation period was first required prior to any readings being taken.

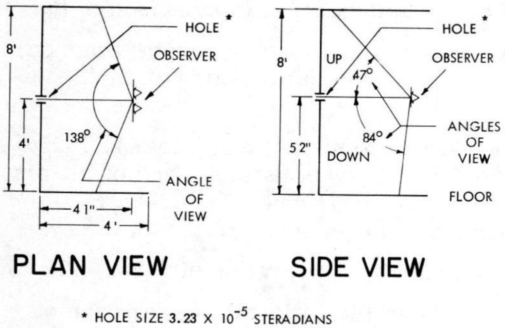


Figure 7. Dimensional sketch of indoor environmental chamber showing vertical and horizontal angles of view to observers. Light sources to provide background brightness were located to either side of observer at about eye level and were shielded from observer.

Although the environmental chamber consisted of ½ an 8-ft cube, very uniform brightness over the visual field (Fig. 8) was possible by the particular lighting system employed. The Guth evaluator was placed behind the opening (source size = 3.23×10^{-5} steradians) in the environmental chamber. This source size was a constant throughout the test and represented the same visual angle at 41 in. as the 2⅝-in. diameter evaluator source size viewed at approximately 41 ft outdoors.

Instructions to the observers on the conduct of the test were read to each person so that all received the same information. Test equipment was set up in a large, black room assuring the necessary quiet and disturbance-free atmosphere required by this type of psychological study. Only the experimenter and the observer were in the room at the time of the observations, with the experimenter located at the rear of the booth (Fig. 9).

Observers consisted of an all-white population of 52 people, 22 female and 30 male. Age range for the group was 40 yr; latitude of birthplace range, 21 deg in north latitude. During the course of the study, three sets of data (all female)

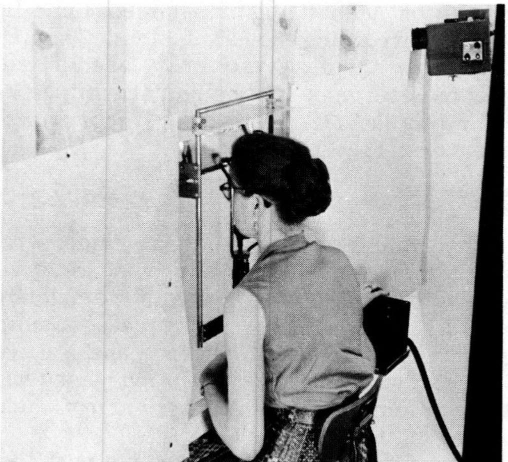


Figure 8. View of observer (center) in the environmental chamber looking at the flashing spot of light (at upper left). Hand control is located to the observer's right, and the brightness meter for making brightness calibrations is at the upper right.

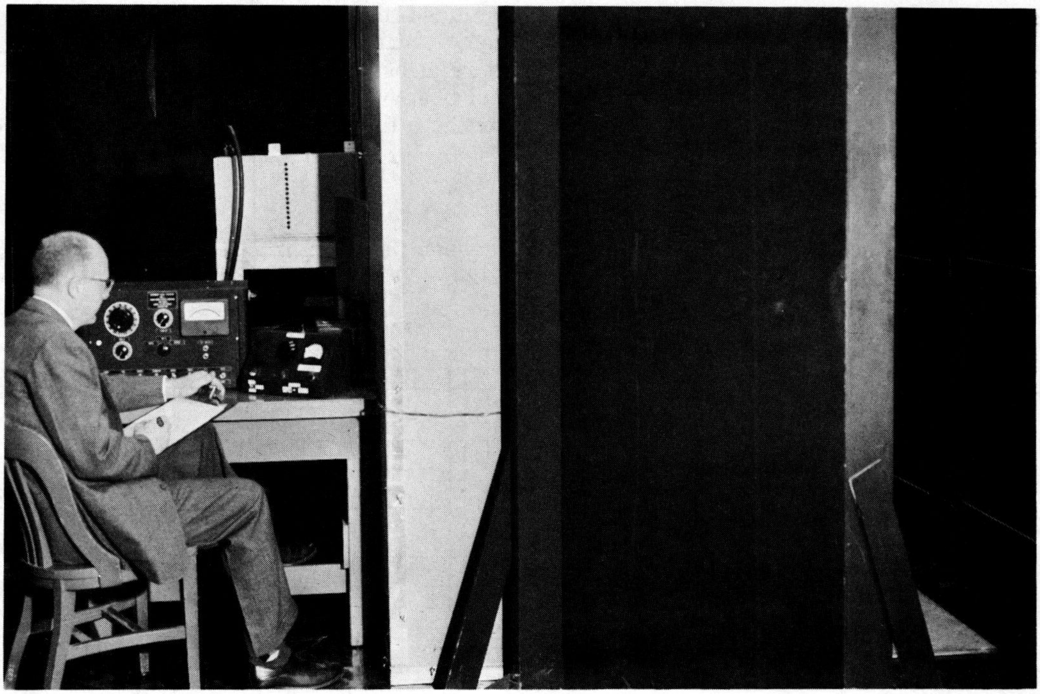


Figure 9. View of read of environmental chamber (center) showing baffled entrance to chamber (extreme right) and control area at left. Guth discomfort glare evaluator light source box is above and to the right of the large control cabinet.

had to be eliminated because of either inconsistent or insufficient data. Thus, results which follow have been drawn from a total of 49 reliable sets of data. Educational background of observers varied from high school to those meeting the Master's requirement at a college level. Observers represented management, office, and factory workers in a typical industrial organization, and were selected to cover a wide range of age (Fig. 10), latitude of birthplace (Fig. 10C), educational background, and sex (Fig. 10B). The degree of success is evidenced in the preceding illustrations. Infor-

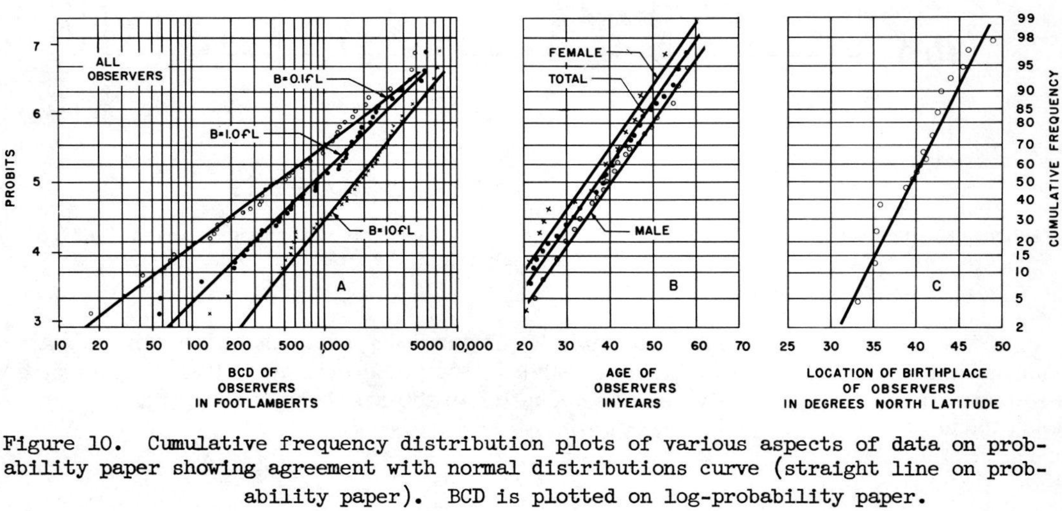


Figure 10. Cumulative frequency distribution plots of various aspects of data on probability paper showing agreement with normal distributions curve (straight line on probability paper). BCD is plotted on log-probability paper.

mation on the latitude of birthplace has been included to see if this had any correlation with BCD. In making this attempted correlation, it was assumed that early environment plays a large part in any cause and effect relationship that might exist between BCD and latitude. In addition to the selection of observers by any of the aforementioned requirements, all observers participating in the full-scale outdoor night observations of comfort were obviously included.

RESULTS

Figure 11 shows the excellent agreement between the results of this work compared with those obtained by previous investigations (20, 27). A detailed statistical analysis

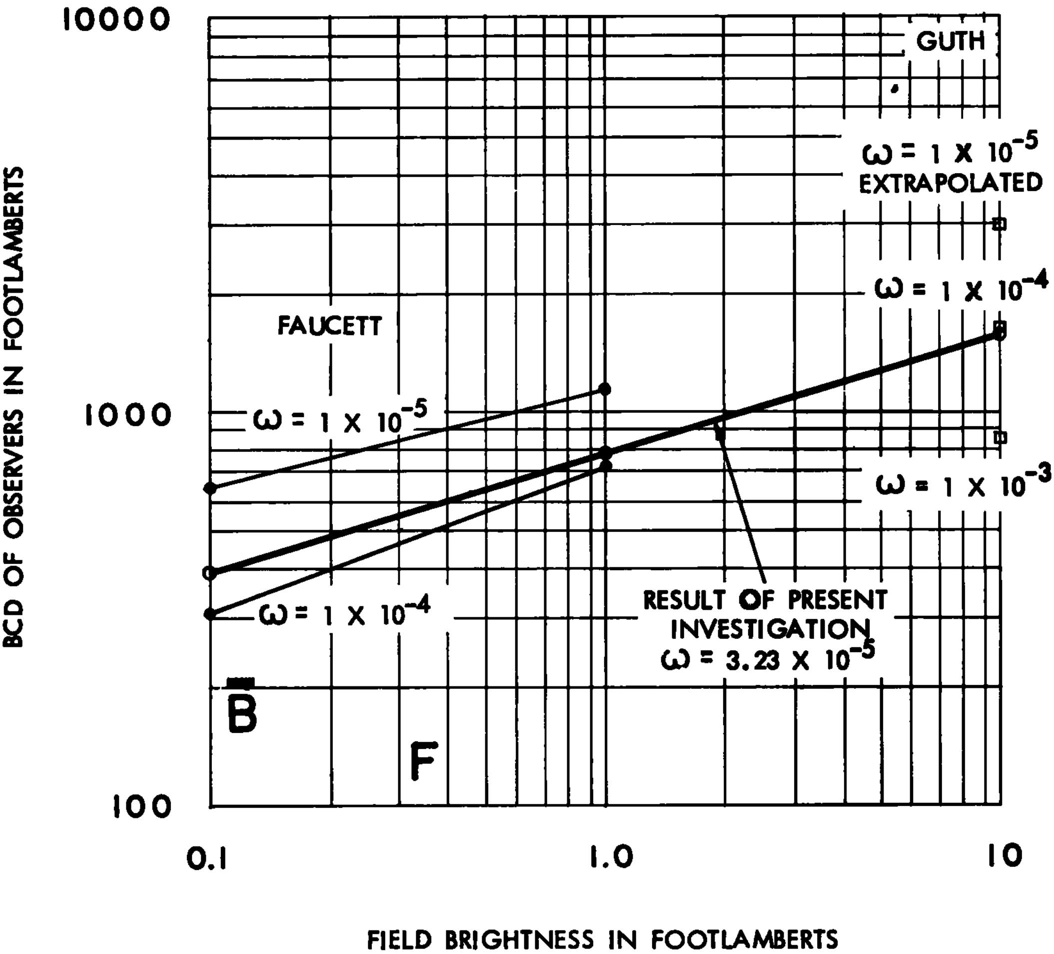


Figure 11. Results of BCD versus field brightness found in the present investigation as compared with results of previous work by Faucett and Guth.

(25) of the data has been included in Table 2. It should be noted that although the arithmetical averages have been included in Table 2, the geometric mean (G_m) values have been used throughout the analysis. The equation of the resulting curve (Fig. 11) has been found to be:

$$\bar{B} = 800F^{0.30}$$

TABLE 2

(A) SUMMARY OF ALL STATISTICAL DATA SHOWING RESULTS AT THREE FIELD BRIGHTNESS FOR MALE, FEMALE, AND TOTAL OBSERVERS

	Field Brightness									North Latitude	Age
	Female			Male			Total				
Basic BCD Data	0.1	1.0	10.0	0.1	1.0	10.0	0.1	1.0	10.0	(deg)	(yr)
No. of observers	19	19	19	30	30	30	49	49	49	49	49
Arithmetical averages	1410	1940	2780	850	1230	2340	1090	1480	2510	39	38.2
Geometric mean Gm	538	892	1630	347	692	1550	417	777	1590	39	36.4
Minimum (Gm values)	30	55	132	9	15	37	9	15	37	28	21
Maximum (Gm values)	4760	6000	7940	5900	5660	7310	5900	6000	7940	49	61
Range (Gm values)	4730	5945	7808	5891	5645	7273	5891	5985	7903	21	40
Median (Gm values)	509	861	1700	398	858	1915	436	861	1840	37.5	39
Standard deviation, σ (Gm values)	1685	2140	2680	1222	1241	1831	1470	1660	2200	4	10.7
Coefficient of variation, V (Gm values) (%)	314	240	164	352	179	118	352	213	138	10	29.4
Mode										39.4	39.5
Calculated correlation data:											
BCD vs. north latitude											
Product moment correlation Coefficient, r							-0.083				
Calculated correlation data:											
BCD vs. age											
Product moment correlation Coefficient, r							+0.12				

(B) DATA SIMILAR TO TABLE 2A EXCEPT USING "LOG BCD" AS THE BASIC QUANTITY IN ALL CALCULATIONS

		Female 0.1	Female 1.0	Female 10.0	Male 0.1	Male 1.0	Male 10.0	Total 0.1	Total 1.0	Total 10.0
Geometric mean G_M	BCD	457	813	1520	269	576	1350	331	661	1410
	Log BCD	2.66	2.91	3.18	2.43	2.76	3.13	2.52	2.82	3.15
Standard deviation, σ (log BCD)		0.64	0.55	0.47	0.66	0.54	0.48	0.66	0.55	0.48
Coefficient of variation V (log BCD) (%)		24	10	15	26	20	15	26	20	15
Standard error of mean S_x (log BCD)		0.15	0.13	0.11	0.12	0.10	0.09	0.10	0.08	0.07

Figure 12 has, in addition to the curve for the total population, separate curves for (a) all male observers, (b) all female observers, and (c) the eleven outside nighttime observers. As can be seen, at the lower field brightnesses there is a greater difference between male and female observers than at the 10 fL level, with women having a higher BCD value than men by approximately 50 percent. A study of Table 2 will show that, although women have approximately the same range of BCD, the standard deviation is greater at all three field brightnesses. These results would indicate a difference in BCD sensation between males and females, particularly at low field brightness, but perhaps a larger population sample would have brought the curves closer to that of the total population.

Although eleven observers volunteered for the outdoor night observations and a large quantity of data have been collected on various observers and street lighting systems, observers 6, 7, 8, and 9 (Fig. 12) have been selected for the purpose of this paper. The geometric mean of the BCD sensations of these four observers at 0.1 and 1.0 foot-

TABLE 3

A DETAILED SUMMARY OF STATISTICAL DATA ON BCD VERSUS NORTH LATITUDE

	NORTH LATITUDE				
	25^0-29.9^0	30^0-34.9^0	35^0-39.9^0	40^0-44.9^0	45^0-45.9^0
Observers	1	3	22	20	3
BCD Minimum	793	436	30	9	94
BCD Maximum	793	5900	4490	4760	2050
BCD Range	0	5464	4460	4751	1956
BCD Median	793	1410	334	555	148
BCD Gm			364	381	
σ			1074	1553	
V			295%	408%	

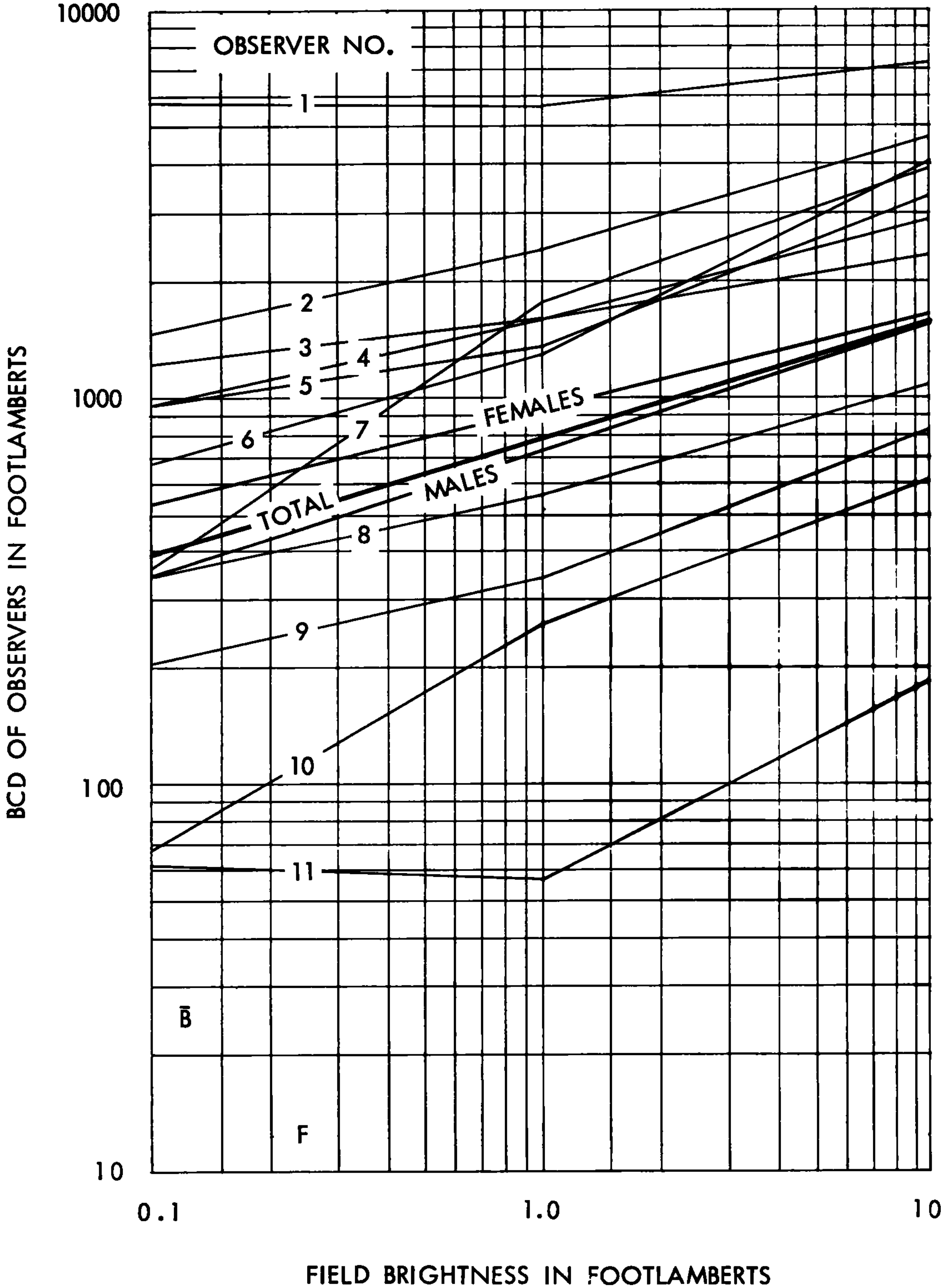


Figure 12. Curves for data on BCD versus field brightness for all male, female and outside nighttime observers, as well as total observer population.

lambert field brightness falls very close to that of the total population. Data on the other observers have been included so that the range and individual variations can be noted.

CORRELATION TESTS

A correlation test for the relationship of BCD versus latitude of birth gave negative results. Results are summarized in Table 2 and Figure 10C. The negative product moment correlation coefficient (26) of -0.083 indicates practically no correlation. The negative sign of "r" would seem to indicate that whatever little correlation exists is such that a decrease in north latitude is associated with an increase in BCD sensation. Table 3 gives results of a statistical analysis of the two principal latitude groupings (of which a sufficient number of observers were available). This also indicates very little difference between the two groups of data. A scatter diagram also showed no definite pattern. Figure 10C, which shows a plot of the data on probability paper, indicates a normal distribution of observers over the range of north latitude covered by the data.

A correlation test for the relationship of BCD versus age was also tried. This also gave negative results. Results are summarized in Table 2 and Figure 10B. The positive product moment correlation coefficient of 0.12 indicates practically no correlation. The positive sign of "r", however, would seem to indicate that whatever little correlation exists is such that an increase in age is associated with an increase in BCD sensation. A scatter diagram also showed no definite pattern. Figure 10B, which shows a plot of the data on probability paper, indicates that a better choice of observers (particularly female) with regard to age could have been made, although male and total populations indicate a normal distribution of observers over most of the age range. The problem, of course, is the inability of finding older men and women within the avenues of approach that were made available in the process of selecting possible observers. It should also be noted that the greatest number of drop-outs or rejects from the originally selected observer group were from the female group.

For the variation of individual BCD sensations at any field brightness, see Table 2 for the statistical data and Figure 10A for a plot of the data on probability paper. All three curves indicate a right-skewed distribution with the values for the geometric mean and median, all below a BCD value of 2000 fL. Readings, however, trailed off to almost 8000 fL.

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Illumination Requirements for Roadway Visual Tasks

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●BLACKWELL (1) has recently reported a general quantitative method for establishing the illumination levels required for adequate performance of various visual tasks encountered in interior environments. Inasmuch as there are no significant visual factors involved in performing outdoor tasks which are not also involved in performing interior tasks, the general method should be useful in establishing illumination levels for outdoor as well as indoor visual tasks. The present paper reports the establishment of illumination levels required for the performance of typical visual tasks involved in night driving, on the basis of the 1959 method. Of course, there are always special problems involved in the application of any general method in a new connection and in this case, new procedures and instrumentation were required for use of the method with roadway visual tasks. However, the basic assumptions and data used in connection with roadway visual tasks are identical with those used previously in connection with interior tasks.

THE LIGHTING SPECIFICATION METHOD

For the present purpose, a brief summary of the method proposed in 1959 for establishing illumination levels for various visual tasks will suffice.

An extended study was first made of the quantitative performance of normal young observers when presented visual tasks varying in size and contrast at various levels of background or adaptation luminance. In one series, the observers were not required to search and scan for the task, but were presented their tasks under optimal conditions in order to maximize their performance. Visual capacity to perform the tasks was determined for various durations during which the task might be presented. This study revealed the background or adaptation luminance value required to perform a visual task of fixed size and contrast during a fixed exposure time. Data were available for various quantitative levels of performance accuracy.

Study of patterns of eye movements during continuous visual work reveals that the normal eye will pace itself at a rate of about 5 fixational pauses per second. On this basis, it was decided that the visual system would be provided a reasonable level of "visual capacity" if it were enabled to assimilate one item of visual information per fixational pause. The criterion level of visual performance built into the lighting specification system was established as a visual capacity of 5 assimilations per second (APS), at an accuracy level of 99 percent.

Of course, observers must usually search and scan for visual information under far less than optimum conditions. A second series of studies required the observers to perform visual tasks under realistic conditions of search and scanning. Performance data obtained under these conditions were compared with similar data obtained under the optimum conditions studied previously. It was found that allowance could be made for the differences between the realistic dynamic conditions and the optimal conditions by use of a "field factor" of 15, representing that fifteen times more task contrast is required in the one case than in the other. It was assumed that the conditions of the dynamic experiments were reasonably typical of use of the eyes in various actual tasks. Therefore, a factor of 15 was used in adjusting the absolute values of the original data for the purposes of the lighting specification system.

A standard performance curve was then derived for the visual task consisting of a

*Deceased Aug. 26, 1960.

bright disc with a 4-min angular diameter, which appeared on a uniform background of lesser luminance. This curve is reproduced as the solid curve in Figure 1. It defines precise values of background luminance required for 4-min standard targets of varying physical contrast to just meet the criterion level of performance capacity and accuracy specified. It is apparent that the lower the task contrast, the higher will the background luminance have to be to maintain the task at the selected performance criterion.

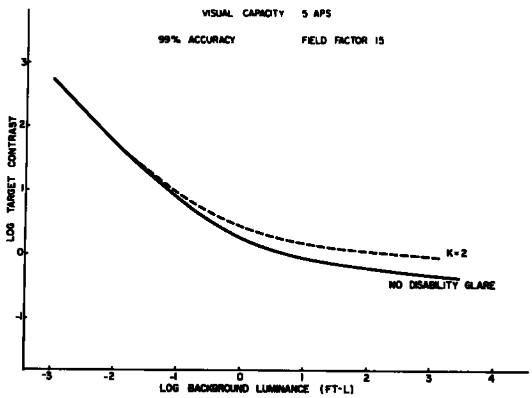

Figure 1. Standard performance data for a 4-min disc target. Solid curve represents no disability glare. Dashed line represents a degree of disability glare as described in the text.

Now, a practical visual task can be rated in difficulty in terms of the specific physical contrast value for the 4-min standard task which makes the two tasks of equal difficulty. Once such an equivalence has been established, the performance curve for the 4-min standard task may be used to establish the precise background luminance needed to maintain the practical task at the performance criterion. Requisite illumination may be computed from the value of required luminance from measurements of the reflectance characteristics of the task. The equation between standard and practical tasks is made in an instrument known as the Visual Task Evaluator (VTE). The device reduces both the standard and practical tasks to near the visibility threshold so that a reasonably precise equivalence can be established. After assessment with the VTE, the difficulty of each practical task may be described fully by a value of "equivalent contrast" for the standard task found to have equal difficulty. Only one value of background luminance and hence one value of illumination can provide the criterion level of visual performance for each practical task.

The original report of the lighting specification method included a statement concerning its use under circumstances in which there is substantial disability glare in the field surrounding the visual task. The basic idea goes back to an earlier paper by Blackwell (2). Blackwell has shown that the disability glare effect can be introduced into visual performance data such as those presented in the solid curve in Figure 1 by constructing curves such as the dashed one shown in the same figure. This curve represents a value of K = 2 in which

$$K = \frac{B + B_V}{B} \tag{1}$$

in which

B = luminance of the task background in the absence of disability glare; and
B_V = total equivalent luminance produced by all sources of disability glare within the field.

It is possible to construct a performance curve for any value of K of interest by geometrical construction in only a few minutes, following the method described (2).

Of the several expressions for B_V extant, the authors prefer the one reported by Fry (3) which may be written

$$B_V = \sum_{i=1}^{n} \frac{10 E_i}{\theta_i(\theta_i + 1.5)} \tag{2}$$

in which

E_i = illumination produced by a point glare source on the entrance pupil of the eye; and

θ_i = the angle between the point glare source and the line of sight of the eye, measured in degrees. The value of θ_i must always equal or exceed 1 deg.

Of course, it would be possible to compute the value of B_V for the environment of each visual task of interest, but it would hardly be practical. Instead, the authors have developed the idea suggested earlier by Fry (4) that a photoelectric photometer be used in obtaining a value of B_V immediately from the environment surrounding a visual task.

EXPERIMENTAL APPARATUS AND PROCEDURES

In addition to standard items of photometric equipment, three special items of measurement equipment were used. These are shown in Figure 2 in the outdoor site used for measurements at Hendersonville, North Carolina. The large optical device on the right is the VTE. The telescopic device on the tripod to the left is a Pritchard Photoelectric Photometer. What looks like an extra lens near the foremost leg of the tripod is the attachment used to obtain values of B_V by physical measurement.

The Pritchard photometer consists of a telescope and photomultiplier tube, arranged so that the photometer measures the luminance of small distant areas. The attachment for measuring B_V represents a "bug-eye lens" which images a full 180-deg view of the environment in the plane of a photographic absorptive mask. The lens was designed and built by Fry, whereas the authors have prepared the absorptive mask. The mask was designed to weight incoming flux from various portions of the environment in accordance with Eq. 2. An opaque mask obscured the inner 2-deg diameter of the field.

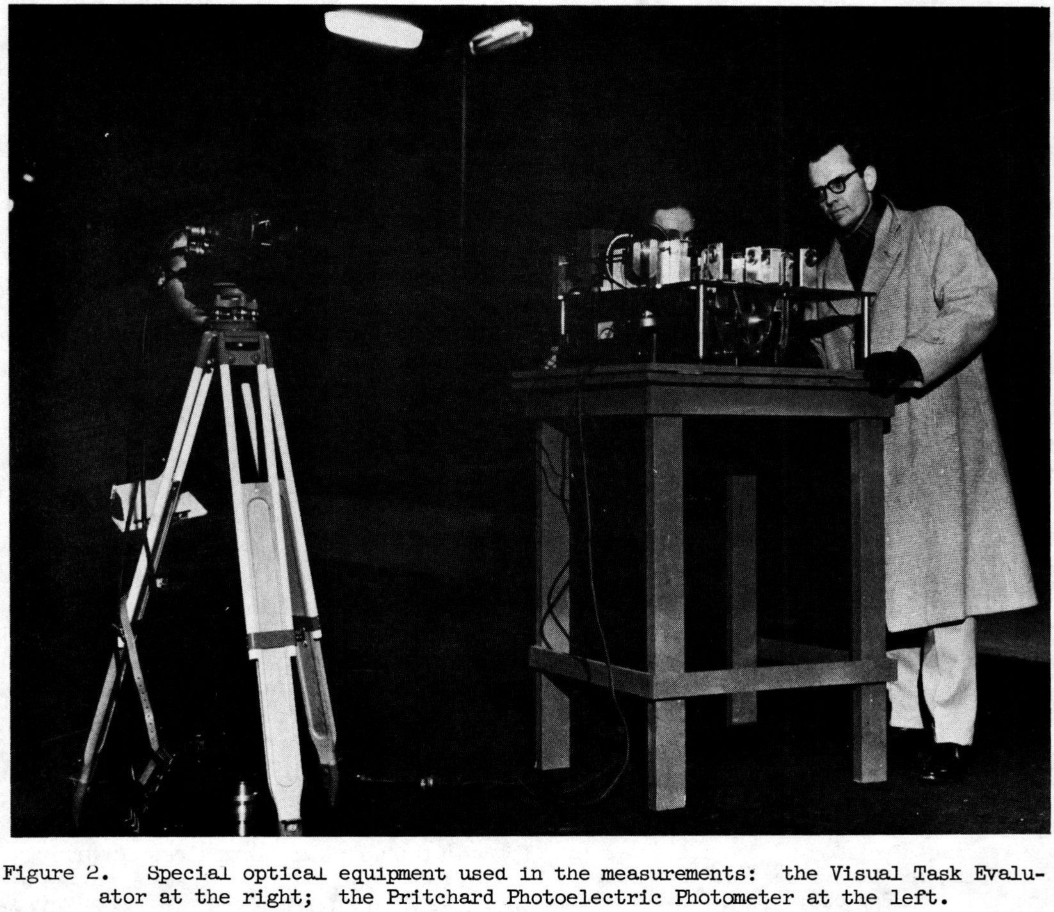

Figure 2. Special optical equipment used in the measurements: the Visual Task Evaluator at the right; the Pritchard Photoelectric Photometer at the left.

Thus, the photometer automatically integrated components of disability glare from all portions of the environment for a particular visual task and gave an experimental value of B_V.

Measurements were made on a special street used for street-lighting research and demonstrations, a daytime view of which is shown in Figure 3. The right half of the roadway was paved with asphalt, the left with concrete. Each pole had fluorescent,

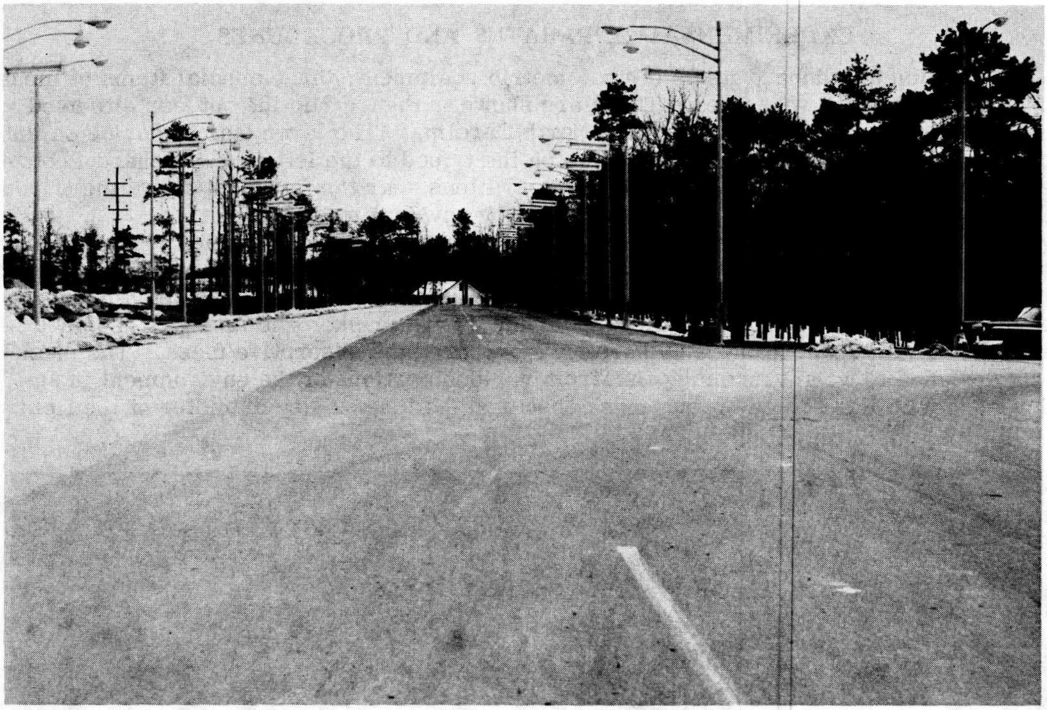

Figure 3. Daytime view of the outdoor testing facility at Hendersonville, North Carolina.

incandescent, and mercury fixtures. The poles used were spaced 200 ft apart on each side of the roadway, in staggered locations. The dimensions of the lanes and the positions of the luminaires with respect to the lanes may be judged from Figure 4. The roadway poles, luminaires, layout and pavement surfaces were intended to represent generally accepted American practice in roadway lighting installation. Further details concerning the installation may be obtained from the Outdoor Lighting Department of the General Electric Company which developed and maintains the installation.

Figure 4. Schematic elevation of the outdoor testing facility. The code used in identifying the luminaires is: F-fluorescent; I-incandescent; and M-mercury.

A variety of realistic targets were used to represent visual tasks of importance to night driving in areas where street-lighting would be used. For example, Figure 5 shows a mannequin located in the center of the concrete roadway, in what is called the driving lane, with the incandescent luminaires in use. The distance between successive luminaires on the left side is 200 ft, with the opposite luminaires occurring at the 100-ft midpoints. The nearest luminaire is on the left side in this case. When the asphalt pavement was used, the arrangement of luminaires was reversed left to right so that in this second case the nearest luminaire was on the right side. For most measurements, there was a total of six luminaires but the arrangement of five shown in the figure was employed in the earliest studies. With an approximately 30-ft mounting height, there were non-uniformities in pavement luminance as may be noted in the figure.

Illumination data for various locations along the roadway is required. These were obtained at 20-ft intervals down the roadway with a Macbeth Illuminometer and standard test plate.

The basic procedure may be described briefly, as follows: A target, such as the mannequin, was set up at a given location on the roadway. The measurement equipment was set up either in a mobile shed or in the back of a closed truck at a known distance from the target. The VTE was used to assess the difficulty of the target exactly as it would appear to a driver proceeding along the roadway. From this assessment, a value of the equivalent contrast of the 4-min standard target was obtained.

The Pritchard photometer was first used to measure the average luminance of an area of the environment containing the target, having a 2-deg diameter. The disability glare attachment was then placed on the Pritchard photometer and a value of B_V was obtained corresponding to the case of an observer viewing the target ahead.

Subsequently, a performance curve (such as the dashed curve in Fig. 1) was constructed for the value of K corresponding to the experimental values of B and B_V. The value of equivalent contrast obtained in the VTE was entered on the ordinate and the

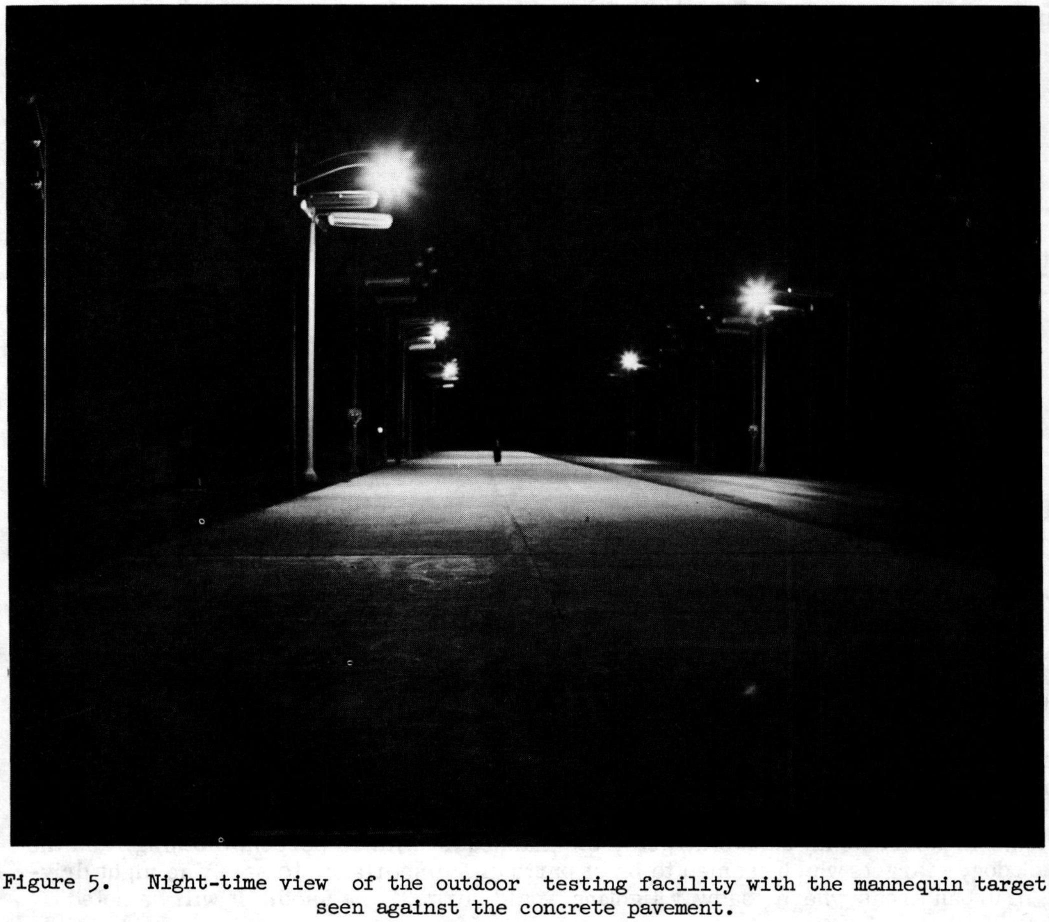

Figure 5. Night-time view of the outdoor testing facility with the mannequin target seen against the concrete pavement.

point of intersection with the appropriate (dashed) performance curve was used to define the precise background luminance level required for adequate performance of the visual task, in the presence of the measured amount of disability glare.

While in the field, measurements were made of the actual illumination falling on a test plate oriented horizontally. The requisite horizontal illumination was obtained from the relation

$$E_r = E_o \frac{B_r}{B_o} \tag{3}$$

in which

E_o = the horizontal illumination actually obtained;
B_r = the luminance required for adequate performance of the task; and
B_o = the average luminance of task and surround actually obtained.

Eq. 3 is actually no more than a method for determining the reflectance of some portions of the pavement for illumination coming from luminaires in a particular position with respect to the target.

EXPERIMENTAL DATA

It was intended that as good a sample as possible of typical roadway visual tasks be investigated. Nine tasks were originally selected for evaluation, in order to obtain some idea of their relative difficulty. Measurements were made on asphalt, with incandescent luminaires. Viewing distances of 180 and 200 ft were used and the results were averaged. The location of the measuring equipment was fixed inasmuch as it was mounted within a wooden shed. The target appeared either 40 or 60 ft beyond the first luminaire on the same side.

Illumination values required for nine different tasks are given in Table 1, in order of task difficulty. It is apparent that the illumination level required for roadway lighting varies enormously depending on whether the task is as large and easy to see as an automobile, or as small and difficult to see as a simulated hole in the pavement. The range of illumination values covers the limits of modern roadway lighting at one extreme and modern interior lighting at the other. These values emphasize the significance of specifying a particular visual task when considering illumination requirements.

TABLE 1

REQUIRED ILLUMINATION LEVELS FOR NINE TASKS[1]

Task Description	Horizontal Illumination (ft-c)
1. Old automobile	0.341
2. Mannequin, with clothing of 60% reflectance	0.358
3. Mannequin, with clothing of 20% reflectance	0.414
4. Yellow cone marker	0.436
5. Toy dog, with light fur	1.52
6. Toy dog, with black fur	1.80
7. Overturned bicycle	10.8
8. Brick obstacle	926.
9. Simulated hole in pavement	>1000.

[1]Asphalt pavement, incandescent luminaires, 180- and 200-ft viewing distances.

After completing these measurements, the authors decided to concentrate their additional measurements on two targets, the mannequin with 20 percent clothing and the black dog, —targets which seemed to be of particular importance to safety in night driving in urban areas where roadway lighting would normally be used. It will be noted from Table 1 that the selections fall near the middle of the original nine tasks in terms of difficulty so that these tasks are by no means extreme.

Because individual roadway installations will vary in the type of luminaire and pavement surface used, the effect of these two variables on the illumination required for adequate visibility of the mannequin and the dog was next studied. These measurements were made at viewing distances of 180 and 200 ft with the same fixed location with respect to the luminaires as before.

Data relating to the effect of luminaire type are given in Table 2. It appears that there is a small difference in the requisite illumination which depends on the luminaire type, with the least illumination being required with incandescent luminaires. On the average, 6 percent more illumination is required for fluorescent and 27 percent more when mercury luminaires are employed. These differences are perhaps not large, but they will be used in analyzing the data to avoid data bias due to luminaire type.

TABLE 2

EFFECT OF LUMINAIRE TYPE ON REQUIRED ILLUMINATION LEVELS[1]

Incandescent	Mercury	Fluorescent
	(a) Mannequin	
0.218	0.432	0.339
0.274	0.498	0.429
0.318	0.654	0.509
0.374	0.852	0.601
0.395	1.31	0.677
0.463	1.48	0.920
0.471	0.871 ft-c	0.579 ft-c
0.472		
0.474		
0.482		
0.598		
1.32		
0.488 ft-c		
	(b) Dog	
0.481	0.517	0.873
0.558	0.636	1.02
0.664	0.692	1.17
0.664	0.875	1.21
0.780	1.83	1.40
1.10	2.96	1.46
1.10	1.25 ft-c	1.19 ft-c
1.10		
1.32		
1.33		
2.16		
2.98		
1.18 ft-c		

[1]Asphalt and concrete pavements, 180- and 200-ft viewing distances. All values are horizontal illumination (foot-candles).

The data relating to the effect of pavement surface are given in Table 3. Here, as expected, the effect of pavement type is different in direction for an object such as the dog which is of lower reflectance than either the asphalt or concrete and an object such as the mannequin which has a reflectance intermediate between that of asphalt and concrete. The dog is easier to see on concrete because it more nearly matches the asphalt in reflectance. There is little difference in the visibility of the mannequin on the two pavements because she differs in reflectance to about the same extent from either asphalt or concrete.

TABLE 3

EFFECT OF PAVEMENT TYPE ON REQUIRED ILLUMINATION LEVELS[1]

Asphalt	Concrete
(a) Mannequin	
0.218	0.274
0.374	0.318
0.395	0.339
0.429	0.463
0.432	0.471
0.472	0.498
0.474	0.509
0.482	0.598
0.601	0.677
0.654	0.852
0.920	1.31
1.48	1.32
0.577 ft-c	0.636 ft-c
Concrete/asphalt factor = 1.10	
(b) Dog	
0.875	0.481
1.02	0.517
1.10	0.558
1.10	0.636
1.10	0.664
1.17	0.664
1.32	0.692
1.40	0.780
1.83	0.873
2.16	1.21
2.96	1.33
2.98	1.46
1.58 ft-c	0.822 ft-c
Concrete/asphalt factor = 0.519	

[1]Incandescent, fluorescent, and mercury luminaires, 180- and 200-ft viewing distances. All values are horizontal illumination (foot-candles).

It was decided to standardize on an asphalt pavement and incandescent luminaires for the next series of measurements. In this series, the viewing distance was fixed at 200 ft, and both the targets and the measuring equipment were moved along the roadway, so that the targets would be viewed under different geometries with respect to the luminaires. The targets were placed at locations 20 ft apart. A total of eleven positions was used, the first and last of which represented the case where the targets were directly under the luminaires. One of the eleven locations corresponded exactly to that used in the earlier studies. Illumination values for each of the eleven locations are given in Table 4, with the values for the location used in the earlier studies starred in each case. It is apparent that by chance a location was selected for the first studies which required the least illumination of any possible location. It is also apparent, as expected, that the location of the targets with respect to the luminaires has a considerable effect upon the illumination requirement. The average values in Table 4 should represent the most reasonable values to use for the selected luminaire and pavement conditions, because there is equal interest in providing adequate visibility for all positions of a pedestrian or dog with respect to the luminaires.

The best over-all illumination value for a 200-ft viewing distance would presumably consist of a composite value for all possible types of luminaires and both types of pavement surface. Such an over-all value may be estimated by using the data contained in Table 4, together with data given in Tables 2 and 3. There is reasonable supposition that the relative values obtained in the earlier studies and given in Tables 2 and 3 can be applied to the data presented in Table 4 to estimate what would have been obtained had all locations of the targets under all luminaires and with both pavements been studied. The average values of Table 4 are first corrected for the bias introduced because the illumination requirement is less for incandescent luminaires than for fluorescent or mercury luminaires. A multiplying factor of 1.11 corrects the values obtained with incandescent luminaires to the values to be expected from equal numbers of the three types of luminaires. A multiplying factor of 1.05 corrects data for the

TABLE 4

REQUIRED ILLUMINATION LEVELS FOR TASKS AT ELEVEN LOCATIONS[1]

Mannequin	Dog
0.415*	0.816
0.534	1.63
0.556	1.65
0.688	1.90
0.726	1.91
0.796	2.25
1.28	2.62
1.82	3.08
2.62	3.10
3.44	3.26
3.60	4.63
1.50 ft-c	2.44 ft-c

[1]Asphalt pavement, incandescent luminaires, 200-ft viewing distance. All values are horizontal illumination (foot-candles).
*Location studied previously.

mannequin obtained with asphalt alone to the average to be expected from equal numbers of concrete and asphalt pavements. A factor of 0.76 corrects data for the dog from asphalt to an average of both types of pavements. The resulting values of requisite illumination are as follows:

Mannequin	1.74 foot-candles
Dog	2.06
Average	1.90

The value of 1.90 foot-candles represents the best estimate of the illumination requirement for the average of the two tasks, when viewed from a 200-ft distance, with equal numbers of each luminaire and pavement condition.

It should be apparent from the foregoing that the illumination requirement varies considerably depending on the luminaire, the pavement, the visual task, and the location of the task with respect to the luminaires. Thus, an average value of 1.90 foot-candles may be difficult to interpret. For this reason, a frequency distribution has been calculated to illustrate the percent of times the mannequin or dog will be adequately visible for various possible illumination values.

A cumulative frequency distribution is presented in Figure 6. It was constructed as follows: Each value in Table 4 represents a task (either mannequin or dog) at some location with respect to the luminaires, there being 22 tasks in all. The factors in Tables 2 and 3 provide a basis for estimating the illumination requirements for each of these tasks for each of the three luminaire and two pavement types. Each value in Table 4 was multiplied by a factor for each luminaire type and another for each pavement type, so that there were considered to be 6 times 22 tasks in all. The distribution curve in Figure 6 represents a cumulative tally of the 132 illumination values obtained in this way. (Inasmuch as the curve is skewed, a 50 percent value is obtained at a value somewhat less than the value of 1.90 obtained previously as the average value.) It is apparent that nearly 6 foot-candles will be necessary in order to provide adequate visibility for all possible instances in which either the mannequin or dog could occur at a 200-ft viewing distance.

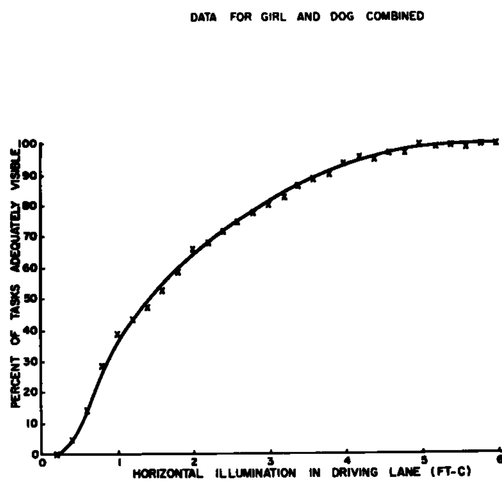

Figure 6. Frequency distribution of percent of times either the mannequin or dog will be adequately visible as a function of illumination level.

Using precisely the same techniques, measurements have also been made at seven viewing distances other than 200 ft, ranging from 180 to 400 ft. Incandescent luminaires and asphalt pavement were again used. All eleven target locations with respect to the luminaires were studied at each distance. The average data are presented in

Figure 7, relative to the average illumination value obtained at a viewing distance of 200 ft. It is evident that the illumination requirement increases as viewing distance increases with a comparatively small change between 180 and 280 ft, but with a very rapid increase as viewing distance increases beyond 280 ft. A value of nearly 5 times as much illumination is required at 300 as at 200 ft, and more than 25 times as much is required at 400 as at 200 ft.

A few measurements have been made in which the targets were placed in the curb lane. Both pavement types were involved, but only incandescent luminaires were used. Viewing distances of both 180 and 200 ft were used. In each case, a curb-lane measurement was always paired with a driving-lane measurement under the same conditions. The data obtained are given in Table 5. It is apparent that nearly three times more illumination is needed when the targets are in

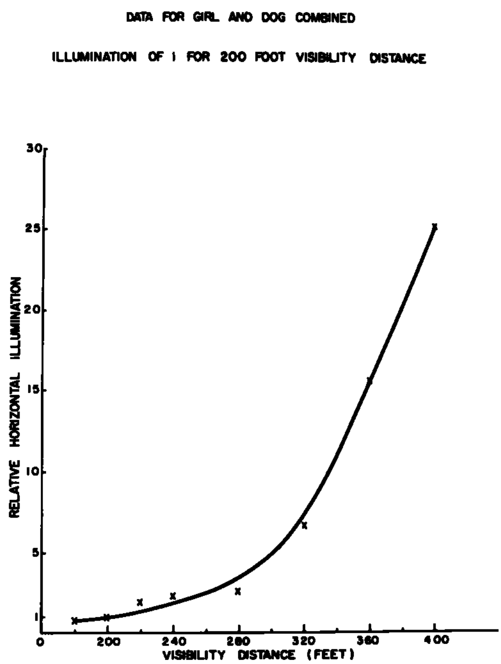

Figure 7. Relation between relative illumination and distance to the targets.

TABLE 5

REQUIRED ILLUMINATION LEVELS FOR TASKS IN CURB AND DRIVING LANES[1]

Curb Lane		Driving Lane
(a) Mannequin		
0.399		0.374
0.498		0.395
1.75		0.472
4.29		1.32
1.74 ft-c		0.640 ft-c
Curb/driving factor = 2.72		
(b) Dog		
0.810		0.664
0.930		0.664
0.985		1.10
2.28		1.32
2.58		1.33
17.6		2.98
4.20 ft-c	Curb/driving factor = 3.14	1.34 ft-c
Average curb/driving factor = 2.93		

[1]Asphalt and concrete pavements, incandescent luminaires, 180- and 200-ft viewing distances. All values are horizontal illumination (foot-candles).

the curb lane than when they are in the driving lane. This result is not due to the fact that illumination is less in the curb lane to begin with, but reflects the fact that the visual task is more difficult due both to confusion introduced by trees and obstacles along the roadway and due to disadvantageous luminance distributions.

SUMMARY AND DISCUSSION

Rather extensive illumination data have been presented for each of two roadway visual tasks; that is, seeing a mannequin and a black dog at various distances down the roadway, with a variety of luminaire types and pavement surfaces. All measurements have been made under an illumination geometry which is representative of generally accepted practice in this country. The data suggest that an average value of 1.90 foot-candles of horizontal illumination is required for adequate visibility of these targets when they appear in the driving lane 200 ft ahead. Nearly three times this much illumination, or nearly 5.7 foot-candles will be required for the same targets to be adequately visible at the same distance when they appear in the curb lane. If the targets must be seen 300 ft ahead in the driving lane, more than 9 foot-candles of illumination will be required and for 400-ft visibility in the driving lane nearly 48 foot-candles will be required. Preliminary measurements indicate that there are more difficult roadway visual tasks than these, which will require even higher levels of illumination.

These data reveal that there are visual tasks in night driving of sufficient difficulty so that interior levels of illumination will be required if these tasks are to be adequately performed. These results should not be surprising because the factors of small size, low contrast, and short viewing time will result in difficult visual tasks whether indoors or outdoors, and high illumination levels simply are required for adequate performance of such tasks. The present data do not suggest that impractical levels of roadway lighting are to be recommended for practical use, but they do provide a basis for evaluating what kinds of gains in visibility and hence improvements in the safety of night driving are to be expected with various increases in roadway illumination.

One caution must be observed in interpreting the present data. It has been shown that the required illumination levels depend importantly on the geometry of illuminating visual tasks. The interpretations of required illumination levels will be absolutely accurate only if these levels are provided with an illumination geometry identical to that studied in the tests. It is manifestly impossible to produce horizontal illumination of 48 foot-candles with the mounting heights and pole spacing involved in the tests although it is possible to approach 5 foot-candles with a similar lighting layout. Inasmuch as the visual task may be more visible with the geometry required to produce higher levels than with the geometry studied, it is unsafe to place even scientific significance on illumination values in this report exceeding 5 foot-candles. It is to be hoped that illumination geometries can be discovered which will provide the desired visibility of the more difficult visual tasks with considerably lower illumination levels than the very high values suggested in this report. Efforts in this direction should be encouraged in every possible way.

ACKNOWLEDGMENTS

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Driver Performance Related to Interchange Marking and Nighttime Visibility Conditions

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● NIGHTTIME DRIVING CONDITIONS offer special problems of visibility. This is especially true at highway intersections. As a driver proceeds over any highway system, he continually arrives at a series of intersection choice points. Most drivers know where they want to go, but they do not always know exactly how to get there. It is, therefore, of obvious importance to develop and utilize systems which will enhance nighttime visibility and thereby provide drivers with optimal information about the route or routes they may be following.

These considerations point up the importance of providing adequate markings and conditions of visibility at highway intersections. Highway systems throughout the country have made wide and effective use of illumination and reflectorization to accomplish these aims. A good deal of research utilizing direct physical measurements has been performed in an effort to assess the degree of visibility improvement under a variety of conditions of illumination.

In addition to widespread research on levels of visibility and their relative effectiveness, attention has been given to the relative utility of different marking systems in directing or guiding driver performance. As mentioned previously, appropriate guidance of drivers is particularly important at intersections; the marking system should be sufficient to reduce any potential confusion or error on the part of the driver.

These considerations led to the present study designed to discover possible effects of different nighttime visibility conditions and different highway marking systems on driver performance. Studies reported here were undertaken over a period of seven weeks during the summer of 1959. The experiments were conducted in the State of Minnesota on a cloverleaf interchange formed by the intersection of US 61 and Minnesota State Highway 36. A variety of experimental conditions of varying visibility and using varying systems of highway markings were used and driver performance studied. All experimental studies were conducted during night driving conditions between the hours of 9:30-11:30 P.M.

EXPERIMENTAL METHOD

Five major experimental conditions were employed during the period of the study.

Condition I might be called the normal operating condition. Under this condition, the modern mercury-vapor luminars in use at this cloverleaf interchange were turned on as is usual. Condition I may be described, therefore, as the "fully illuminated" condition.

Condition II was the "dark" condition. Under this condition, the lights were turned off and no special treatment was used other than the reflectorized signs showing the various destinations and turn areas.

Condition III utilized a standard application of reflectorized delineation. Under this condition, the lights remained off, but reflective treatment was employed in the form of amber delineators in the loops and legs of the cloverleaf similar to the standards contained in the Manual on Uniform Traffic Control Devices. The treatment employed under this condition is shown in Figure 1.

Condition IV utilized an experimental method of reflectorization. The reflective treatment which was employed is shown in Figure 2. The luminars remained off, and blue and amber delineators and blue and amber reflective pavement paints were used to indicate areas of exiting and merging traffic. As may be noted, the entire cloverleaf interchange was not treated; only the portions which would be directly visible to a motorist traveling north on US 61 or traversing the ramps in the southeast quadrant received reflective treatment.

Condition V combined the treatments of full illumination and experimental reflector-

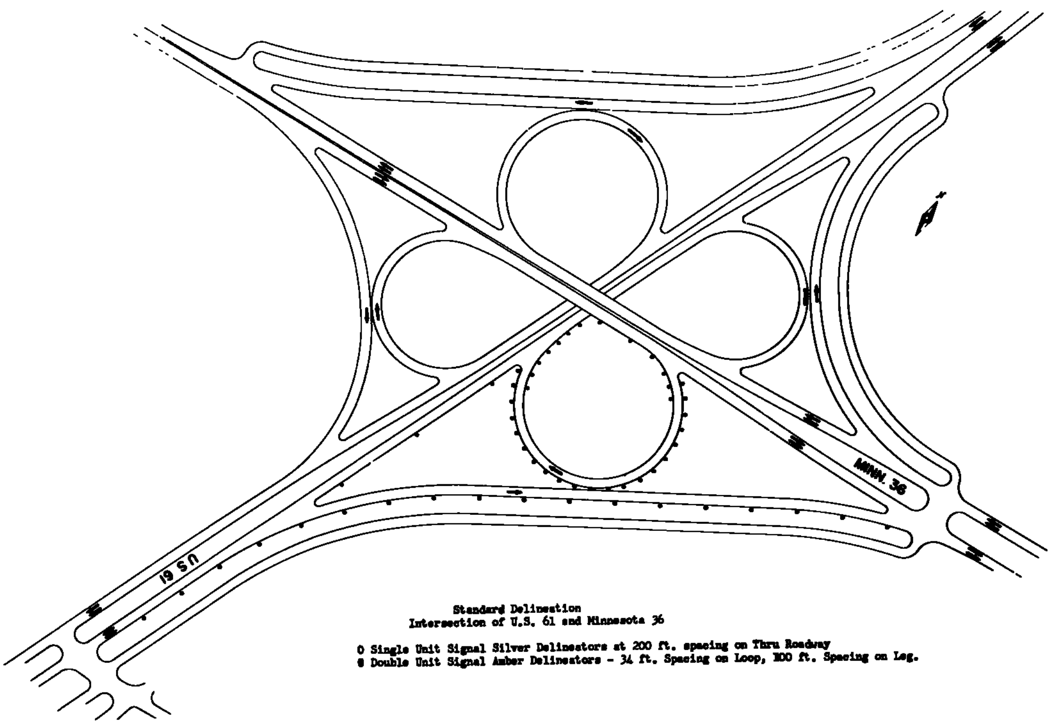

Figure 1. Cloverleaf interchange at intersection of US 61 and Minnesota 36 showing standard delineation treatment.

ization. The luminars were turned on. The reflective treatment was maintained as in Condition IV.

The intent of this study was to study driver performance under these various different conditions of visibility and highway marking systems. Performance was studied by using a carefully developed and carefully conducted interview schedule. Interviewing stations were located at points A and B shown in Figure 2. Motorists interviewed at Station A were those who had just left US 61 and were about to enter and proceed in an easterly direction on Minnesota 36. Motorists interviewed at Station B were those who had proceeded straight through the interchange from south to north on US 61 and also those who had just entered US 61 from Minnesota 36 via the cloverleaf loop in the southeast quadrant.

Prior publicity via press, radio, and TV referred to the fact that a study was to be conducted using various experimental conditions. None of the publicity described details of the conditions nor was any information supplied which could be helpful to local drivers in interpreting the meaning of the various experiments.

As motorists approached points A and B, they were signaled to stop and were asked to answer a series of questions requiring about 5 min (Questionnaires A and B). If a driver indicated he was in a hurry, he was permitted to proceed without delay. Only a few drivers chose not to take part in the study.

Driver performance was studied by interviews because it is believed that such procedures provide information not available by other means. For example, it was believed important to learn not only what the driver actually did in getting his vehicle through the intersection but also to learn of what he saw; whether or not he had difficulty getting through the intersection; and whether or not he became confused at any point. The interest was basically in driver performance plus driver impressions, feelings, attitudes and over-all responses to the total system as presented to him at the intersection.

THE QUESTIONNAIRE

After a series of planning conferences, interview schedules were developed which were designed to obtain information in six major areas (Questionnaires A and B).

First, data bearing on personal information, such as sex, age, and the extent to which the driver was familiar with the intersection were obtained.

Second, each driver was asked whether he had or had not experienced any difficulty in traversing the interchange.

Third, each driver was asked whether or not he could offer any suggestions for improving the interchange to make it easier to recognize the proper route through the intersection.

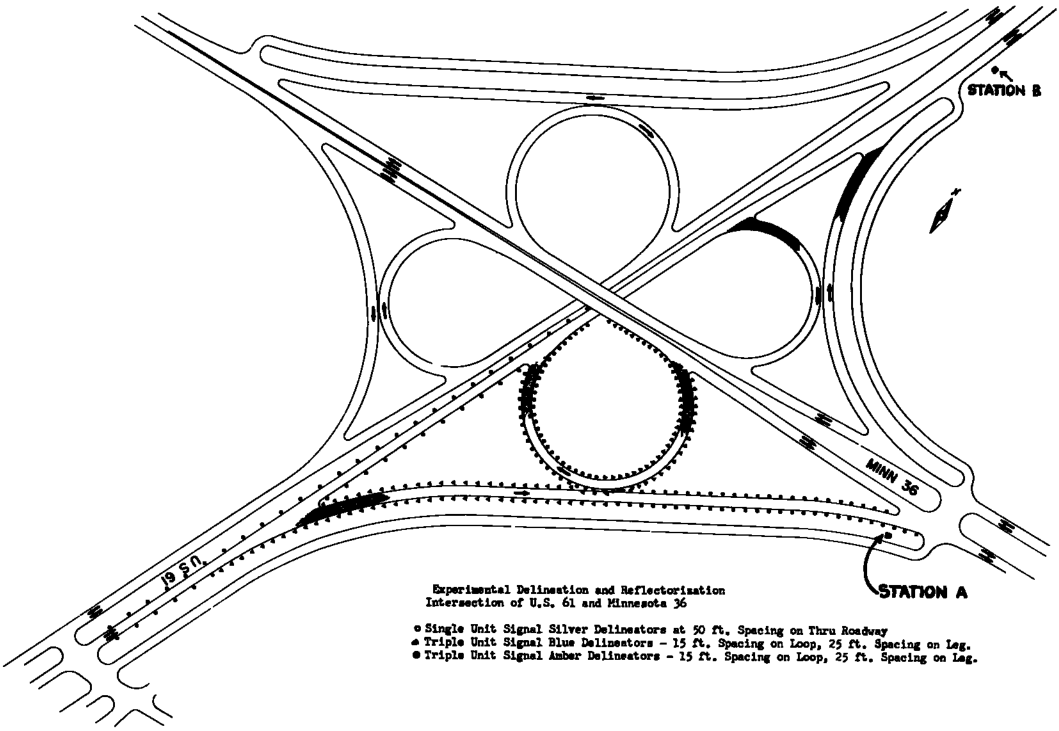

Figure 2. Cloverleaf interchange at intersection of US 61 and Minnesota 36 showing experimental reflectorization treatment.

Fourth, the driver was asked what helped him to recognize certain critical response zones such as areas of exiting and merging traffic.

Fifth, each driver was asked to describe the markings he had noted and how he had interpreted or utilized them in his travel through the interchange.

Finally, each driver was asked to give his own personal opinion or impression of the reflectorized treatment employed under Conditions IV and V.

SAMPLE CHARACTERISTICS

A total of 1,133 motorists was interviewed at the two stations, A and B. The numbers interviewed ranged from 199 under Condition V to 270 under Condition I.

A large majority of the motorists interviewed were men, comprising 970 of the drivers; only 163 were women. Somewhat fewer than one-half the drivers were in the age range 26-40 with the remainder being distributed equally between the under 25 and over 41 groups. Sample characteristics with respect to sex and age are shown in Figure 3.

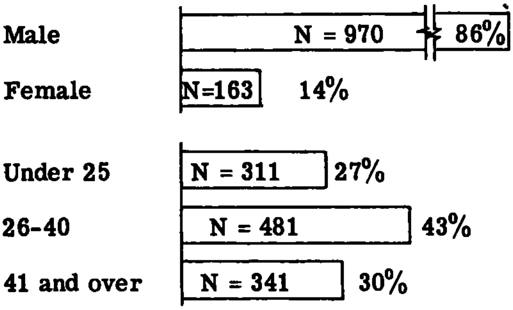

Figure 3. Sex and age distributions of motorists participating in the study.

A large majority of drivers participating in the study were familiar with the cloverleaf interchange. More than one-half said they used the interchange daily. An additional 30 percent reported using the interchange at least once a week or oftener. Fewer than one in six reported being totally unfamiliar with the interchange. These figures suggest that the performance and opinions obtained from respondents in this study were informed ones, and, as such, should reflect an awareness of particular driver needs in this specific driving situation.

Examination of the frequencies of use of the intersection by drivers under the different experimental conditions showed no differences. At both interviewing stations, Chi-Squared tests of significance suggest acceptance of the Null Hypothesis that frequency distributions do not differ under the various conditions. This is important because it shows that respondents under the various conditions are comparable with respect to their familiarity with this interchange.

RESULTS

Difficulty Experienced

Only a small minority of respondents said they had difficulty making their way through the intersection. The numbers and percents of persons saying they had some difficulty are given in Tables 1 and 2. It may be noted that at Station A, the highest incidence of driver difficulty occurred under Conditions II and III. Under these two conditions, nearly one out of eight drivers experienced difficulty locating the exit ramp to Minnesota 36. Under the "fully illuminated" and "experimentally reflectorized" conditions, practically no one (fewer than 1 in 50) experienced difficulty.

TABLE 1

NUMBERS AND PERCENTS OF DRIVERS INTERVIEWED AT STATION A WHO REPORTED SOME DIFFICULTY TRAVERSING THE INTERCHANGE

Condition	Had Some Difficulty		Had No Difficulty	
	No.	Percent	No.	Percent
I. Fully illuminated	2	2	84	98
II. Dark	10	14	62	86
III. Standard delineation	8	11	67	89
IV. Experimental reflectorization	0	0	67	100
V. Combined — illumination and reflectorization	2	4	50	96

Note: $X^2 = 15.4$ $P < 0.001$

This finding is important for two reasons: (1) lighting is shown to be an effective way of reducing driver confusion and possible error; and (2) the experimental reflectorization is shown also to be an effective means of reducing driver difficulty in traversing the interchange.

At Station B, only 12 drivers (about 1 percent) experienced any difficulty traversing

TABLE 2

NUMBERS AND PERCENTS OF DRIVERS INTERVIEWED AT STATION B WHO REPORTED SOME DIFFICULTY TRAVERSING THE INTERCHANGE

Condition	Had Some Difficulty		Had No Difficulty	
	No.	Percent	No.	Percent
I. Fully illuminated	1	1	183	99
II. Dark	3	2	185	98
III. Standard delineation	2	2	129	98
IV. Experimental reflectorization	5	4	130	96
V. Combined — illumination and reflectorization	1	1	146	99

Note: Data shown above cannot be tested for statistical significance because of low cell frequencies under the "Had Difficulty" column.

the interchange. This is an expected result because it is easier to drive straight through an intersection than to locate a particular point or turn off. It should be noted, however, that 5 of the 12 drivers reported having experienced difficulty under the condition of experimental reflectorization. Unfortunately, it is difficult to interpret this result because the extremely low cell frequenciesprecludeusing the Chi-Squared test of statistical significance.

Suggestions for Improvements

Tables 3 and 4 give the numbers of motorists who volunteered suggestions for improving the marking or visibility of the intersection in some way. At both stations, fewest suggestions for improvement occurred under the two conditions employing experimental reflectorization. The differences among the percents given in both tables are statistically significant.

TABLE 3

NUMBERS AND PERCENTS OF DRIVERS INTERVIEWED AT STATION A WHO OFFERED SUGGESTIONS FOR IMPROVING INTERCHANGE VISIBILITY AND/OR MARKINGS

Condition	Offered Suggestions		Offered No Suggestions	
	No.	Percent	No.	Percent
I. Fully illuminated	26	30	60	70
II. Dark	34	47	38	53
III. Standard delineation	27	36	48	64
IV. Experimental reflectorization	13	19	54	81
V. Combined — illumination and reflectorization	7	13	45	87

Note: $X^2 = 21.6$ $P < 0.01$

It is noteworthy that a substantial decrease in suggestions for improvement occurred between Condition II and Condition I and that a somewhat larger and significant decrease occurred between Condition II and Condition IV. Apparently the reflectorized treatment is effective in offering both adequate visibility and guidance.

TABLE 4

NUMBERS AND PERCENTS[1] OF DRIVERS INTERVIEWED AT STATION B WHO OFFERED SUGGESTIONS FOR IMPROVING INTERCHANGE VISIBILITY AND/OR MARKINGS

Condition		Offered Suggestions		Offered No Suggestions	
		No.	Percent	No.	Percent
I.	Fully illuminated	16	15	89	85
II.	Dark	22	20	89	80
III.	Standard delineation	16	20	66	80
IV.	Experimental reflectorization	9	13	63	87
V.	Combined — illumination and reflectorization	10	10	94	90

Note: $X^2 = 5.9$ $P < 0.20$

[1]This question was not asked of drivers who had entered US 61 from Minnesota 36.

A study of the actual suggestions made by those motorists who offered them gives further meaning to these results. Under Condition I, the major suggestion was that more signs be placed at the intersection; a few motorists also suggested the use of marking such as arrows on the pavement, markers along the side of the road and more vivid center stripes. Under Condition II, the major complaint apparently was caused by the darkness. Although some motorists still mentioned the need for more signs and markings, most simply said "Turn on the lights." Under Condition III, suggestions for improvements included most of the factors mentioned under the first two conditions. Suggestions under Condition IV were fewer in number (as given in the tables), and seemed somewhat more specific than those offered under the first three conditions. Fewer suggestions were offered under the combined conditions of illumination and reflectorization than under any other condition. This is evidence that a large majority of drivers believed both visibility and guidance to be adequate.

Markings Useful to the Driver in Guidance

Regardless of the experimental condition, the vast majority of drivers exiting onto Minnesota 36 from US 61 believed the route markings gave them adequate information about where to turn. The percent of drivers saying this ranged from a low of 90 percent under Conditions II and III to a high of 97 percent for Condition IV. Most drivers, apparently because of their familiarity with the interchange, already knew where to turn. In addition, however, it appears that the sign indicating the approaching turn was a primary source of guidance for drivers encountering the first three conditions. Under the experimental reflectorization, however, the sign seemed less important, and the delineator and pavement treatments were mentioned more often. This could be due partly to the "newness" of the experimental treatment. It is possible that the pavement colors stood out so sharply as to attract driver attention and comment to a greater degree than might have been the case, had the drivers been more familiar with the experimental reflectorization.

Motorists who were driving through the intersection from south to north on US 61 were nearly unanimous in their belief that the through route was sufficiently well marked. Another significant need for through motorists, however, is to be clearly aware of areas of exiting and merging traffic. These are critical response areas for the motorist and it is in and near these areas that improved visibility and guidance may be most important. Data in Tables 5 and 6 give information about identification of these areas under the various experimental conditions.

It may be noted that areas of merging and exiting traffic were recognized by a high majority of drivers. The highest degree of recognition for merging areas occurred under Conditions IV and V. Differences among the five conditions are highly significant statistically.

TABLE 5

NUMBERS AND PERCENTS OF THROUGH TRAFFIC DRIVERS SAYING THEY COULD OR COULD NOT IDENTIFY AREAS OF MERGING TRAFFIC

Condition	Could Identify Merging Areas		Could Not Identify Merging Areas	
	No.	Percent	No.	Percent
I. Fully illuminated	92	90	10	10
II. Dark	102	94	7	6
III. Standard delineation	66	83	14	17
IV. Experimental reflectorization	69	96	3	4
V. Combined — illumination and reflectorization	101	97	3	3

Note: $X^2 = 16.0$ $P < 0.01$

The interview schedules also requested information about the methods used by drivers in recognizing areas of merging and exiting traffic. More than one-half the drivers under the last two conditions mentioned the colors on the pavement and on the delineators as important sources of information. Few drivers (just more than 1 percent) under the reflectorized conditions mentioned traffic flow as giving them evidence about merging and exiting areas; under the first three conditions, about 10 percent identified traffic flow as their major source of information. It is evident, therefore, that many drivers (more than one-half) do associate the experimental reflectorization treatment with the identification of areas of merging and exiting traffic. It is difficult, however, to judge whether or not this is of practical importance. Even under the "dark condition," 94 percent of drivers successfully identified areas of merging traffic; one may well question, therefore, whether the increase in successful identification to 97 percent for Conditon V is of any practical consequence; further research is needed on this question.

TABLE 6

NUMBERS AND PERCENTS[1] OF THROUGH TRAFFIC DRIVERS SAYING THEY COULD OR COULD NOT IDENTIFY AREAS OF EXITING TRAFFIC

Condition	Could Identify Exiting Areas		Could Not Identify Exiting Areas	
	No.	Percent	No.	Percent
IV. Experimental reflectorization	71	99	1	1
V. Combined — illumination and reflectorization	100	96	4	4

[1]This question was not asked of drivers under the first three experimental conditions. Hence no meaningful comparison may be made.

Driver Responses to Fully Reflectorized Treatment

As explained previously, the interview schedules were designed, in part, to elicit opinions and impressions from motorists concerning the experimental reflectorization employed in Conditions IV and V.

A large majority ot motorists recognized intended relationships among the various markings. For example, more than one-third of the motorists noted that the blue of the exit ramp matched the blue of the sign indicating the location of the exit. It also was common for motorists to associate the amber or yellow colors of the pavement and delineator treatment with SLOW or CAUTION. There was nearly unanimous agreement that the reflectorized treatment was helpful in driving. Many motorists volunteered comments indicating a generally favorable attitude toward this particular experimental treatment.

DISCUSSION

This study was undertaken to study driver performance and opinions under different conditions of night visibility and under the impact of various highway marking systems. Motorists taking part in the study were, as a group, highly familiar with the interchange chosen for study; and were in a position, therefore, to offer informed opinions concerning the effects of the several experimental conditions employed. Since differences in driver opinions and performance were obtained under the various conditions, it is evident that drivers show substantial concern and awareness of different night driving conditions. Opinions obtained from drivers in this study suggest that they are more confident, have less difficulty, and have a better opportunity to do a good job of night driving when visibility and guidance are improved either by illumination, reflectorization, or both. More drivers experienced difficulty in traversing the interchange and more drivers made suggestions for improvements under the "dark" and "standard delineation" conditions than under the other three experimental conditions.

The results of the study also provide clues concerning the possible effects on night driving performance of the experimental reflectorization employed in Conditions IV and V. It appears that the reflectorization treatment is readily related by the motorist to certain night driving needs. For example:

1. A significantly smaller number of motorists made suggestions for improvements under Condition V — the combined condition of full illumination and experimental reflectorization — than under any of the other four conditions. The proportions of motorists making suggestions increased progressively for conditions of "experimental reflectorization," "full illumination," "standard delineation" and "dark."
2. Conditions of "full illumination" and "experimental reflectorization" appeared equally effective in reducing the incidence of driver difficulty in traversing the intersection.
3. More than one-half the drivers under Conditions IV and V identified the pavement reflectorization as indicating areas of merging and/or exiting traffic.
4. It was the opinion of the large majority of drivers under Conditions IV and V that the experimental reflectorization was an effective and helpful means of providing night driving guidance.

The over-all results of this study suggest, therefore, that reflectorization as well as illumination can be regarded as an effective means of reducing driving problems related to nighttime visibility conditions. Apparently, a carefully planned and executed reflective treatment is highly accepted, easily followed, and generally helpful.

QUESTIONNAIRE A

FOR MOTORISTS EXITING FROM US 61 ONTO MINN. 36

1. CHECK THE SEX OF DRIVER
   ___Male
   ___Female

2. ESTIMATE DRIVER'S AGE
   ___Under 25
   ___26-40
   ___41-55
   ___56 and over

3. Would you mind telling us what your destination is?___________

4. How often do you come over this intersection?

Daylight (Check one)	Dark (Check one)
___Every day	___
___Several times a week	___
___About once a week	___
___Only once in a great while	___
___Have never been over this intersection before	___

5. Have you answered this questionnaire before tonight?___________

6. Did you have any difficulty at all finding the proper way through the intersection?
   ___Yes, some difficulty
   ___No, none at all

7. If yes, what difficulty did you have?

____

8. What first called your attention to the approaching turnoff for Hwy. 36?

____

9. Do you believe the route markings gave you adequate information concerning where you were to turn? ___Yes ___No

10. If no, why not?___________

11. Exactly how did you identify the point at which you were to turn?___________

12. Can you suggest any improvements that would make it easier for you to recognize turns such as this?___________

YOU HAVE JUST PASSED DIFFERENT ROADWAY MARKINGS.

13. Did you notice them? ___Yes ___No

14. What markings did you notice?

____

15. Can you recall the colors you saw?

____

16. What did the color(s) mean to you?

____

17. Did there seem to be any relationship among the various markings?___Yes ___No

18. What relationships did you notice?

____

19. What do you think of this kind of marking system for intersections such at this?___________

20. Do you believe that this kind of marking system would help or hinder most drivers on intersections such as this?
    ___Help
    ___Hinder
    ___Wouldn't make any difference

Write comments:___________

____

QUESTIONNAIRE B

FOR MOTORISTS DRIVING THROUGH THE INTERSECTION FROM SOUTH TO NORTH ON US 61 AND FOR MOTORISTS USING THE CLOVERLEAF TURN TO ENTER US 61 FROM MINN. 36

1. CHECK THE SEX OF DRIVER
   ___Male
   ___Female
2. ESTIMATE DRIVER'S AGE
   ___Under 25
   ___26-40
   ___41-55
   ___56 and over
3. Would you mind telling us what your destination is?___________
4. How often do you come over this intersection?

Daylight (Check one)	Dark (Check one)
___Every day	___
___Several times a week	___
___About once a week	___
___Only once in a great while	___
___Have never been over this intersection before	___

5. Have you answered this questionnaire before tonight?___________
6. Did you have any difficulty at all finding the proper way through the intersection?
   ___Yes, some difficulty
   ___No, none at all
7. If yes, what difficulty did you have?

   ____
8. What first called your attention to the intersection?___________
9. Did you enter Highway 61 from the cloverleaf turnoff just now?
   ___Yes ___No

IF NO, PROCEED WITH THE FOLLOWING QUESTIONS.
IF YES, SKIP 10-16 AND ASK QUESTIONS 17-25.

10. Can you suggest any improvements that would make it easier for you to recognize intersections such as this?

    ____
11. Do you believe that the through traffic route was sufficiently well marked?
    ___Yes ___No
12. If not, why not?___________
13. Could you tell the points at which traffic left the highway?
    ___Yes ___No
14. If yes, how could you tell this?

    ____
15. Could you tell the points at which merging traffic joined your direction?
    ___Yes ___No
16. If yes, how could you tell this?

    ____

END OF QUESTIONNAIRE FOR THROUGH TRAFFIC

- - - - - - - - - - - - - - - - - - - -

ASK THE FOLLOWING QUESTIONS OF MOTORISTS APPROACHING FROM THE WEST.

17. Do you believe the route markings gave you adequate information concerning where you were to turn?
    ___Yes ___No
18. Did you notice the reflecting posts along the side of the turnoff?
    ___Yes ___No
19. What colors did you notice?___________
20. What meaning did these colors have to you?___________
21. Did you notice the color on the pavement where you entered Highway 61?
    ___Yes ___No
22. What color was it?___________
23. What meaning did the color have to you?

    ____
24. What do you think of this kind of marking system for intersections like this?___________
25. Do you believe that this kind of marking system would help or hinder most drivers on intersections such as this?
    ___Help
    ___Hinder
    ___Wouldn't make any difference

Other Comments:___________

____

Unified Reflective Sign, Pavement And Delineation Treatments for Night Traffic Guidance

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Consideration of the perception factor in night visibility has led to the joint evaluation of a recognized guidance concept and new reflective materials recently installed at a typical interchange. The retro-reflective treatment was specifically designed to distinguish by color, brightness, and position the location and design of exit and merging ramps.

High intensity delineation was used for distant identification. For close approach, paved ramp surfaces were reflectorized for 200-300 ft. Yellow delineation and road surfaces for merging zones formed an integrated system denoting the required caution. For maximum contrast with its complement, and based on airfield practice for off-ramp guidance, a similar system in blue was used for exit areas and pertinent destination signs. Silver through lane delineation was retained with standard green guide signs.

To provide adequate differential between green and blue signs, a distinctive blue sheeting was employed. Color and brightness requirements also established criteria for delineation and reflective road treatments. With upper beams, the reflective blue roadway initially provides 6 foot-lamberts luminance at 200 ft, the yellow, 40 ft-l compared to the untreated pavement returning 0.08 ft-l.

The substantial increase in road surface luminance offers markedly improved contrast over the surround in both color and brightness. Integrated, color-keyed reflective systems thus afforded, suggest a method for effectively providing the motorist's visual cue and guidance needs night and day.

● CONSIDERABLE PROGRESS has been realized in those fields of night visibility related to the visual function and to effective design and use of vehicle lighting, roadway illumination and reflectorization. Substantial improvements in roadway visibility have resulted, in many cases with corresponding and demonstrable improvement in night driving characteristics and safety. However, the ultimate objective of increased perception and safety proportional to the visibility improvement encourages continued research, both for further improvement of visibility aids and their effectiveness.

The 1957 Symposium sponsored by the Armed Forces-NRC Committee on Vision directed attention to many of the pertinent visual problems. Among these was the suggestion that a substantial difference exists between what the driver should see and what he does see. Seeing while driving was defined by Brody as "selective directional seeing in a multivisual environment." Others suggested improvement in presentation of essential information to the motorist. Additional visual problems ascribed to night driving conditions included limited perceptual performance at mesopic levels of luminance, and visual disability or discomfort.

As an aid to selective and effective seeing, reflective materials have long been used on signs, delineators and road markings. Research in this field has increasingly concentrated on brightness, design and application possibilities. The consideration of additional color and shape coding in signs and markings — recommended by the Armed Forces-NRC Committee — has encouraged more research as have a number of related military and industrial applications. As a result, recent technological developments have led to more versatile reflective materials including pavement markings exhibiting notably increased brightness and color utility, a correlate inasmuch as adequate color discrimination at mesopic levels and highway viewing distances requires either substantial luminance or areas.

To test these materials under typical field conditions, a cloverleaf interchange at the intersection of US 61 and Minnesota 36 was selected with the assistance and cooperation of the Minnesota Highway Department for an experimental installation and study. The complexity of the driving task at such locations has been reported by Forbes and Katz together with the need for increased warning distance, visibility, attention value and, particularly, choice limitation. Simple 2-choice channels afford least difficulty, provided sufficient conspicuity to insure early perception particularly after nightfall.

Accordingly, the reflective treatment at the test interchange was designed to clearly distinguish significant features of interchange design; namely, signs and markings, destination, precise location and design of ramps, speed change and through lanes. In view of the common purpose of related signs, speed change lanes and ramps, and to exclude possible confusion from invariable use of similar colored delineation and marking systems, the significant characteristics were further distinguished by color.

Consistent with the established use of yellow to denote caution, yellow reflective materials were employed at on-ramp and merging zones. The traveled surface of on-ramp terminal ends and adjoining speed change lanes were coated with a yellow reflective treatment consisting principally of minute reflective particles and associated binder applied by conventional pavement marking equipment and techniques. For maximum contrast with silver delineators customarily employed on through lanes and tangents, 50 cp/ft-c triple, yellow-amber delineators (dominant wave length 595 m μ) were used on both sides of ramp and alongside the acceleration lane. Delineation and color treated surface of the acceleration lane was visible to through as well as on-ramp traffic.

Deceleration lanes and exit ramps together with relevant signs were similarly identified, using color to establish a relationship between signs, delineation, and roadway, thus simplifying the perceptual task. Search for a distinctive color not presently assigned other traffic control functions led to use of blue which has the additional advantage of providing maximum contrast with the complementary yellow of entrance locations. Required use of blue lighting and reflectorization for airfield taxiway and off-ramp guidance offers an analogous experience which, with similar experimental highway guidance applications elsewhere, suggests the use of blue in bifurcation treatment.

Application of the various reflective components incorporated into the cloverleaf interchange system is shown in Figure 1. Blue pavement areas represent reflectorized sections of exit roadway, paralleled by triple, blue delineators along ramps and deceleration lanes with blue guide signs pertaining to the adjacent exit. Yellow pavement areas represent reflectorized sections of entrance or merging roadways, paralleled by yellow delineation along ramps, acceleration lanes, and the right edge of the through highway preceding merging zones. Adjacent yellow signs are customary standard warning series. The remainder of through lane delineation was accomplished with conventional silver materials and traffic guidance, with standard green signs.

Interchange guidance information therefore is first presented to the approaching, north-bound motorist on conventional, green, 2-mi and 1-mi advance guide signs. Confirmation is subsequently provided by the color treatment as blue signs and delineation corresponding to the east-bound deceleration lane first appear, followed closely by the blue pavement treatment on approach areas, ramp surface and continuing with ramp delineation. Indication of merging lanes and identification of exit ramps to the north is similarly achieved by the distinction apparent between conventional through route markings, yellow at entrance points, and blue at exits. In the experimental Minnesota application, this treatment was installed on US 61 and the four appendant ramps at intersection with Minnesota 36 for the north-bound direction of travel. Abbreviated speed change lanes at this older interchange were sufficiently long to permit up to 150 ft of taper for test purposes. Roadway reflectorization covered these lanes and extended 200 ft up leg ramps from the nose, 150 ft for loop ramps. Conventinal 200-ft delineator spacing was used for the approach but decreased within the interchange to emphasize

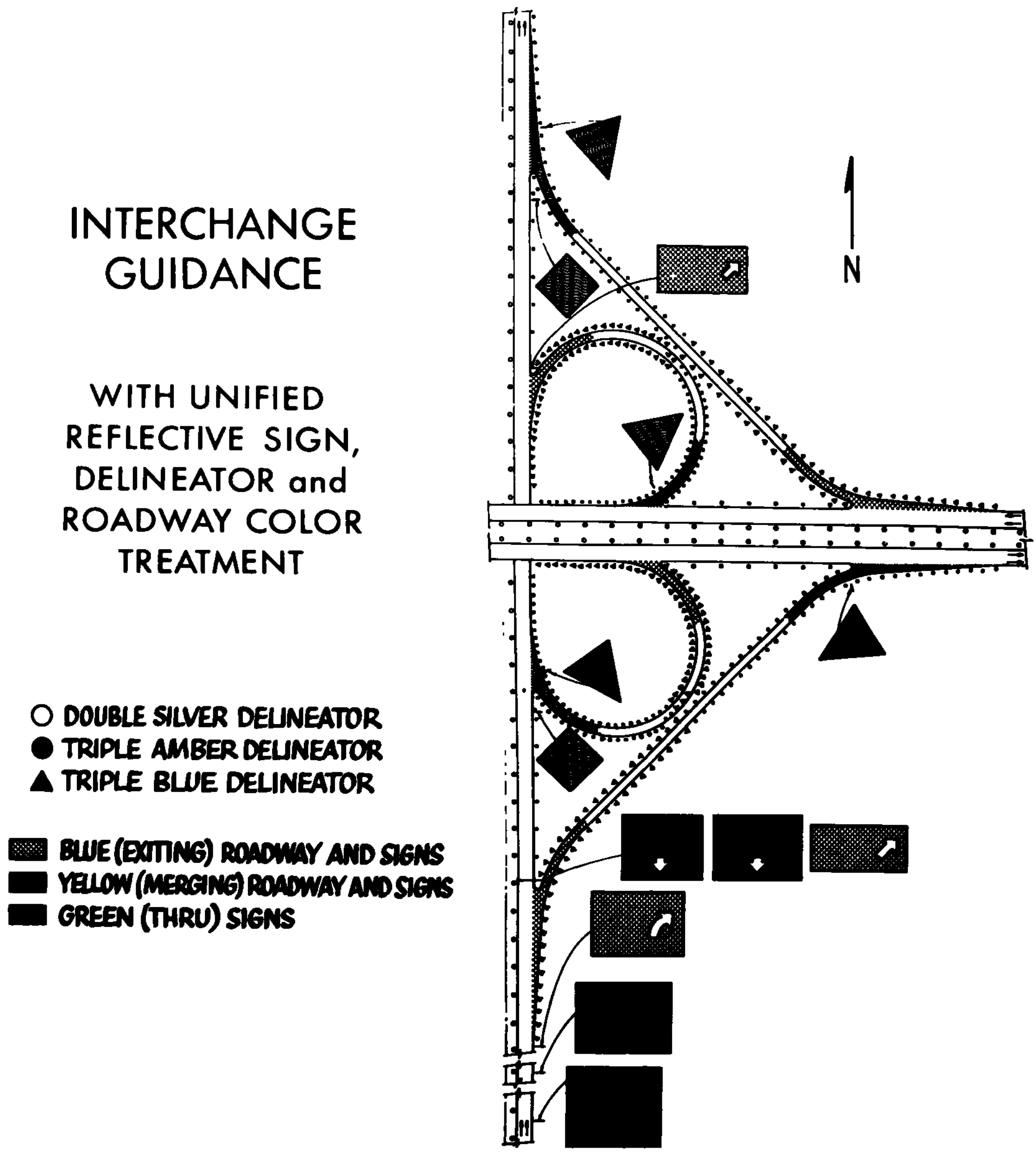

Figure 1. A unified reflective sign, delineator and roadway color treatment showing order of presentation for northbound traffic through a typical interchange. Similar systems may be employed in a number of related traffic guidance applications.

significant design features for effective distant perception. Within the interchange, 50-ft spacing was employed for through lanes, 25 ft for leg ramps and 15 ft for loop ramps, including connecting speed change lanes. Sign legend materials and sizes followed interstate standards with some legend modification in the absence of fully limited access or overhead sign structures (Fig. 2).

Previous use of reflectorized blue background signs in juxtaposition with green signs has led to some question of color discrimination. The dominant wave length of conventional blue reflective sheeting is approximately 495 mμ and peak reflectance 498 mμ compared to approximately 520 mμ for both in the case of the standard green. The similarity of hue (blue-green, green-blue) and possibility of confusion at night led to the development of an attractive blue reflective sheeting with a peak reflectance deep in the blue end of the spectrum (475 mμ) and relatively high saturation in the red (620-700 mμ), resulting in a distinctive indigo-blue and subjective brightness similar to that of standard green.

Purity and reflectance of blue roadway treatment and delineators were similarly adjusted to provide dominant wave lengths of comparable value and sufficiently blue to be unmistakable (Fig. 3). Role and limited size of delineators together with reduced visual sensitivity to blue necessitated blue delineation of relatively high brightness. A construction of standard size resulted, with a characteristic value of 489 mμ and luminance of 6 cp/ft-c — a signal adequate to meet minimum long-range visibility requirements. Directional reflectance values for these retro-reflective components at representative

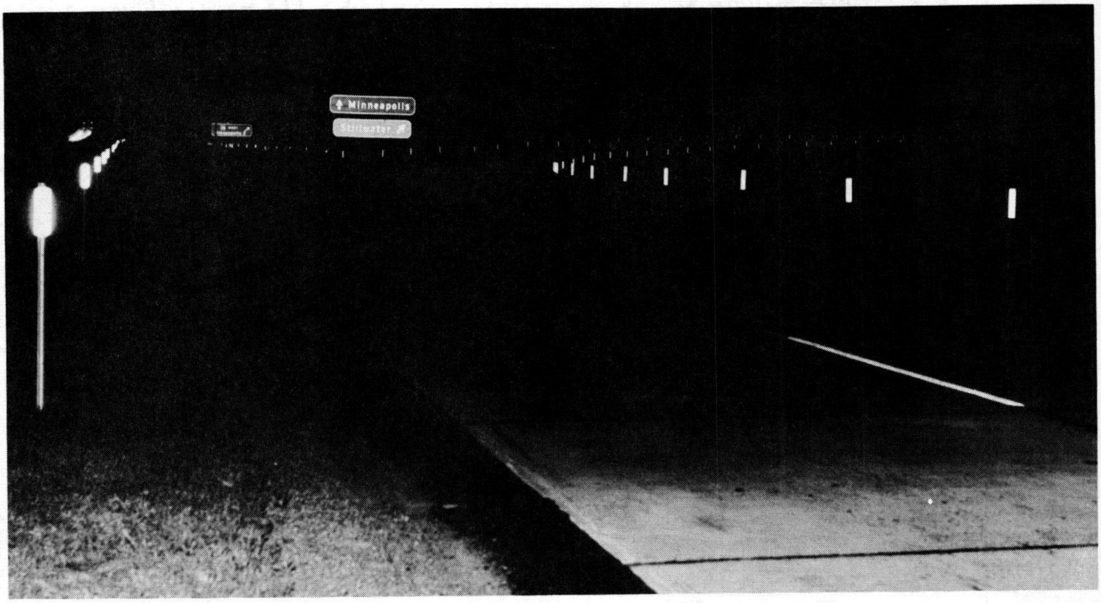

Figure 2. Night view of bifurcation treatment at exit ramp.

observation and incidence angles were established with a modified spectrophotometer. These are shown together with a 90 percent reflectance, diffuse white surface, relative to perfectly diffusing white.

Colored reflective roadway treatments are shown in terms of specific luminance (ft-l/ft-c) at divergence angles corresponding to viewing distances ranging from 1,000-80 ft (Fig. 4). Values are based on retro-reflective performance at representative entrance angles (88 deg) and exhibit initial efficiencies comparable to like-colored reflective sign materials and 20-500 X greater at applicable divergence angles than a hypothetical, 18 percent reflectance roadway surface. Relative to a perfectly diffusing, standard white surface, the brighter, yellow treatment increases luminance in the order of 65 X at 0.5 deg divergence, the blue 4 X.

Initial luminance of the treated road surface at 80 to 1,000 ft is shown relative to available headlamp illumination (Fig. 5). Upper and lower beam performance was derived from iso-candle curves based on representative output of the Dual Headlamp System (GE-4001 and 4002) and current headlamp-driver relationships, with vehicle centered in a straight, 12-ft lane. Luminance of right and left edges viewed with upper beams are identical for those distances considered. In view of lamp design features, lower beams understandably provide increased luminance at the right relative to the left edge.

Luminance of a conjectural 18 percent reflectance surface is illustrated as a standard of comparison with the treated roadway in establishing relative performance at all distances with upper and lower beams. Field measurements and limited published data

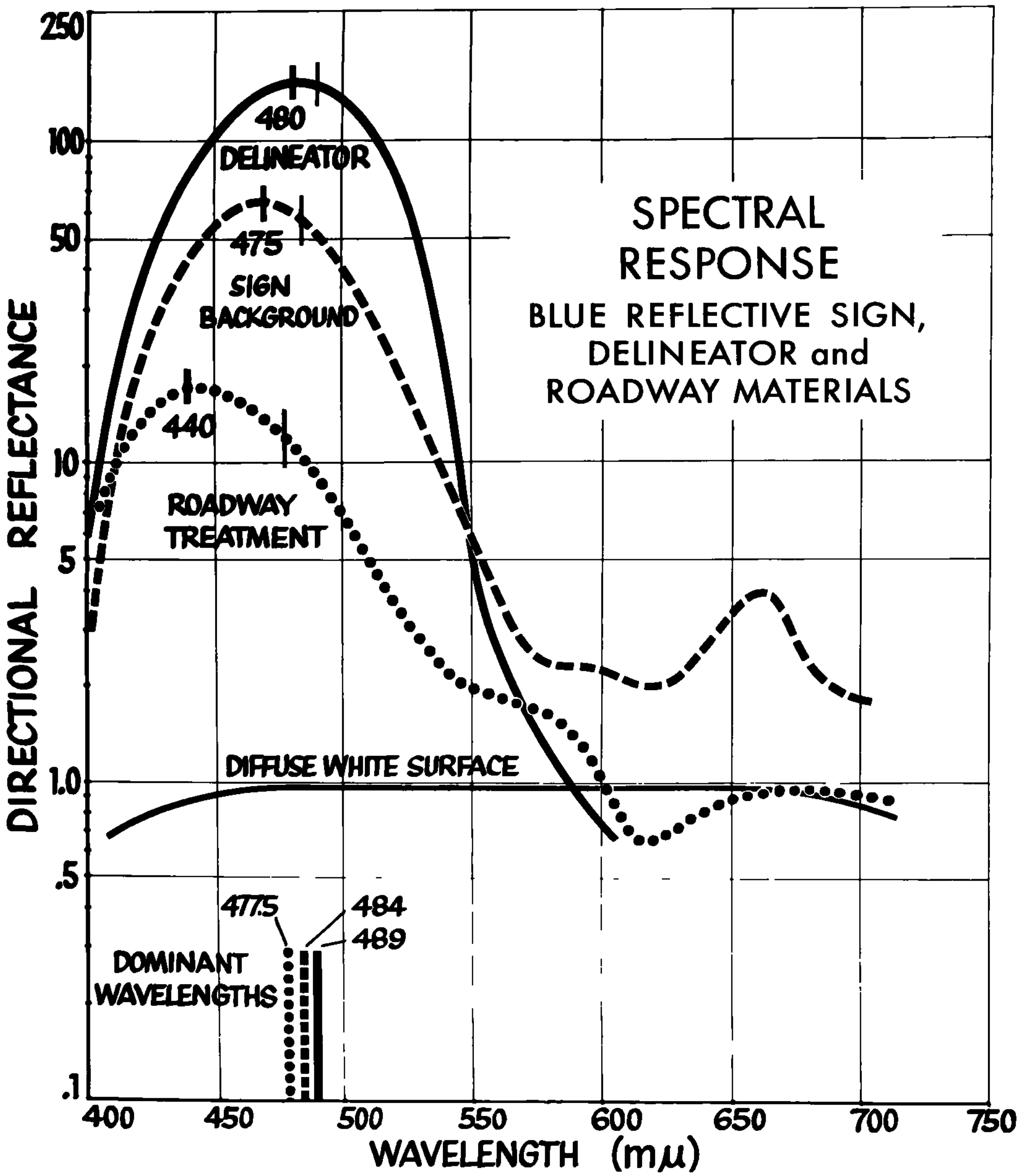

Figure 3. Spectral distribution of blue reflective signs, delineators and roadway marking materials shown relative to a diffuse white surface. Figures for spectral response at peak reflectance and dominant wavelength are given in millimicrons.

reveal typical pavement brightness illuminated with upper beams on the order of 0.08 foot-lamberts at 200 ft. At this distance with high beams, the reflective blue surface initially is shown to provide 6 foot-lamberts luminance, the yellow 40 ft-l, suggesting a 500-fold increase over a conventional pavement surface exhibiting 0.08 ft-l luminance. This relationship applies equally to wet surfaces in the case of those portions of the experimental application designed to perform wet or dry throughout their useful life, and appears independent of pavement texture.

Although the luminance of reflective pavement treatments is relatively independent of pavement surface type, brightness is quite naturally a function of the projected pavement area. Horizontal ramp or speed change lane surfaces subtend a vanishingly small angle at distances greater than 1,000 ft. In addition, intersection surfaces may be temporarily covered with snow or ice or partially obscured by preceding vehicles, strongly establishing the warrant for supplementary delineation. The several reflective components may therefore contribute in varying proportion to the total perceptual purpose.

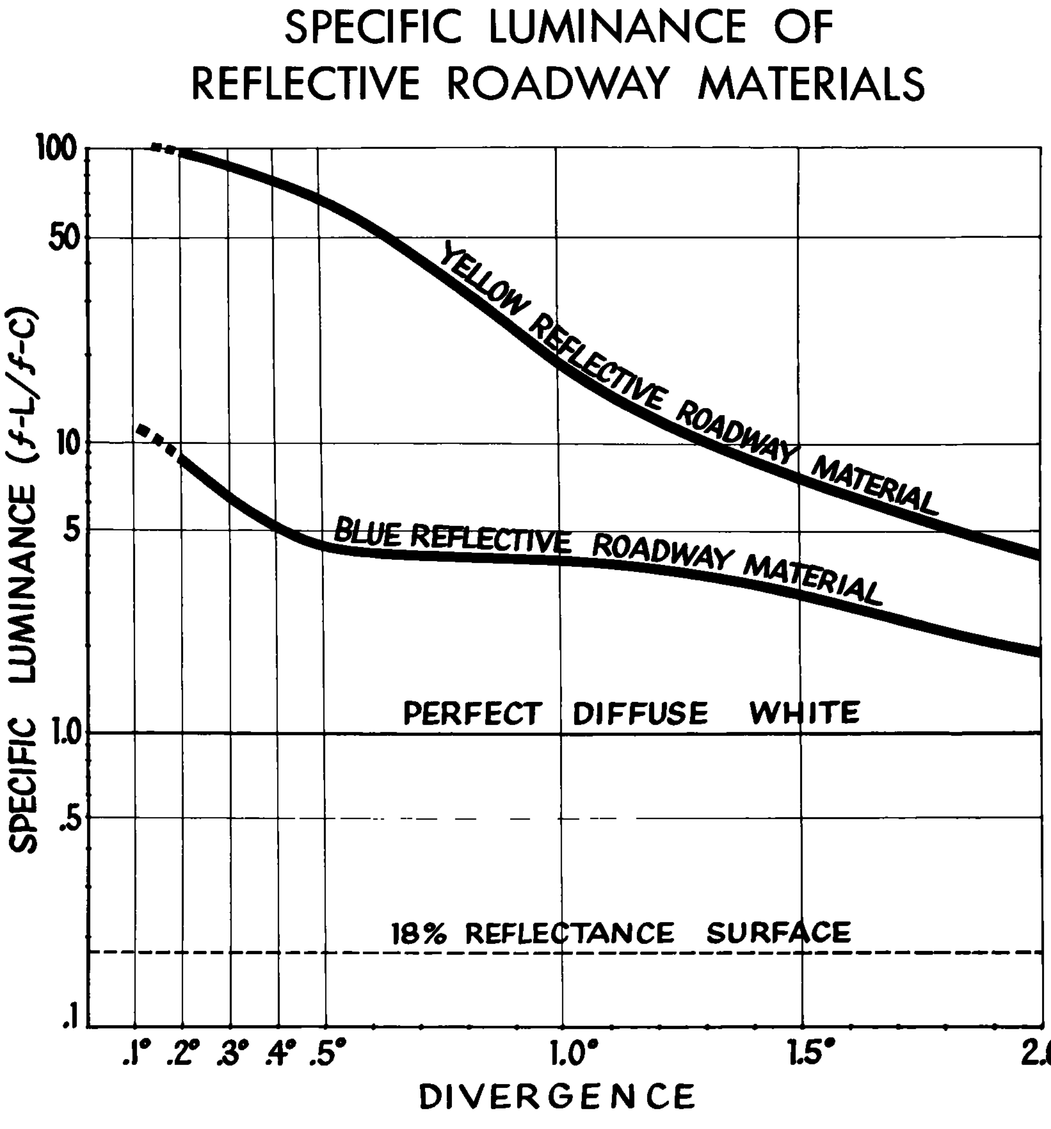

Figure 4. Specific luminance (foot-lamberts per foot-candle) of reflective roadway materials at divergence angles of 0.2 to 2.0 deg (approximately 1,000 to 80 ft). A diffuse surface exhibiting 18 percent reflectance and a perfectly diffusing white surface are shown for comparison.

Significant reduction of the perceptual impact through aberrant color deficiency is unlikely at the wave lengths in question. Frequency of tritans (blue-yellow deficient) has been found to be less than 0.008 percent in contrast with the more prevalent red-green

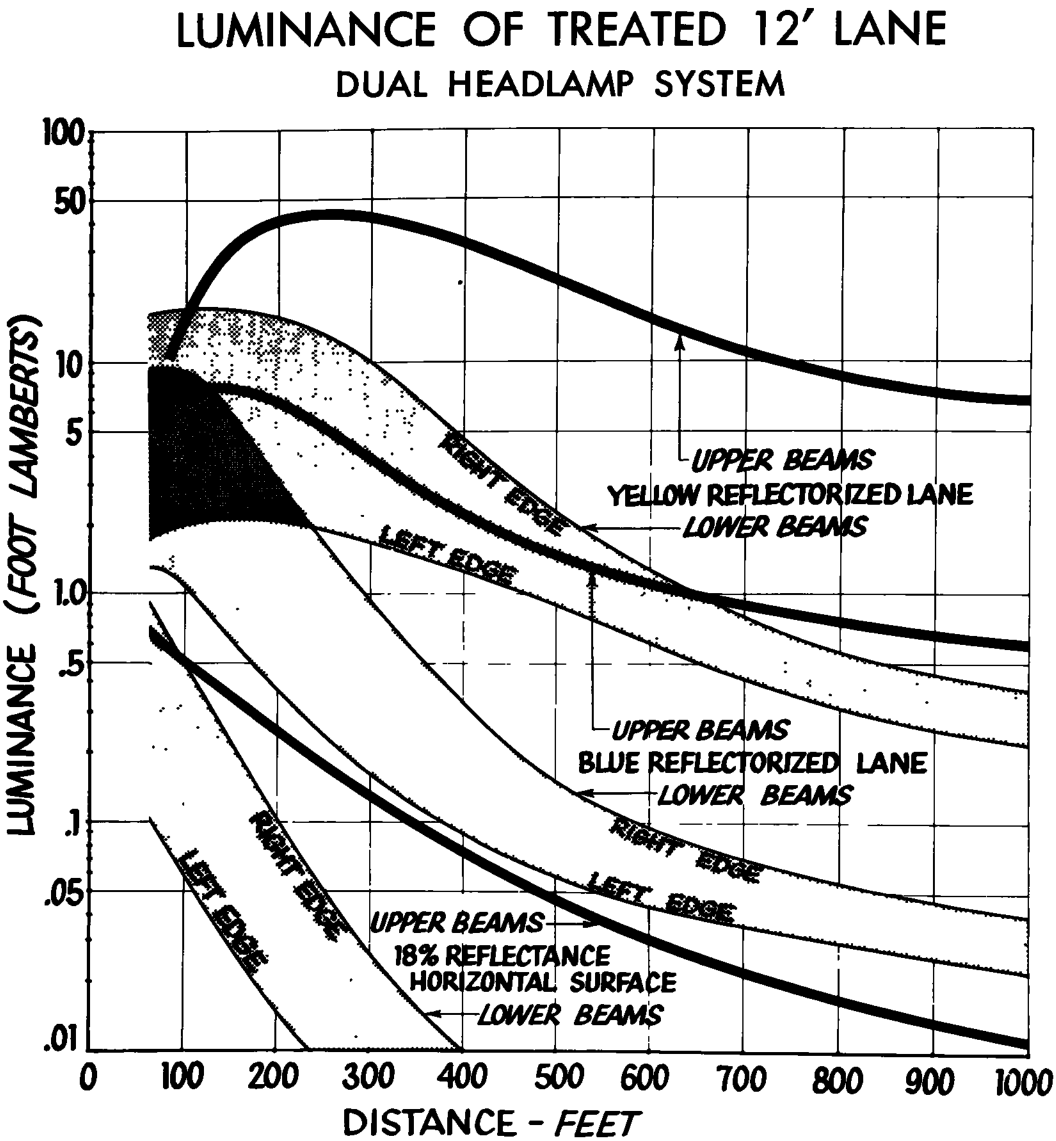

Figure 5. Luminance of treated roadway surface seen from 100 to 1,000 ft with Dual Headlamp System (G.E. 4001 and 4002) shown relative to an 18 percent reflectance roadway surface. Luminance of a straight 12-ft lane is shown from left to right for each color and upper and lower headlamp beams.

defectives. Their incidence has generally been found to be at least 2 percent of the adult population and the vast majority of this group are acutely perceptive of blue. Individuals deficient in ability to perceive yellow comprise the greatest rarities, suggesting that the complementary use of blue and yellow in this application offers the least likelihood of confusion, and provoking far less serious question than the color of traffic signal ware.

Choice of the particular location was largely dictated by the desirability of analyzing relative benefits of such treatment where established expressway traffic patterns and representative pavement surfaces, ambient illumination and lighting existed. Studies of driver attitudes, traffic characteristics and performance were undertaken in cooperation with the Traffic and Planning Division of the Minnesota Highway Department. These studies were conducted over a seven-week, midsummer period before and after installation of the reflective color treatment and included, in turn, conventional delineation, modified interstate standard delineation and supplementary illumination.

It is not in the scope of this paper to report the results of these studies, however, the substance of completed work and expressions of other investigators suggest that valuable insight has been gained into the night visibility problem and effective techniques disclosed both for assessment and improvement of the perceptual element. Because all seeing depends on light, perception on contrast levels, and guidance on perception, effective guidance is dependent on both luminance and contrast. Intense retroreflective brightness, with contrast afforded by color as well as generally low background luminance, presages extensive new perceptual and guidance opportunities.

Color-keyed, reflective guidance systems should be restricted to readily distinguished hues and applications for maximum effectiveness. Indiscriminant color use may serve to defeat rather than enhance the effort to reduce driving complexity. Inasmuch as distinctive colors are limited, their application should be well considered, though not overlooked. Well conceived, unified reflective systems suggest a method that may effectively provide for the motorist's visual cue and guidance needs as well at night as by day.

ACKNOWLEDGMENT

The author is indebted to the Minnesota Department of Highways, and, in particular, J.E.P. Darrell and associates of the Division of Traffic and Planning for their assistance in making this study possible. He also gratefully acknowledges the counsel and extensive assistance of his associates in the Reflective Products Division Laboratory.

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Visual Characteristics of Flashing Roadway Hazard Warning Devices

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Previous investigations of the visual characteristics of flashing light sources, for the most part, have been made at low-energy levels at or near a visual threshold by means of extended sources. Although the results of these investigations have proved useful, they are not directly applicable to the design of portable battery-operated warning lights where conditions are somewhat different. These devices are usually first seen as nearby point sources under suprathreshold conditions. New data have been developed which relate to the important physical characteristics, such as flash duration and wave form, that directly affect the perceptual clues provided by such warning devices.

The effect of duration and wave form on the effective intensity of point sources of flash energies of 0.1 candlepower-seconds (red light) has been investigated by performing intensity matches between two modulated sources, one of which has a fixed duration and peak intensity. At this flash energy, which was chosen as being significantly above a visual threshold for a dark-adapted eye and as being readily obtainable by currently manufactured devices, flashes that have durations longer than 50 milliseconds require more energy to have an equal visual effect than flashes of shorter duration. This result is highly important to the conservation of battery energy.

Other factors that influence the design of battery-operated units (for example, flash rate, flash energy, and placement of units) are discussed.

● THE PURPOSE of this work was to study most of the visual characteristics of flashing light sources that might affect their effectiveness in attracting attention and to relate the findings to the design of battery-operated portable roadway hazard warning devices.

The major physical factors considered in this study were: flash duration, maximum intensity, wave form, flash rate, and the energy content of the flash. The important psychological factors were: apparent intensity as a function of flash energy, visibility threshold for detection of the presence of light, and the effect of flash duration on the ability to judge the position of the source.

PROCEDURE

Literature Survey

A survey of the existing literature of the effective intensity of flashing lights was made to determine if there were sufficient information available to answer the major questions involved in the design of portable roadway hazard warning lights.

Two serious limitations were discovered in the previous investigations. First, most of the studies were made with flashes that were at a visual threshold and were not directly applicable to the present problem, which involves suprathreshold visual conditions. Second, the energy required to produce the flashes was not restricted, whereas with battery-operated devices the energy consumption is highly important, because this determines battery life.

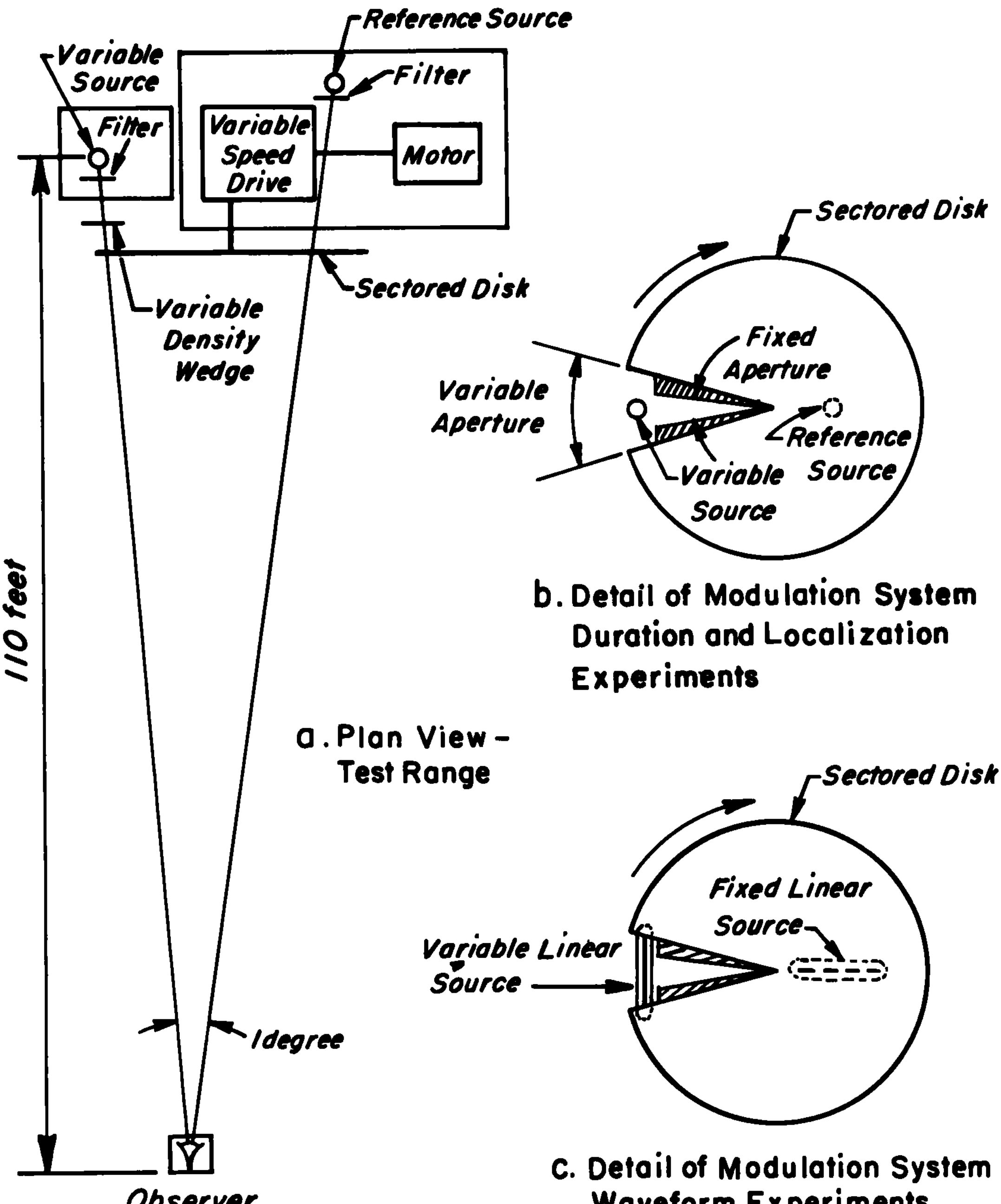

Figure 1. Layout of experimental equipment.

Experimental Work

Because of the limited application of previous research on flashing lights to this particular problem, it was necessary to conduct a series of experiments with the lighting conditions as nearly as possible like those that a motor vehicle operator might encounter at night when approaching a hazard. The environmental factors were approximated as closely as possible. For instance, one requirement was a long, totally darkened test area. The laboratory room used as the experimental test range had a clear length of 110 ft (Fig. 1). It was also desirable to use realistic sizes and colors of lights.

Other investigations had indicated that the size of a light source studied was an important factor in threshold measurements. The smaller sources produced more sharply defined effects which could be interpreted for sources of larger area. For example, referring to Figure 6, the studies on single nerve fibers by Hartline (1) produced a sharp break in the resulting curve (Curve 3). Sources of larger extent studied by Blondel and Rey (2) produced more gradual effects as shown by Curve 4. Further studies by Graham and Margaria (3) and Karn (4) substantiated the gradual sharpening of the curve with a decrease in source area but they found no change in the critical duration at which the transition takes place.

It was reasoned that if the foregoing held true for threshold conditions, then the use of small sources for supra-threshold conditions could be expected to produce useful data which could be extended for sources of larger area as, for example, Curve 2 in Figure 6. The smallest sources used in these experiments were approximately ⅛ in. in diameter and subtended an angle of 20 sec at 110 ft. This size is less than the minimum angle of resolution, therefore the source acted as a point of light. This condition approximates a 4-in. diameter warning unit seen at 1,000 ft.

The color of the test sources was a red similar to that used on some existing warning lights. This color was chosen for two reasons: first, red is the color usually encountered under actual conditions, and second, the peripheral retina is relatively insensitive to red light, so there is little or no distraction caused by scattering of light in the eye. Observations during a portion of the experiments using a white source confirmed this, as the scattered light was distracting.

It is felt that the results shown in this report are applicable to other colors since Rouse (5) has found that the "time-intensity" relation is independent of color.

A square wave form was used in most of the experiments (except for the section on wave form) because of the ease in computing the total energy in the flash and for reproducibility in the event that a cross check is desired.

The experimental program was set up to obtain data on the following variables:

1. Total luminous energy per flash;
2. Duration of flash;
3. Wave form of flash;
4. Flash rate; and
5. Localization in space.

EQUIPMENT

Sources

Two types of sources were used in the investigation, "point" and "linear." The point sources were obtained by means of 6-volt, 32-cp automotive headlamp bulbs that were entirely shielded except for a ⅛-in. opening. The linear sources were 110-volt, 25-watt, GE 25 T 10 tabular incandescent bulbs, shielded so that only 2 in. of the filament in the direction of the observer were visible. Red filters were interposed between the sources and the observers (Fig. 1).

Modulator

The modulation of the light sources was achieved by means of a variable-opening, sectored disk that was driven by a ½-hp AC motor through a Vickers variable-speed hydraulic transmission. Two sources could be alternately modulated by the same disk by placing each diametrically opposed along the radii of the disk. Hence, many combinations of flash rate and flash duration could be selected. The 2-ft 6-in. diameter of the sectored disk permitted a separation of 1 deg (2 ft at 110 ft) from the observer between the two sources being modulated by the same disk.

Detector

The flashes were monitored by a photoelectric system employing a color-corrected, RCA 1 P 21 photomultiplier tube whose output was fed into a Du Mont 403 Oscilloscope. The traces were recorded by means of a Du Mont oscilloscope camera, Model 353, having a Polaroid back. The system enabled the precise monitoring of the flash duration, instantaneous intensity, and repetition rate as the x-axis was calibrated by the line frequency to read in time units and the y-axis was calibrated by an incandescent standard lamp to read directly in candlepower (Figs. 2 to 5).

Power

The pair of light sources used in each series of experiments was each independently supplied with power. In the case of the automotive lamps, one lamp had a fixed 6-volt DC supply and the other a variable AC supply controlled by the observer. One of the linear sources had a regulated 120-volt AC supply and the other a variable supply controlled by the observer. The photomultiplier tube in the detector was supplied by a well-stabilized high-voltage DC supply.

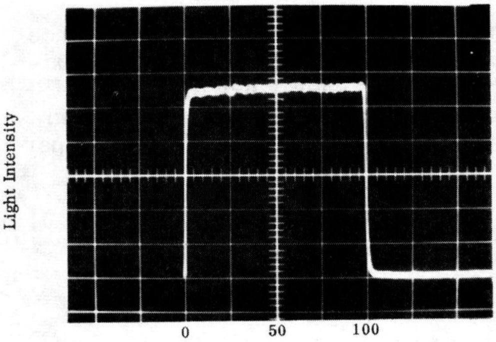

Figure 2. Typical square wave shows response of photomultiplier-oscilloscope system. Finite rise time is due to source size (1/8-in. diam).

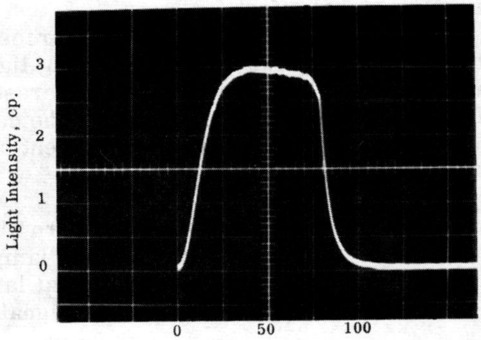

Figure 3. Incandescent source with transistorized electronic flasher. Approx. square wave modified by thermal inertia of light-weight filament. Flash energy 0.068 cp-sec (red), 0.20 cp-sec (amber).

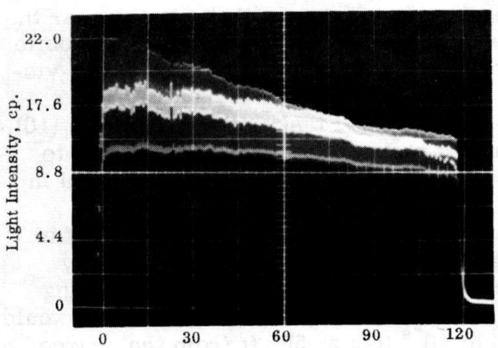

Figure 4. Neon source with transistorized electronic flasher. Flash energy 1.4 cp-sec.

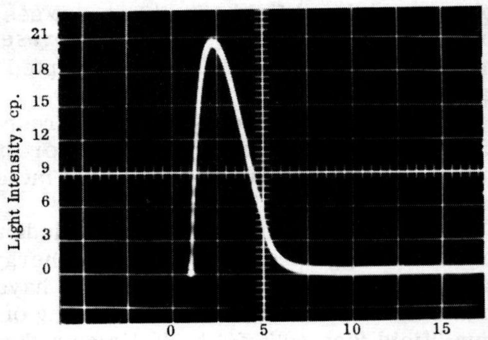

Figure 5. Neon source with mechanical-inductive flashing system. Flash energy 0.06 cp-sec.

TEST RESULTS

Energy Content

The important subject of energy content is probably the most difficult one to treat in the laboratory. One of the main difficulties involved in the determination of the minimum required luminous energy per flash is the choice of the state of visual adaptation or the range of adaptations to be considered. The adaptation level of the motor vehicle operator at night ranges over a wide distribution of values and is usually difficult if not impossible to determine with available techniques. The visual threshold and the minimum intensity that can be perceived are directly related to the level of adaptation. Assuming one could arrive at a reasonable choice of adaptation level, one would still be faced with the decision of determining how far above threshold the flash energy should be. The relationship between signal intensity and its effectiveness is not known. In other words, if a signal intensity is 50 times threshold intensity, it is not necessarily 10 times more effective than a signal at 5 times threshold, nor 50 times more effective than a threshold signal.

It is generally agreed that the brightest lights in a field of view command the most attention and that flashing lights have more attention value than non-flashing lights. With so many extraneous flashing sources in a driver's purview, it is desirable that critical warning lights should be among the brighter ones encountered. Thus, the choice of flash energy is reduced to a compromise between economic feasibility and maximum signal effect.

As an indication of some of the sources having a similar flash rate and appearance with which the roadway hazard warning lights have to compete, the following approximate values of flash energy are of interest. The luminous energy per flash may be defined as the integrated area under the candlepower versus time curve and is given in cp times seconds. Roadway-abutment and division-strip warning lights used on per-

Light Source	Flash Energy
Red passenger car turn signal	12 cp x sec
Red truck turn signal lamp	40 cp x sec
Red intersection signal lamp	40 cp x sec
Yellow intersection signal lamp	340 cp x sec

manent hazards fall withing this range of values. The foregoing represent "on-axis minimum values" using 60 flashes per minute as the rate and assuming a square wave of light output with a 40 percent effective "on" time for the incandescent sources.

The literature on the visibility of flashing lights is meager insofar as the minimum necessary luminous energy per flash is concerned. Minimum perceptible values (threshold) have been roughly determined for various sizes of source, viewing distances, states of dark adaptation, color of light, time for seeing, and location in the field of view (2-9). These data show an enormous range from 3×10^{-10} to 9×10^{-7} ft-c at the observer's eye as the minimum perceptible values (threshold) for the wide variation in experimental and field conditions. It seems reasonable to assume that a value near the top of the range (say 10^{-6} ft-c) is representative of a threshold value for an automobile driver who is only partially dark adapted and may not have his full attention on the visual task.

In other recent studies relating threshold values of visual tasks to performance (10), "field factors" have been developed for the required changes in threshold contrast to provide adequate values. The "field factors" for many tasks have been established in the range of 5 to 50 times threshold.

Considering all of these factors, judgment must be exercised in the selection of a minimum suggested luminous flash energy for a portable battery-operated roadway hazard warning device. The authors have examined devices that are currently being manufactured and have evaluated many of them for luminous flash energy. These would give "field factors" of 4 to 40 times a threshold of 10^{-6} ft-c at 500 ft from the source, neglecting atmospheric absorption. Most units will develop a maximum flash energy in the range of 0.10 to 1.0 cp x sec with red light.

With red light, more color contrast is available with the usual sources in the field of view at night so it has become accepted practice in automotive lighting design (11) to use a ratio of 1:2.5 between red and amber for equal signal effect.

Therefore, for roadway hazard warning devices the minimum suggested values for the luminous energy per flash are 0.10 cp x sec/flash for red and 0.25 cp x sec/flash for amber colored units. Admittedly these are arbitrary but they represent values at least several times threshold and they are available in the better quality portable roadway warning devices that are in current production.

Factors such as attenuation by fog or the glare due to oncoming headlamps have to be considered. A decision also has to be reached as to how much money one is willing to invest in battery power to cover all contingencies and to what extent one should try to cover them.

These minimum values should be the in-service maintained luminous energies and should be available at all points within a central cone extending to 5 deg around the photometric axis of the device. The specified light distribution should be in substantial agreement with automotive rear signal lights as recommended by the Society of Automotive Engineers (12).

Duration of Flash

The subjects were seated 110 ft from the sources in a darkened room and viewed the flashes binocularly (Fig. 1). Two point sources were placed on opposite sides of a sectored disk axis on a horizontal diameter. The left source could be attenuated by means of a remotely controlled variable density wedge. The two sources were at unequal distances from the center of rotation of the disk, so the angular size of the opening through which the sources were viewed could be made unequal (Fig. 1). There was only one opening in the sectored disk so that the two sources were presented alternately. The disk was driven at a speed of 60 rpm so that 120 alternate flashes per minute were presented. This speed was judged by most observers to be the most comfortable one at which to make the measurements.

The right source was held constant at 10 cp and 10 milliseconds duration (0.10 cp x sec luminous energy) while the left source had its duration changed for each run and its candlepower adjusted by the subject until the alternate flashes appeared equal in subjective intensity or signal effectiveness, depending on which criteria the subject chose for his match. The two sources had the same color at all times.

Five observers made a total of 456 readings and developed the technique. Table 1 gives the averages of 144 additional readings by four other observers which are in substantial agreement to the previous 456 observations.

TABLE 1

INTENSITY MATCHES

Variable Duration (Left Source) (ms)	Matching Intensity (Left Source) (cp)	Matching Flash Energy (Left Source) (cp x sec)
10	10	0.10
20	5.1	0.10
33	3.4	0.11
41.5	2.75	0.11
45.5	2.4	0.11
50	2.45	0.12
55.5	2.3	0.13
62.5	1.96	0.12
71	1.9	0.135
83	1.8	0.15
100	1.8	0.18
250	1.1	0.27

The foregoing table gives the average setting by the observers of the candlepower of the variable source for different flash durations required to match the constant source. The right source remained constant at 10 cp and 10 milliseconds giving a flash energy of 0.10 cp x second. The energy of the matching flash is also given.

Table 1 indicates that it requires a gradually increasing amount of energy to match a 10 millisecond flash with a flash whose duration is gradually increasing. A log plot of flash energy versus duration shows more clearly at which point the energy required to match a 10 cp-10 millisecond flash begins to increase (Curve 1, Fig. 6).

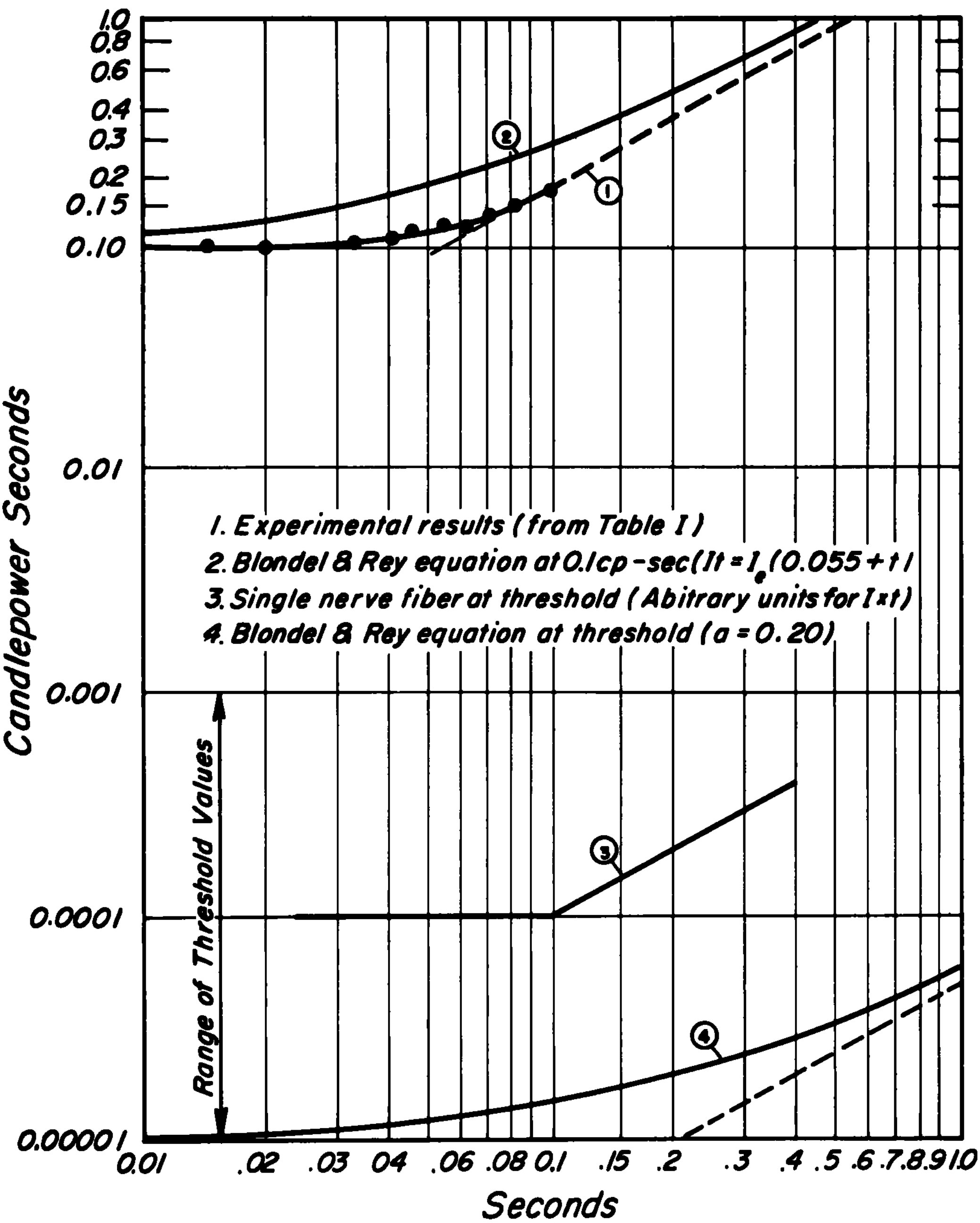

Figure 6. Flash energy vs duration of flash for equal effective intensity.

Also included in the graph are the lines indicating the results of previous work for a single nerve fiber and sources of large extent made at threshold condition (Curves 3 and 4). It can be noted that the curve for a single nerve fiber has a sudden transiton at 100 milliseconds. The first portion of this curve represents the condition wherein the photochemical process within the retina is predominating. The later portion of the curve is controlled by the characteristics of the nerve fiber and indicates a condition of saturation. Because the shape of the curve for supra-threshold conditions seems to tie in with the data for threshold conditions, it is believed that an extrapolation that approaches Curve 2 (Blondel and Rey) is valid for sources of finite extent under supra-threshold conditions. For example, a 4-in. warning lamp subtends an angle of 72 sec at 1,000 ft or a little more than three times the subtence of the "point" sources used in the experiments; therefore, one could expect that the transition in the neighborhood of 50 milliseconds would be a little more gradual or more nearly like Curve 2. In essence, the use of the "point" sources in these experiments (Curve 1, Fig. 6) is an effort to pinpoint more carefully the transition point on the curve of duration versus flash energy. Curve 2 was computed from the Blondel and Rey (2) equation $[I \times t = I_e(a \times t)]$, using a value of a = 0.055 in the manner of Toulin-Smith and Green (8). Curve 2 does not represent experimental points as do the points on Curve 1.

The data clearly show that when the flash energy is in the neighborhood of 0.10 cp x seconds, the flash duration should not be longer than 50 milliseconds if the energy must be conserved. At lower values of energy per flash the transition duration is closer to 100 milliseconds which is the limiting case under threshold conditions as determined by Blondel and Rey (2). At flash energies higher than 0.10 cp x sec, the transition duration could be expected to decrease to somewhat less than 50 milliseconds but not appreciably.

Wave Form

In order to study the effect of wave form on the signal effectiveness, two linear sources were used. One source was oriented parallel to the sector edge and the other was oriented perpendicularly to the sector edge (Fig. 1).

Hence, a square wave was compared against a triangular wave. Table 2 gives the average results of 40 readings by four observers in which the intensity of the square wave was adjusted until it was equal in appearance to the triangular wave. It is to be noted that the energy contained in the triangular flash would just be equal to that contained in the square flash when both have equal peak intensities and the square flash has one-half the duration of the triangular flash.

TABLE 2

SQUARE AND TRIANGULAR FLASHES FOR EQUAL VISUAL EFFECTIVENESS

Wave Form	Duration (ms)	Peak Intensity (cp)	Flash Energy (cp x sec)
Triangular	28	10	0.14
Square	14	10.8	0.15
Triangular	82.4	3.5	0.14
Square	41.2	2.8	0.12
Triangular	124	3.5	0.22
Square	62	2.6	0.16

As long as the duration is less than the critical duration, it appears to matter little how the intensity is distributed in time and what combination of intensity and duration is used so long as the flash energy is constant. Other investigations (6) have shown this reciprocity to hold down to durations as short as a few microseconds. The results of this experiment confirm the findings of Table 1, namely, that it requires more energy at durations longer than a given critical value than at shorter durations to cause a given sensation of subjective intensity. It is also interesting to note that it requires more energy for a match when the wave form is triangular than when it is square when one or both flashes are longer than the critical transition duration. This effect implies that for flashes longer than the critical duration the distribution of intensity should maximize the energy in the minimum duration. Hence, a square wave of intensity would be the best choice.

Flash Rate

It was not possible to set up an adequate experiment to determine the most effective flash rate, however, some observations can be made. An enhancement of the subjective intensity by a factor of approximately 2 was noted for flash rates of about 8-12 per second (Brucke Phenomena). Thus, for a doubling of the effective intensity at this higher frequency the battery power consumption would be multiplied about 8-12 times over a flash rate of 1 per second, hence, flash rates in this range were considered impractical for battery-operated devices. Studies by Gerathewohl (13) indicate that for sources with high visual contrast there is little visual difference between a flash rate of 1 per second and 4 per second, therefore, from the standpoint of maximum battery life, 1 flash per second would be the better choice.

No references were found in the literature to studies of flash rates slower than 60 per minute, thus, additional work is necessary to determine the effectiveness of flash rates slower than 60 per minute. Personal experience in tests made on automotive flashers by the authors indicate that approximately 40 flashes/minute is about the minimum value acceptable for high energy flashes in the order of 40 cp x seconds. At the present, one can only say that as the flash rate is decreased below 60 per minute, the aspect of the source changes from a localized flashing appearance to that of an indeterminant source slowly turning on and off without a high demand for attention.

Localization

The term localization is used here to signify the ability of the driver to judge the distance and position of the hazard with respect to the roadway. This ability of the driver is another important factor in the design of portable roadway hazard warning devices. It is important to know whether flash duration and repetition rate affect this ability and if so, in what manner.

The small amount of work to be found in the literature is negative (7). Observations during the conduct of the experiments on duration and wave form did not indicate any correlation between flash duration and localization.

A series of judgments were made in the following manner: In the first group the subject was asked to estimate the separation in distance units between two modulated sources that were equal in duration and intensity. The peak intensity of the flash was held constant throughout the first series and only the duration was varied. In the second group, the intensity was increased while the duration was decreased to maintain a constant effective intensity. The actual separation of the two stimuli was 2 ft.

The results indicate no correlation between the ability to judge the separation distance between two flashing sources and the duration of their flashes. However, the results are not sufficiently conclusive to disprove a correlation. Even when the two sources were burning steadily, there was no significant change in the judgment of the separation. Two steadily burning point sources isolated in space offer little information as to their physical separation (Tables 3 and 4).

The effect of pattern on localization has not been studied as a part of this report. Other investigators have stressed the importance of pattern and the rate of change of the pattern with speed as a major factor in visual judgments (14, 15). This factor should not be overlooked in the placement and number of roadway hazard warning devices used at a particular location.

TABLE 3

JUDGMENT OF LINEAL SEPARATION OF TWO MODULATED LIGHT SOURCES WITH INCREASING DURATION AND INCREASING SUBJECTIVE BRIGHTNESS (PEAK INTENSITY = 10 CANDLEPOWER = CONSTANT)

Run No.	Duration (ms)	Subject JH (ft)	SM (ft)	DD (ft)	HG (ft)	KF (ft)
1	5	4	2	3	2	2.5
2	10	5	4	4	1.5	3
3	20	3	2	3	2	3
4	30	3	4	4	2	3
5	40	4	3	4	2.5	2.5
6	50	3	3	3	2.5	3
7	75	2.5	3	3	2	4
8	100	3	3	3	2	4
9	250	3	3	3	2	3
10	∞	3.5	3	2	2.5	2.4

TABLE 4

JUDGMENT OF LINEAL SEPARATION OF TWO MODULATED LIGHT SOURCES WITH DECREASING DURATION AND EQUAL SUBJECTIVE BRIGHTNESS

Run No.	Duration (ms)	Subject JH (ft)	SM (ft)	DD (ft)	HG (ft)	KF (ft)
1	200	3	1.5	3	2	3
2	100	2	2	4	1.5	3
3	50	3	3	3	1.5	3
4	25	3	4	4	1.5	4
5	16.6	4	4	4.5	1.5	4
6	12.5	3	4	2.5	2	3.5
7	10	3	3	-	2	3

CONCLUSIONS

1. For flashes of light that are to be above the threshold value of energy required for the detection of the presence of the light by a motor vehicle operator under normal conditions at night, an energy content of at least 0.10 candlepower-seconds of red colored light or 0.25 candlepower-seconds of amber colored light should be developed in the principal viewing directions (assumed to be within 5 deg of the photometric axis). These values are several times the minimum perceptible values for a representative state of adaptation of a motorist and are 100 to 1000 times the minimum perceptible values for a completely dark adapted eye. Moreover, they are several hundred times less than the energy in an automotive turn signal or a flashing traffic signal. At present there is no technique to use except experience in establishing the energy content of a flashing light to give an adequate warning signal. The better designed roadway hazard warning devices now manufactured will meet the above requirements.

2. The flash duration need not exceed 50 milliseconds total time. Any time less than 50 milliseconds will give a constant effective intensity for the same energy in the flash (cp x seconds = constant). Any time greater than 50 milliseconds will require more energy to give the same effective intensity for the flash.

3. The effective intensity of the flash is independent of the wave form when the dur-

ation is below 50 milliseconds, however, when the duration is above this value, the most effective wave form is that which most closely approximates a square-wave.

4. The flash rate need be no faster than 60 flashes per minute for an effective signal and could possibly be slightly slower than this value, but further study is necessary to determine this point.

5. Localization — no correlation between ability to judge separation distance and flash duration was detected. More work needs to be done on patterns of light and synchronization of flashes to convey distance information.

The two main requirements of a hazard warning system are to attract the driver's attention to prepare him for an unusual situation and to provide some clue as to the position and extent of the hazard.

The first requirement can be satisfied by a single flashing source that is of sufficient intensity and duration to be above the visual threshold. It may be advisible to combine the energy consumed in several weaker randomly flashing lights into one stronger light so that it might be more comparable in flash energy to some of the commonly encountered warning signals having luminous flash energy in the order of 40 candlepower-second.

The second requirement is best met either by providing ample illumination of the hazard to reveal its form and texture or by delineating the hazard by a group of light sources arranged in a meaningful configuration.

Possibly both requirements could be met by a group of flashing sources each of luminous energy in the order of 0.10 cp x second, that are arranged in a meaningful pattern and synchronized to flash simultaneously. Such a group, flashing in unison, probably would be as effective as a single higher intensity flashing source used in combination with a pattern of steady burning lights.

It is suggested that an absolute minimum of three random flashing lights should be considered for marking any roadway hazard and that these should be grouped within a visual angle of not more than 1 deg when the driver is 500 ft to the nearest unit and when the driver is in the most critical traffic lane on the road with respect to the hazard. The number and pattern of lights for marking any given hazard should receive additional study in order to arrive at suitable recommendations for field use.

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Advancement in Roadway Lighting

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● SIGNIFICANT ADVANCEMENT in roadway lighting depends on the combined action of many people, including the best engineering skills, scientific research personnel, and facilities.

One of the objectives of this paper is to arouse interest in the benefits which will be produced by attention to better seeing conditions for night driving. The scientific resources available, which should be directed toward the improvement of night seeing conditions, include the personnel of all federal and state highway departments, and some universities, institutes, associations, and committees.

Also, individual contributions based on thoughtful use of one's knowledge should be highly significant. To make progress, knowledgeable, shrewd people must speak up, tell what they know, and show how it can help improve the tremendous multibillion dollar industry or business of night motor vehicle transportation.

Many American people desire, or may be required, to drive the streets and highways after dark or before dawn. During the hours of darkness roadway lighting should be appropriately used to extend and continue the efficient and pleasant use of motor vehicle transportation facilities.

POSSIBLE PUBLIC BENEFITS

Serious consideration should be given to the public benefits of good night seeing conditions such as:

1. Night transportation should also operate efficiently.
2. Increase value of automotive-highway investment.
3. Better environment for social, recreational, business activities.
4. Development of useful land areas.
5. More pleasant, less fearsome night driving.
6. An improved standard of night living for night motorists.

Helping provide these benefits by means of good night seeing conditions is the humanitarian objective which has impelled the development and more widespread use of roadway lighting. The lighting of municipal streets, highway interchanges, and roadways extending through, around, beyond, and between sizeable centers of population and business activity is worthy of immediate attention.

Night Transportation Should Also Operate Efficiently

Efficient motor vehicle transportation requires reasonable night as well as day speeds. When roadway lighting is used to provide good seeing conditions, safe or critical speeds are higher than for dark streets or highways. The economic value of time saved with higher critical speeds justifies many roadway improvements, including roadway lighting for night traffic. The economic benefit is used in the justification of many roadway improvements. The saving may amount to more than the cost of roadway lighting. Roadway lighting should increase safe speeds by 10 to 20 mph.

When only 2,500 vehicles per night increase average speed from 45 to 60 mph, the economic value of time saved amounts to $6,000 per mile per year (Fig. 1). This is based on the outmoded $0.02 per vehicle minute estimate. When time is evaluated at the current rate of $0.06 per vehicle minute, the economic saving is increased to $18,000 per mile per year.

Critical, or safe, night driving speeds are higher and more nearly approach daytime speeds when lighting is provided for good seeing.

Utilize Highway Capacity During Darkness.—The after-dark, evening, or early morning capacity or efficiency of roadways depends on the seeing conditions provided. Operations such as avail of passing opportunities, headways, lane use, and merging

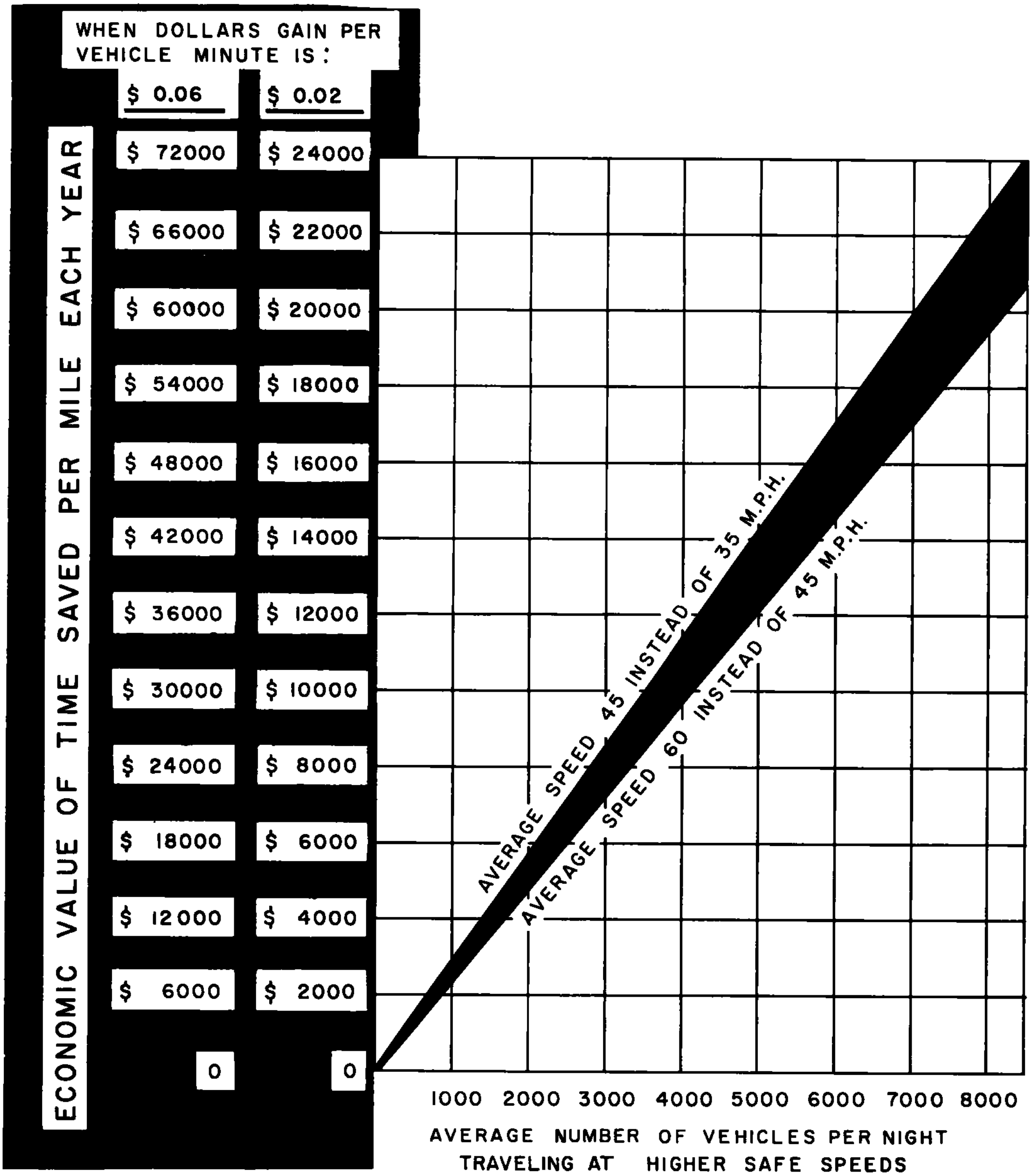

Figure 1. Economic value of time saved, due to higher critical or safe speeds, also applies to night traffic. Roadway lighting should increase safe speeds by 10 to 20 mph. When only 2,500 vehicles per night increase average speed from 45 to 60 mph, the economic value of time saved amounts to $6,000 per mile per year. When time is evaluated at $0.06 per vehicle minute, this economic saving is increased to $18,000 per mile per year.

of vehicles are improved by lighting for good seeing. The safe, expeditious movement of large numbers of vehicles requires quick and accurate seeing on which good driving judgment is based.

The U.S. Bureau of Public Roads, the Connecticut State Highway Department, and other interested agencies are seriously considering engineering studies of the improvement in heavy traffic conditions, such as capacity achieved by means of roadway lighting.

Increase Value of Automotive-Highway Investment

Better seeing conditions for night driving will continue, extend, and expand the benefits of motor vehicle transportation. Increasing the dividends received from a world-wide multibillion dollar investment—industry or business—may be considered vital to progress.

Pleasant, attractive night driving conditions encourage increased use of streets, highways, autos, trucks, and buses. Turnpike toll highways are being lighted to assist and attract night motorists. The lighting of interchanges is most prevalent.

The increase in financial dividends through motor fuel tax revenue may be reinvested in additional facilities for the public benefit. Figure 2 shows an example of the state and Federal motor fuel tax revenue that may be generated by night use of streets, or highways by various volumes of traffic. After-dark use may account for sizeable proportion of the over-all fuel tax receipts.

Those who use these facilities at night and provide this substantial revenue may believe that they should be appropriately aided by the improvement in seeing conditions which roadway lighting provides. Improvement of roadway and vehicle facilities usually attracts and encourages the people to make more use of such facilities.

The appropriate use of roadway lighting is a night use improvement which may produce an appreciable increase in motor fuel tax revenue. If the average increase in traffic volume is 3,000 vehicles per night, the increase in revenue to the state is more than $5,000 per mile per year. In addition, there may be an annual increase of $2,500 per mile for the Federal road program. The motor fuel tax receipts shown in Figure 2 are based on the assumption that the average vehicle consumes one gallon of gasoline for each 15 miles of travel. The $0.07 per gallon state tax and the $0.035 per gallon Federal tax are representative.

Better Environment for Social, Recreational, Business Activities

It has been estimated that a large percentage of the over-all travel-use of streets and highways in the United States is generated by social and recreational motives. Family contacts during the evening hours may be considered highly important.

Tourists may be an attractive business enterprise as well as an activity which brings pride of one's community. It is generally reasonable to assume that the people do not desire that all such activities be confined to the daylight hours.

Some countries are purposefully floodlighting buildings, foliage, monuments, and installing lighted fountains to obtain beautiful effects for the benefit of tourists as well as the local populace. Obviously the roadway paths to be traveled to and from such centers of attraction should be adequately lighted.

Often people enroute to a destination may prefer to drive at night rather than delay, or instead of having less time the next day for sight-seeing or business activity.

Night street or highway travel may be a matter of necessity in getting to, or from, centers of employment or shopping. Peak traffic conditions may occur during the hours of darkness or near-darkness, particularly during the short daylight hours of winter. Road capacity and traffic efficiency may be most important at night. It has been estimated that 90 percent of the people in the U.S. travel by automobile. Trucks, buses, and air or rail terminals now also operate on a 24-hr basis for the delivery of people and goods. Night shift employees and after-dark customers deserve serious consideration. Lighting is good business.

Shopping centers and other roadside business establishments remain open after dark. They enhance their own private business at night by providing lighting on their property for the comfort, convenience, and protection of their customers.

The wide extent of this privately financed lighting activity should be an indication of the public desire and approval of appropriate lighting on the streets and highways which provide access to after-dark business establishments. These customers should not be rushed away for a hurried return home in order to avoid driving or walking along dark streets or highways.

Continuation and extension of prosperity during the hours of darkness is a normal, logical public desire. Many activities which aid the general over-all economy of an

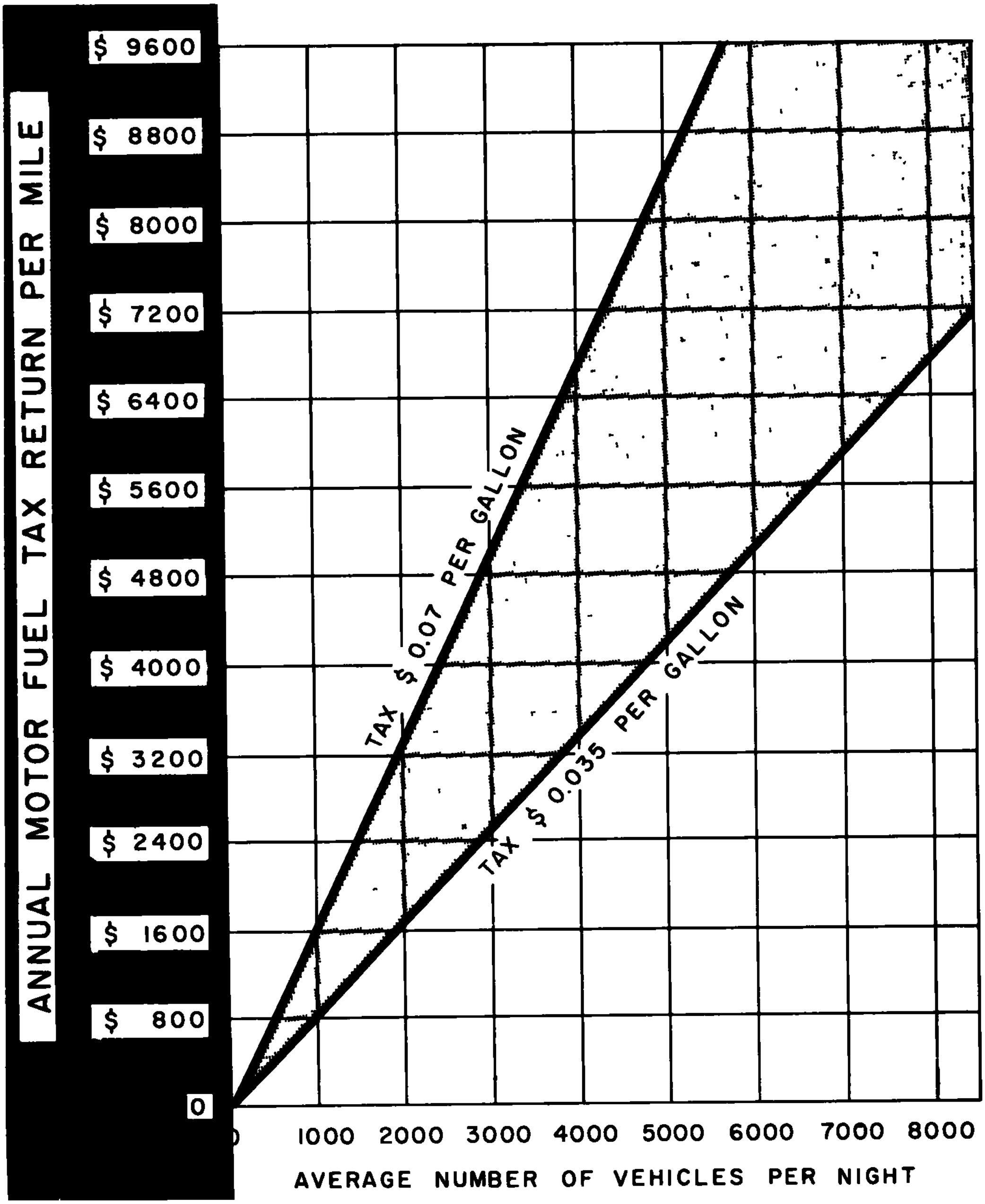

Figure 2. Night use of motor-vehicle transportation facilities generates a sizeable proportion of state and Federal motor fuel tax receipts. Increased night use with the encouragement which good seeing provides should produce an appreciable increase in fuel tax revenue for over-all, day-as-well-as-night, improvement of the roadway system. When the volume (or the increase) of night traffic averages only 3,000 vehicles per night, the annual state revenue is more than $5,000 per mile. In addition, there is $2,500 for the Federal road program, including a small percentage for research. The motor fuel tax receipts are based on consumption of 15 miles per gallon of gas, and $0.07 and $0.035, state and Federal tax, respectively.

area may be kept open—and made even more prosperous—during the hours of darkness by using the highly efficient lighting aids that are now available.

Development of Useful Land Areas

After-dark access to an area with comfort, convenience, and safety is an obvious requisite for area (property) desirability and development. This benefit results from almost all highway improvements. Roadway lighting appropriately used should favorably affect property values. Night living in a community is more pleasant and secure when lighting is provided.

More Pleasant, Less Fearsome Night Driving

"Drive at night" is a reasonable suggestion when good seeing conditions are provided to produce a pleasant, attractive, convenient motorist experience. Roadway lighting helps provide an environment free from fear.

The "don't-drive-at-night-if-you-can-avoid-it" attitude may apply to motorists who are fatigued or otherwise handicapped; but even when partially incapacitated people do persist in driving after dark, good seeing conditions assist them.

Good seeing is also essential for the protection and assurance of the other motorists or pedestrians who also happen to be on the road at night—the "other fellow" who may be shielded by another vehicle must be seen to be avoided.

The traffic safety benefits of good night seeing conditions are generally appreciated. Roadway lighting for good seeing helps the driver discern an impending traffic situation soon enough and at a distance in advance which is sufficient to avoid collision.

Being able to see the vehicle path ahead, the roadway, its alignment, and objects thereon often make the difference between a safe versus hazardous condition.

Removing the "cloak of darkness" by means of lighting is an effective aid to control of night criminal activities.

This is well known by the police. There are many instances in which robbery, vandalism, etc. have been appreciably decreased by adding the protection of lighting.

And the journey-trouble-stops (such as a flat tire) along a highway at night are less fearsome to contemplate when lighting has been provided to aid repairs or law enforcement.

An Improved Standard of Night Living for Night Motorists

Roadway lighting helps raise the standards of night living for night motorists, pedestrians, and others who do not desire to confine their activities to the daylight hours. Insurance costs should be lowered by the general use of lighting.

The economic gains and dividends to be attained by means of lighting may be large and worthy of very serious evaluation and consideration. A progressive attitude toward night activities may favorably influence the value of property. The value depends on usefulness when the people have the time and the desire to utilize. Increasing the value received from the public automotive-highway investment may produce a tremendous over-all improvement in the national or local economy.

For example, an automobile would be of little or no value if it must stay in a garage. Such facilities are of more value if they can be used—at night as well as during the day—with comfort, convenience and safety (Fig. 2).

Other Benefits

There are also other motivations, opportunities, and obligations which should place use of adequate roadway lighting and evaluation of its benefits uppermost in the minds of engineers and scientists, as well as all others who represent the American public, night business activities, and night motor vehicle transportation.

Good roadway lighting is an obvious indication of community progress and desire to prosper. Such an improvement of night living conditions should be seriously considered by all those responsible and accountable for the public welfare.

STUDY IMPROVEMENT IN NIGHT TRAFFIC CONDITIONS

The sizeable potential increase in night use and the value of streets, interchanges, and highways extending through, around, beyond, and between sizeable centers of population and business is worthy of immediate attention.

Roadway lighting advancement is notable because of the number of installations being made, the extent and amount of light being provided, also because of the adherence to the technology by which the essential good seeing conditions are achieved at nominal cost. Obviously this involves the engineering approach.

The night transportation industry, business, and prosperity, can be benefited by evaluating the economic improvement produced by adequate seeing. Figure 3 is an over-simplification of the objective factors. Evaluation and appraisal of the benefits, including comfort, convenience, facilitation, efficiency, accident prevention, and freedom from fear, is essential. The roadway lighting considered should be effective in

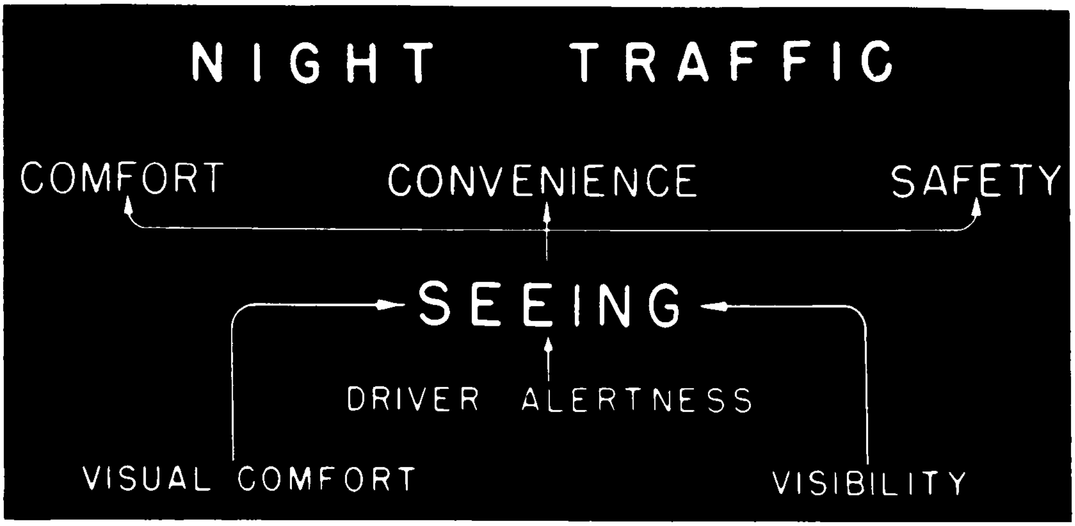

Figure 3. Public or operational traffic benefits derived from pleasant and efficient night use of the multibillion-dollar investment in automotive transportation facilities requires good seeing conditions. Effectiveness of roadway lighting is improving the seeing factors and visual comfort; visibility may now be rated so as to provide a basis for evaluation and ratings for the resultant increase in night traffic benefit.

producing visual comfort, visibility, and proper driver aspect.

Night traffic studies include the following:

1. Highway safety study.
2. Connecticut Turnpike study.
3. Texas intersection studies.
4. Michigan State driver efficiency studies.
5. Studies encouraged by I.T.E. Committee on Roadway Lighting.

Highway Safety Study

One of the recent significant traffic and seeing developments has been the publication of a report of the Highway Safety Study conducted under the direction of Charles W. Prisk, U.S. Bureau of Public Roads.

This report stresses the need for better and more general understanding of the fundamentals in:

> ...transportation, driver research,...perception,...judgment,...decision making,...fatigue,...loss of vigilance,...skill fatigue,...

etc. Considering all advantages to driver and other social advantages, it can be concluded that modern street lighting adequately designed and operated, does improve safety in most city situations ...the driver becomes 100 percent involved since obviously no action takes place on the highway except at his instigation...there is less critical knowledge about him...the ways in which the demands of the task are adapted to the characteristics of the human being will be a determinant of the safety and efficiency with which the highway-transportation system will function...the highway itself is the one permanent structure of highway safety, working 24 hours a day every day in every year to fulfill its public service function....

...Comfort, convenience, and safety are considerations of importance equal to a consideration of capacity, in today's highway planning. This concept of adequate facilities requires modern techniques for handling traffic...The Bureau of Public Roads has initiated appropriate cooperative studies with State authorities so that sorely needed new concepts, criteria, and techniques will be developed for determining the true value of continuous lighting on rural highways.

Additional pertinent excerpts from this report are presented for ready reference in Appendix C.

Connecticut Turnpike

Congratulations are due the U.S. Bureau of Public Roads for their research studies of roadway lighting, such as those conducted on the Connecticut Turnpike (2, 45). Traffic volumes were low during the studies which have been made. It is hoped that studies and analysis will be continued on this highway and the 17-mi extension into the City of New York which will soon be lighted continuously.

Texas Intersection Studies

The U.S. Bureau of Public Roads is also cooperating with the Texas Transportation Institute and the Texas Highway Department in studies (2) of intersection illumination.

Michigan State Driver Efficiency Studies

T.W. Forbes' paper on "Some Factors Affecting Driver Efficiency at Night" is given elsewhere in this Bulletin.

Institute of Traffic Engineers Committee on Roadway Lighting

The foregoing is also in line with the Resolutions Favoring Research on Roadway Lighting which was Adopted by Institute of Traffic Engineers Committee on Roadway Lighting, Detroit, Michigan, September 23, 1957. "The I.T.E. Committee on Roadway Lighting strongly endorses additional research on the benefits of roadway lighting, including driver comfort, traffic safety, roadway capacity, and other factors."

USE ILLUMINATING ENGINEERING AID

Some of the aids available for the improvement of night motor vehicle transportation have been developed by illuminating engineering, its industry, and initiative. Recent advancement will be discussed under the following headings:

1. Products which are more efficient and effective in producing good seeing.
2. Improved roadway lighting practice essential for efficient night transportation.
3. Ratings for evaluation of the visual seeing effectiveness of roadway lighting systems.
4. Instrumentation recently developed for field measurement of seeing factors.

More Efficient Products

The efficiency with which lamps and luminaires produce seeing has been appreciably increased during the past year, further enhancing a long-range upward trend. In announcing new products in June 1959, the General Electric Outdoor Lighting Department's General Manager stated "a luminaire sells for 20 percent less per lumen of output than in 1939—the cost of other things the utility buys have gone up—coal up 130 percent since 1939; copper up 200 percent; steel up 165 percent; but street lighting luminaires are down 20 percent. Here is what has happened to what cities buy: roadways up 250 percent; public buildings up 175 percent; motor vehicles up 150 percent; street lighting luminaires down 20 percent."

Installation, maintenance, and power costs are reduced by new mercury lamps which not only produce more than 50 lumens of light per watt, but also operate 9,000 hr, more than 2 years, with only 12 percent reduction in light output. A few years ago the few lamps that lasted that long had as much as 50 percent loss of light when operated 2 years. This is a 4:1 improvement in light output at the end-of-two-year lamp life. Replacing lamps once every 2 or 2½ yr obviously involves much less labor than was required for filament lamps which were replaced two or three times each year. This is as important for remote intersections as for systems of several hundred or several thousand luminaires.

The trend in roadway lighting (predicted 10 years ago) is back to arc lamps now in the form of mercury arc discharge lamps.

The use of 1,000-watt mercury lamps, producing more than 50,000 lumens in each luminaire, is rapidly increasing along with a general appreciation of the visibility really essential for night driving.

A contribution by the luminaire manufacturers is a completely new look in luminaires involving large tooling investments to lower the costs of installing and maintaining luminaires in the field. The manufacturer now mounts and wires the components inside a sleek, modern die cast housing. The utility or contractor is not now required to mount, and wire, or maintain each component separately. The integrated luminaire comprises:

1. Lamp, reflector, refractor for light direction and control.
2. The ballast-reactor for efficient operation of the mercury lamp.
3. A photoelectric control to automatically turn on the lamp at night when needed, and turn it off in the morning when the light from the lamp is not needed.
4. A single terminal board to which incoming power wires are attached.

New acrylic plastic refractors are now available for some luminaires. This is one answer to glassware breakage, wherever it is a problem.

Another interesting product development has recently been installed on Manahawkin Bridge by the New Jersey State Highway Department. The cost of low mounting height lighting from the bridge rail will apparently be cut in half by using modern production tooling. Some bridge designers do not like poles. Maintenance is easy. Individual units may be used as obstruction markers. The Manahawkin installation is said to be the first actual installation of lighting permanently designed into a bridge railing. The New Jersey State Highway Department has for many years invested in the maintenance and operation of roadway lighting involving many thousands of luminaires.

Sight Production

Due to advances in luminaire developments and proper use of available data, the visibility effectiveness of modern roadway lighting systems continues to increase appreciably and is now much higher than that obtained from roadway lighting as of 20 years ago.

The visibility and visual comfort effectiveness of luminaires is being improved by increased attention to the factors shown in the lower portion of Figure 5 (1, 2, 3, 4, 5, 6, 7, 12, 13). For example:

1. Control, or cutoff, of luminaire candlepower at driver approach distances from the luminaire greater than the top of auto windshield cutoff (shown shaded in Fig. 4) improves visual comfort and visibility:

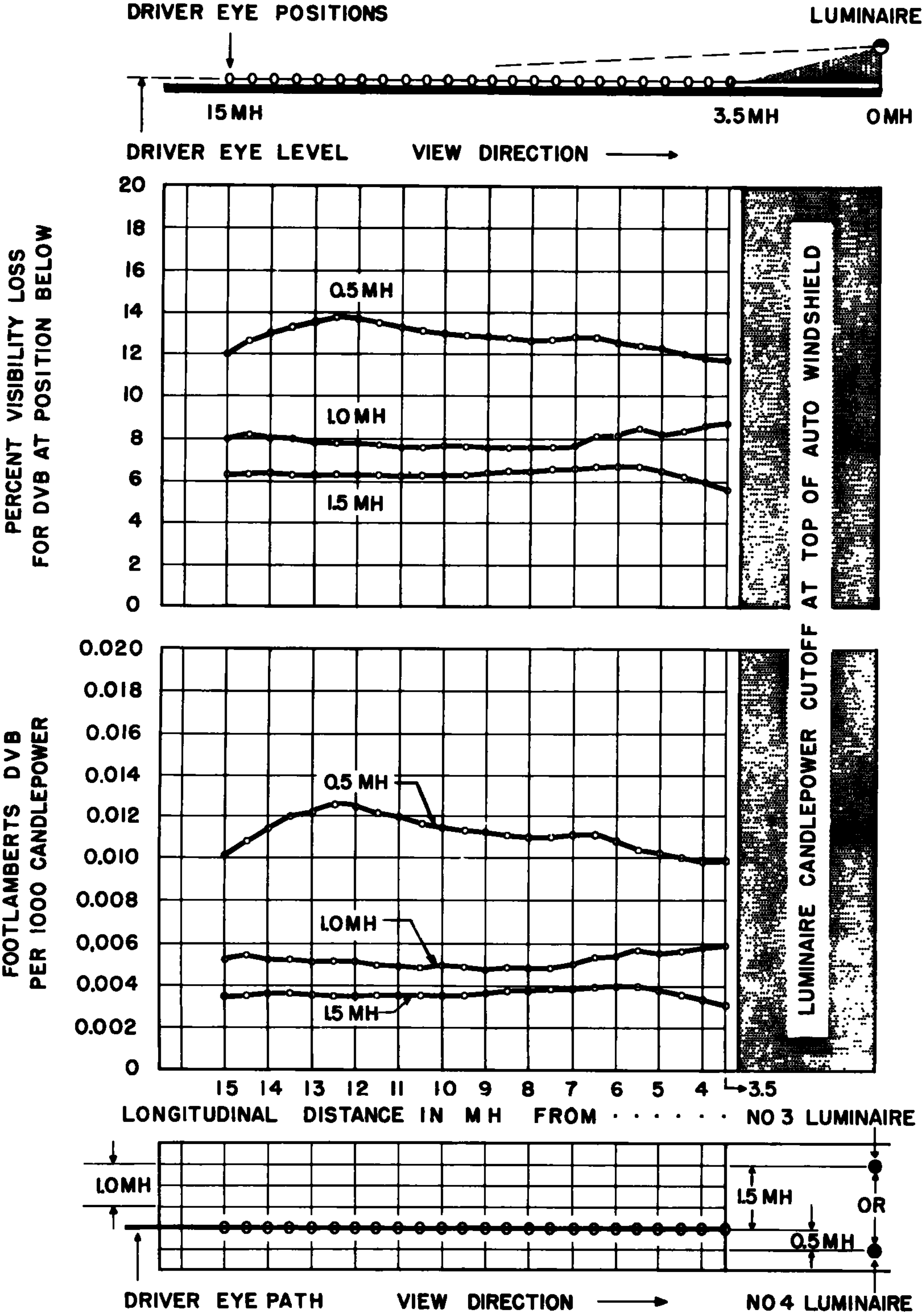

Figure 4. The visibility significance of cutoff, or sharp diminution of candlepower from a single roadway lighting luminaire, at distances greater than top-of-auto-windshield-cutoff, is shown by this data diagram for several representative driver paths along roadway. Luminaire candlepower extending out to longitudinal distances such as 15 MH, or 450 ft from luminaire produces about the same loss of visibility due to DVB as equivalent candlepower extending only 3.5 MH, or 105 ft from luminaire.

a. Visual comfort is improved by decreasing the actual luminaire brightness and the range of fluctuation shown at the left of Figure 5.

b. Visibility is improved by decreasing the percent loss due to DVB (disability veiling brightness) as shown at the right side of Figure 5.

2. Appropriate build-up and proportioning of the candlepower distribution at distances from the luminaire less than the top of auto windshield cutoff (shown unshaded in Fig. 6) increases visibility without detracting from the gains described under "More Efficient Products."

a. The relative effectiveness of candlepower in producing pavement brightness along the roadway (Fig. 6) shows that for reasonable uniformity of pavement brightness, the candlepower should be increased, with increase in longitudinal

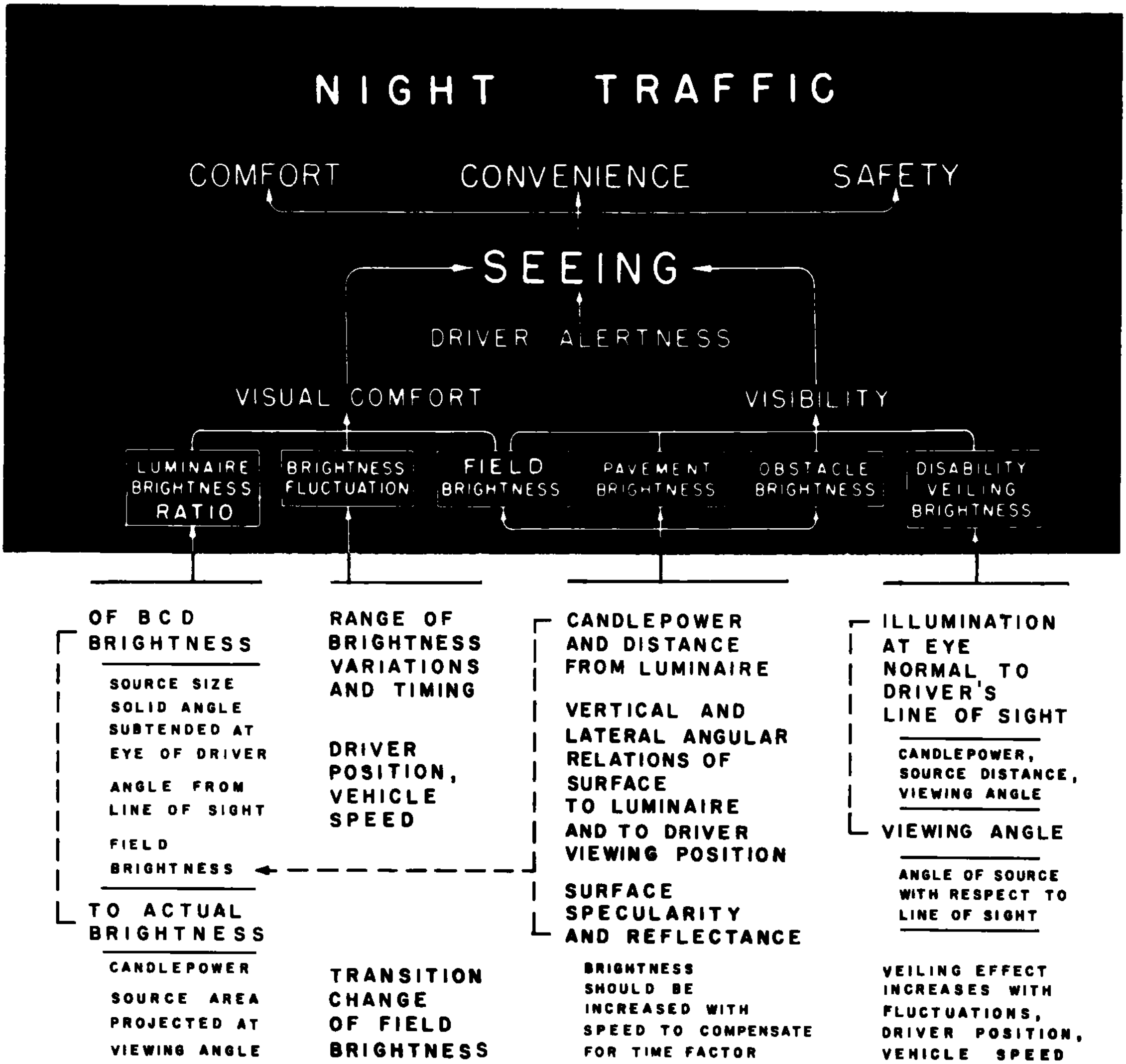

Figure 5. Data, emphasis, control, and balance of roadway lighting factors shown in lower portion, produce the visual comfort and visibility factors in seeing. Intermediate factors such as luminaire brightness ratio, fluctuation, field brightness, pavement brightness, obstacle brightness, and the percent visibility loss due to disability veiling brightness may also be rated and correlated to provide effectiveness ratings in terms of relative visual comfort and relative visibility. This simplification may be presented in terms of the two minimum ratings shown in Figure 3. Night public-traffic benefit is usually contingent on the seeing factor effectiveness of the roadway lighting provided.

distance extending out from the luminaire to distances of 3 to 3.5 MH.

b. Appropriate proportioning of candlepower distribution improves:
   (1) Pavement brightness for visibility by silhouette contrast.
   (2) Obstacle brightness for visibility by reverse silhouette or direct discernment.
   (3) Field brightness for visual comfort. Field brightness is the average integrated brightness in the driver's field of view, including that of the pavement, and objects thereon and nearby.

By comparison of Figure 4 with Figure 6, it is apparent that the cutoff of luminaire candlepower distribution coordinated with the top of auto windshield cutoff with respect to the driver's eyes, for average motorists and representative motor vehicles is highly desirable. This is one of the performance features of modern luminaire development, design, and manufacture.

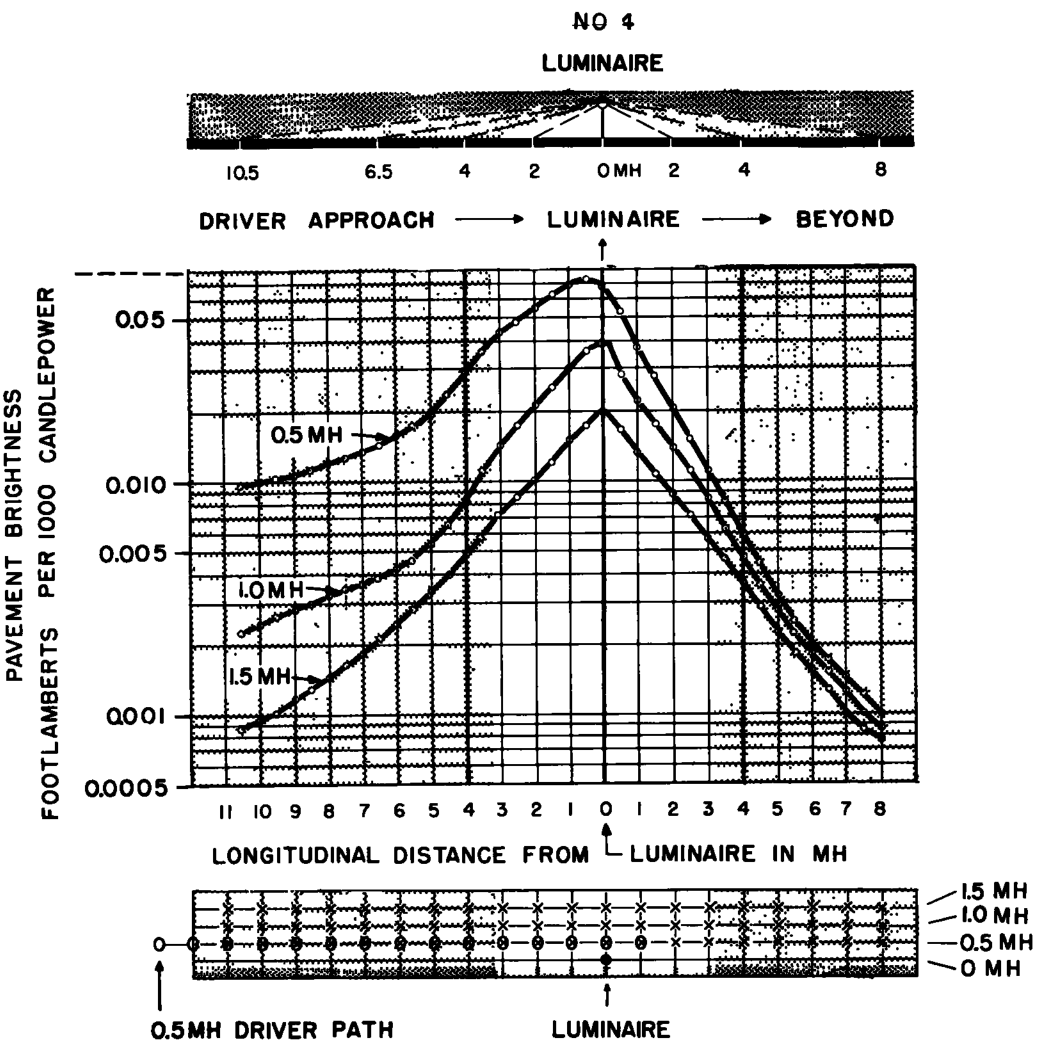

Figure 6. The highly significant pavement brightness factor in roadway lighting visibility is built up by increasing candlepower from luminaire with longitudinal distance up to that of top-of-auto-windshield-cutoff, which is shown shaded in this data diagram. The lower portion indicates driver-observer path, also transverse dimensions with respect to luminaire for representative longitudinal roadway lines along the pavement.

There are exceptions, such as luminaires for residential lighting, where long spacings between luminaires for economy and moderate driving speeds often justify extending the luminaire candlepower cutoff to longitudinal distances beyond 4.5 MH from the luminaire.

Additional information on the features of effective luminaire candlepower distributions and roadway lighting systems is readily available in other papers.

Improved Roadway Lighting Practice

There has been recent world-wide improvement of roadway lighting practice for using luminaires advantageously. The night traffic and seeing objectives, shown in Figure 3, form the broad basis for roadway lighting systems which produce pleasant attractive night driving conditions and generate even greater public enthusiasm. There has been increased effort to use the most effective manner. Also now much more information is available (1, 2, 3, 4, 5, 6, 9, 15, 16, 17, 18, 19, 20, 22, 23, 24, 25, 26).

An engineer's recommendations for the layout of a roadway lighting system have been based on his knowledge, experience, and desire to achieve at least a certain minimum in visibility and visual comfort. He has these seeing objectives in mind which will benefit and are of interest to the motorist. Now, fewer mental interpolations and compromises are necessary.

The lighting installation must serve the fundamental purpose of public benefit—evaluated in public benefit terms of visibility and visual comfort. Improvements in practice have been:

1. Use of seeing factor visual criteria.
2. Provision of transition lighting.
3. Better system geometry.
4. Recipe-type recommended layouts.
5. Clarification of A.S.A. practice.
6. Adequate vs less-than-adequate.

Use of Seeing Factor Visual Criteria.—With public benefit in mind, one of several statements in the 1953 A.S.A. Practice for Street and Highway Lighting (9) can now be implemented. For example:

> Proper distribution of the light from luminaires is one of the essential factors in efficient roadway lighting. The light emanating from the luminaires is directionally controlled and proportioned in accordance with the requirements for seeing and visibility described in Appendix A.

Seeing and visibility data is now more readily available in useful form. The engineer, desiring certain visual comfort and visibility results, based on actual or assumed conditions now considers the following:

1. Luminaire candlepower data along the roadway, tabulated, or plotted, in terms of the driver's eye-level paths, or longitudinal lines along the pavement.
2. Data constants or factors (such as those shown in Fig. 4 and Fig. 6) which when multiplied by luminaire candlepower and/or combined for the proposed roadway lighting system, indicate effectiveness in terms of seeing factors (such as those shown in Fig. 5 and Fig. 7).
3. The characteristics of the system including any desirable variables in visibility criteria such as, pavement, or object, surface reflection of light to provide brightness, luminaire candlepower cutoff; and variables in visual comfort criteria such as, size of luminaires and field brightness.

The methods of presenting and using the requisite data and computing the effectiveness of roadway lighting systems have been outlined in a series of technical papers published by I.T.E., I.E.S., the Highway Research Board, and summarized during 1959 (1-7).

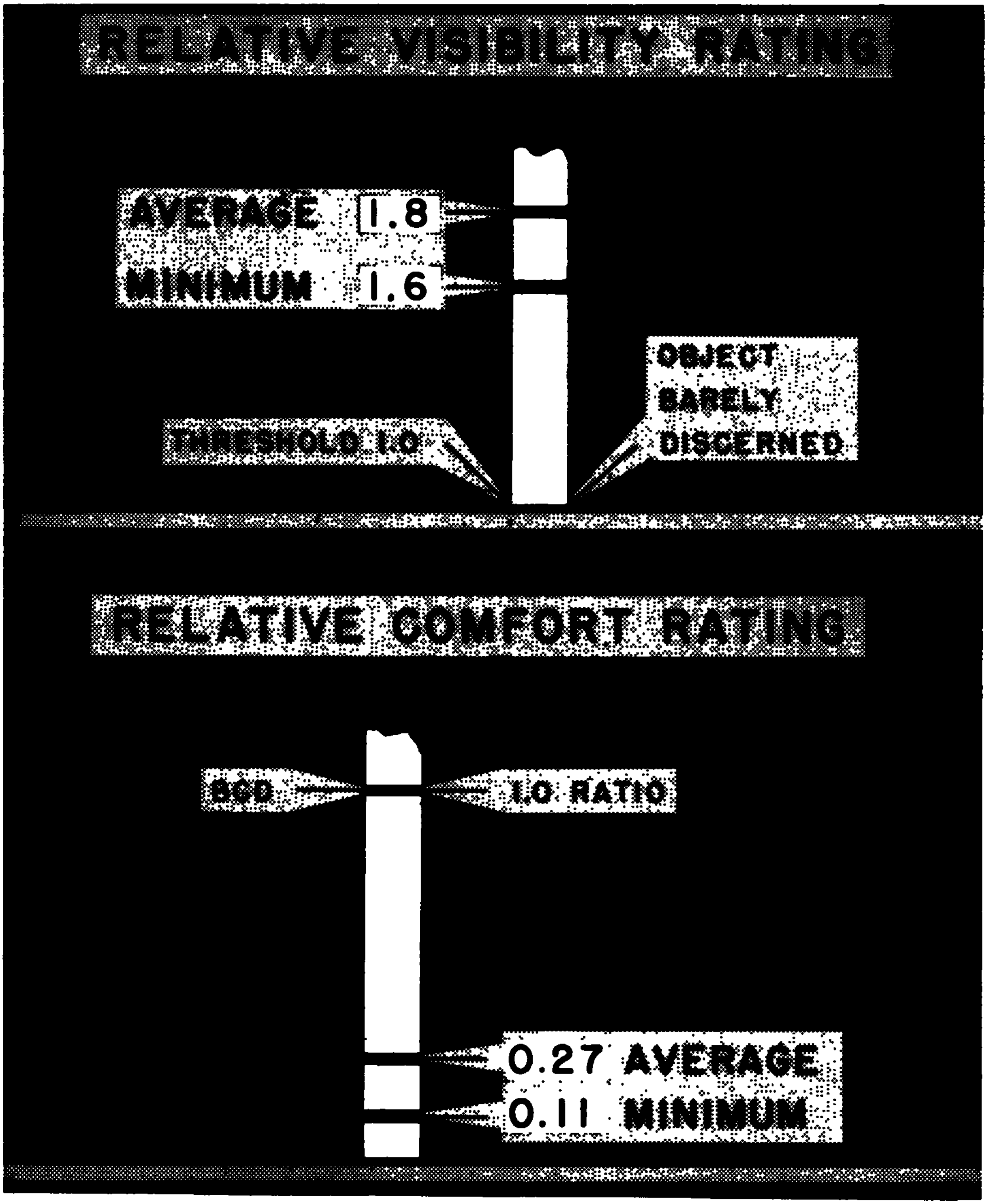

Figure 7. Example of seeing factor ratings for a representative roadway lighting system which provide simplification for the motorist, public officials, and engineers. The minimum ratings are most significant. Visual comfort ratings are relative to the motorist sensation which would be at BCD, the average borderline between comfort and discomfort, for the system of luminaires and the lighted roadway. Visibility ratings are relative to 1.0 threshold, bare discernment, in accordance with the scale of the Low-Range Luckiesh-Moss Visibility Meter

At least one consulting engineering firm (28) is computing visual effectiveness ratings for a client's proposed roadway lighting system. The purpose is to select the most beneficial type of luminaire source combination.

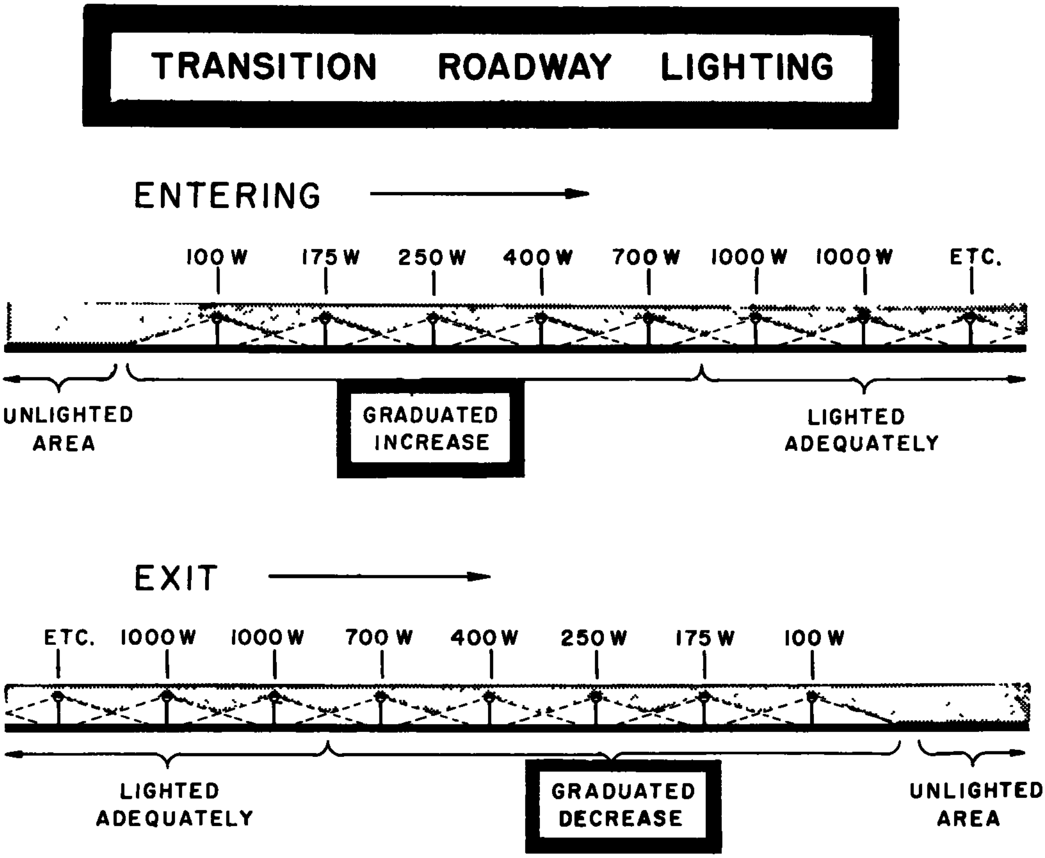

Figure 8. For more pleasant motorist sensation when approaching, entering, or emerging from an adequately lighted system, the lighting may be extended in each approach and exit direction. By using approximately the same spacing and size of luminaire and graduating the size of lamp, the brightness in the driver's field of view is tapered upward or downward for entrance of exit, respectively. The ranges of watt variation shown are now available in mercury lamps.

Provision of Transition Lighting.—The driver sensation when approaching, entering, or emerging from an adequately lighted section of roadway is being carefully considered to make this transition pleasant. Prevailing driving speeds tend to make this change of brightness in the motorist's field of view somewhat abrupt. Gradual build-up and tapering-down the brightness in the driver's field of view may be highly desirable. This may be accomplished by extending the lighting system in each approach and exit direction, approximately the same spacing and size of luminaire, but graduating the size of lamp used.

For example (Fig. 8), if 1,000-watt mercury lamps are being used for the lighted section of roadway, the entering or emerging brightness may be gradually modified by extending the lighted roadway installation to include 5 additional luminaires in each direction. On the approach side of the lighting system, the size of lamps is successively increased. The first luminaire may have 100-watt mercury lamp, the second 175 watt, next 250, then 400, 700, followed up by the 1,000-watt lamp providing the seeing required on the principal or primary portion of the lighting installation. For emerging traffic the lighting is extended with the size of lamps successively reduced from 1,000 watt to 700, 400, 250, 175, and 100 watt in sequence (Fig. 8).

Now the aforementioned flexibility in size of mercury lamps is available; also, the relamping of the different sizes of lamps is now an occasion which occurs infrequently. The replacement time intervals may be longer than two years. Special attention to transition lighting is definitely preferable to providing less than adequate visibility over the principal portion of an entire roadway lighting installation, merely for the purpose of obtaining transition conditions which might be considered to be more pleasant for the motorist.

As the result of studies extending over several years, the Connecticut State Highway Department (29) has adopted recommendations calling for "a lower intensity of illumination in advance of and beyond each complete section of illumination...required to provide for the initial adaptation or accommodation of the eye from darkness to light and from light to darkness. It is generally considered that ten seconds for initial eye adaptation is adequate." Connecticut prescribed 1,000-ft lengths in each direction for rural areas, and 900- and 750-ft lengths for residential and commercial areas, respectively. In addition, "Areas on the main line (state highways) between illuminated

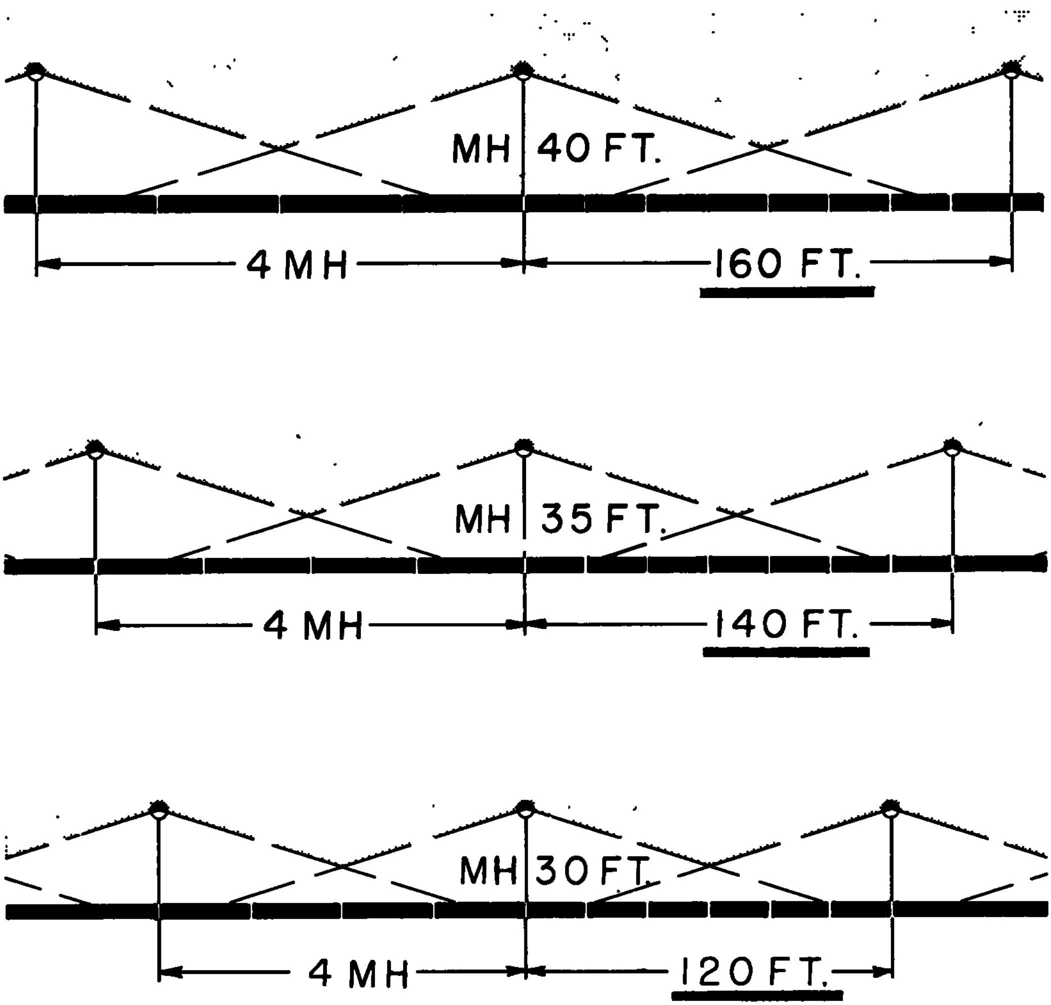

Figure 9. The trend toward higher mounting heights increases the longitudinal spacing distance between luminaires yet maintains the spacing ratio essential for good visual comfort and visibility. There are numerous 35-ft mounting height installations in the United States. Continental European roadway lighting practice includes an increasing number of installations with luminaire mounting heights of 40 ft or higher.

sections may be lighted if such darkness gaps fall within 60 seconds of travel time."

Better System Geometry.—There have been significant improvements in the geometry of roadway lighting systems, particularly with respect to luminaire mounting height, also including the longitudinal and transverse spacing between luminaires and overhang with respect to the edge of the traffic-used pavement. There are numerous installations where the luminaire mounting height is 35 ft, and the trend toward higher mounting heights is increasing rapidly.

One of many advantages of higher mounting is that the principles for good seeing shown in Figure 4 and Figure 6 may be adhered to with an increase in the longitudinal spacing distance between luminaires. For example (Fig. 9), 4 MH luminaire spacing is obviously changed in distance from 120 ft to 140 ft with a change of MH from 30 to 35 ft. Similarly 40-ft MH means an increase to spacing of 160 ft. This means fewer poles per mile of lighted roadway. Larger lamps with good control of the transverse width of candlepower distribution are often desirable to accompany higher mounting heights.

European roadway lighting practice continues to include an increasing number of installations with luminaire mounting height at 40 ft or higher (23, 24, 26, 30).

Recipe-Type Recommended Layouts.—Luminaire manufacturers, individually and as an industry group, now provide recommended layouts for roadway lighting systems in general. Some manufacturers also supply "recipes" for representative combinations of roadway conditions based on the use of a specific type of luminaire and lamp combination. Assumptions are made, which should be stated, regarding dirt accumulation on the luminaire, as well as the depreciation in lamp light output by the time of lamp replacement.

In providing such "recipes," the manufacturer gives serious consideration to the public benefit which will be assured at any time in terms of the seeing factors, visibility, and visual comfort.

Demonstrations of full-scale roadway lighting installations (16) now provide seeing aids for those who desire to visually appraise the effectiveness of "recipes" in providing comfort and visibility. Added value is obtained from such demonstrations when appraisal is implemented by means of standardized targets to be seen quickly, with certainty, and the observers are supplied with meters to measure and rate the relative seeing effectiveness provided by different systems. In Europe (23) this implementation-of-seeing-demonstration-technique has met with outstanding approval and resulted in the adoption of more advantageous lighting for night use of their roadways.

Clarification of A.S.A. Practice.—The 1953 American Standard Practice for Street and Highway Lighting can be misinterpreted as establishing objective goals which are only to be met or equaled. Instead, the real purpose of this publication was to present data regarding minimums, or not-less-than, base requirements which were a representation of practice in the United States current as of 1952, or seven years ago. Such recommendations are to be exceeded to the extent warranted and practicable. In the meantime, interest in encouraging pleasant night motor vehicle transportation has produced considerable progress in general understanding and use of information and data on the motorist and methods for rating and providing the requisite seeing. This paper and the References attached are an indication of progress since 1953. The following excerpts regarding American Standard should be understood:

> An American Standard implies a consensus of those substantially concerned with its scope and provisions...An American Standard is intended as a guide to aid the manufacturer, the consumer, and the general public...American Standards are subject to periodic review. They are reaffirmed or revised to meet changing economic conditions and technological progress.

During July 1959 the Illuminating Engineering Society published (I.E., p. 451) a Resolution of Intent, adopted by its Committee on Roadway Lighting and prepared by a Subcommittee on Interpretation of the American Standard Practice. This Resolution includes the following:

1. "Considerable confusion exists in the interpretation..."

2. "Proper consideration of luminaire and lamp depreciation during operation." The joint opinion of the Chairman of the Roadway Lighting Committee and the Chairman of the Subcommittee on Interpretation is that the foregoing means "when the illuminating source is at its lowest output in service and when the luminaire is in its dirtiest condition."

3. "That the illumination value recommended for limited access highways be expanded to consider such highways in urban areas as heavily traveled streets with no pedestrian traffic and that interchanges on such highways in such areas be treated in as near the same manner as surface street intersections in the matter of illumination."

According to the joint opinion of the Chairman of the Roadway Lighting Committee and the Chairman of the Subcommittee on Interpretation, this means that "in urban areas the average illumination on lighted limited access highways should be:

a. Between interchanges, 0.8 footcandle. This corresponds to the Heavy Vehicular traffic classification in Table 1 and Table 4 when pedestrian traffic is Light or None.

b. On interchange roadways, at least equal to the sum of the illumination values recommended for the two best lighted roadways approaching or entering the interchange."

Adequate vs Less-Than-Adequate.—The seeing effectiveness of roadway lighting systems may vary over a wide range. How much visibility and how much visual comfort may be considered as adequate depends on the public benefit desired, expected, or essential in terms of night motor vehicle transportation.

Evaluation of traffic benefit and other significant objectives will help determine:

1. The comparative importance of the seeing factors, visual comfort, and visibility.

2. The rating which each major seeing factor must have in order that adequacy may be assumed with reasonable assurance.

Current studies here and abroad will help firm-up estimates and recommendations. Continental European design and installation practice is establishing visual comfort as highly essential.

Unless roadway lighting is installed, its visibility benefit is not available. Visual comfort benefit helps get the lighting installed; helps make night driving pleasant and attractive so that the installation is backed by motorist approval and enthusiasm.

In order that public or traffic benefit be appraised and correlated with the visual effectiveness of the roadway lighting on which the evaluation is based, relative ratings are essential for the seeing factors such as visibility and visual comfort. If the roadway lighting has visual ratings which are inadequate, the traffic benefit produced can be expected to be less than the traffic benefit produced by lighting having good visual ratings.

The ratings for quality and quantity of seeing prescribed for new roadway lighting installations should include an estimated allowance, or safety factor, for the expected human capability of typical night drivers. Safety factors are customary in the layout and design of roadways. Seeing is a basic requirement for driving at night as well as during daylight hours.

It is also obviously a good practice to install roadway lighting which provides visual effectiveness ratings on the plus side of adequacy rather than borderline, or less-than-adequate.

On June 19, 1959, it was suggested to the I.E.S. Committee on Roadway Lighting that objectives be studied and that serious consideration be given to presentation of recommendations in terms of:

1. Minimum relative visibility and relative visual comfort ratings.

2. Pavement brightness, one of the principal factors in visibility, under roadway lighting conditions.

3. The minimum at any sizeable traffic-used position on the roadway as well as the minimum at any time, maintained in service.

4. Footcandles.

Minimum Relative Visibility and Relative Visual Comfort Ratings. For public night use of heavy traffic, high-speed highways were somewhat higher than those shown in Figure 7.

Pavement Brightness. A minimum of 0.6 footlambert was suggested. Appendix A and Appendix B show that the 0.6 number happens to be in line with the pavement brightness numbers recommended by the Netherlands (23, 31) and Great Britain (24). Neither of these two countries recommend footcandles. The Netherlands allow a 3:1 "ratio of the average brightness to any minimum in the road picture."

The use of pavement brightness criteria (instead of footcandles) is a definite, significant forward step toward visibility ratings. Generally the conventional types of candlepower distributions and roadway lighting systems which are effective in producing pavement brightness are also efficient in producing obstacle brightness, depending on object reflectance.

A glance at the left and right sides of Figure 5 shows that other control criteria are also essential for visibility and visual comfort. The Netherlands do recommend cutoff of the luminaire candlepower distributions.

The Suggestion for Minimum at Any Sizeable Traffic-Used Position on the Roadway. For the purpose of simplification, a single rating number instead of dual is used. Using the latter, a "minimum recommended average" is prescribed and then this number is supplemented with another ratio number stating that at some positions on the roadway the brightness (or footcandles) may be $1/10$, or $1/4$, or $1/3$ the average. The actual minimum at any position is seldom known.

The seeing task should be seen at any position on the roadway. Discernment usually involves contrasts such as that of an object compared with the brightness of a sizeable adjacent pavement area. The areas can be expressed in visual solid angle at the driver-observer's eyes, or vertical and lateral angles or dimensions.

When certain visibility or visual comfort or brightness is essential, the roadway lighting system should provide it. If in accomplishment of the requisite a surplus is provided at other driver or object locations that should be all to the good, subject only to the efficiency economy requirements of the system. The minimum rating at any position is the most significant and logical criterion.

Footcandles. It should be thoroughly understood that comparison of two roadway lighting systems on the basis of footcandles is limited to instances when other circumstances are identical with respect to: (a) luminaire candlepower distribution extending along the roadway; (b) system geometry including luminaire spacing, mounting height, and overhang; and (c) pavement surface characteristics in reflecting incident light.

In his discussion of a paper published in May 1959, R.E. Ballard, engineer for the Connecticut Light and Power Company, recently phrased his opinion of footcandles very succinctly: "The use of footcandles as a measure of quality of illumination has long been recognized as a ridiculously outmoded crutch. Roadway lighting is intended to produce comfortable optimum visibility and there is not necessarily any relationship between footcandles and visibility as such."

Now that ratings for roadway lighting systems can be readily provided in terms of relative visibility and relative visual comfort, the engineer can transmit to others the seeing effectiveness which he has in mind, and avoid the confusion and complex mental interpolations with respect to benefit derived when footcandle data is used.

Ratings for Evaluation of the Visual Seeing Effectiveness of Roadway Lighting Systems

Seeing factor ratings for the effectiveness of roadway lighting, essential as a basis for progress in the evaluation of public benefit or traffic benefit, are being used here and abroad. To report topically:

1. Visual comfort, visibility, and factor ratings.
2. New requisite visibility-brightness studies by H.R. Blackwell.
3. Additional comprehensive evaluations are desirable.

Visual Comfort, Visibility, and Factor Ratings.—Ratings in use may be commented on as follows:

1. Computed rating method and data available.
2. Outdoor laboratory evaluation of visual comfort.
3. European ratings and studies.

Computed Rating Method and Data Available. Reported in (2) and (4). Provides a method of rating roadway lighting systems in terms of the seeing factors shown in Figure 5. For an example, combination of system conditions, the representative relative visibility, and relative visual comfort ratings are as shown in Figure 7.

The ratings for other existing or proposed roadway lighting systems may be readily computed. In addition to minimum (or overage if desired), relative visual comfort and relative visibility ratings for other factors may be computed; such as, pavement brightness (4), obstacle brightness, disability veiling brightness (DVB) with resultant visibility loss, luminaire brightness, etc.

Conversion constants (15), curves (4), and even nomographs (2, 4) are available for use with photometric luminaire candlepower data along representative longitudinal roadway lines (driver paths, etc.) (5, 6, 7). The extent by which specific rather than generally representative installation conditions are assumed depends on the precision required. Interpolative estimates based on ratings for other similar roadway lighting systems will evolve from use of seeing factor ratings.

Computation has many advantages including:

a. Predetermination or ratings for the effectiveness of proposed or existing roadway lighting systems is provided in readily understandable terms of roadway user benefit.

b. Installation practice luminaire performance variables may be explored, evaluated, and controlled in design for optimum over-all efficiency.

c. Comprehension of objectives will be improved, complexity reduced, and standardization possibilities revealed.

d. An ascending numerical scale is provided for visual comfort whereby improvement is accompanied by a higher number.

e. Progress in dynamic visual research under night driving conditions will be encouraged by a method for the use of laboratory and field data now available and that which will be made available in the future.

f. Time will be conserved. Computation facilitates ratings without the delays, uncertainties, and interference that may arise in field testing. The use of high-speed computer techniques is obviously feasible and desirable. With example ratings available, other ratings may be estimated by interpolative judgment.

The possible effect of new instrumentation in providing a larger scale range of numbers for relative visibility will be discussed under "Blackwell's Studies."

Technical paper presentation of the foregoing ratings and methods resulted in encouraging comments, such as:

> Joseph Barnett, Deputy Assistant Commissioner for Engineering, U. S. Bureau of Public Roads (June 12, 1959): Based on what you already have accomplished toward the evaluation of highway lighting in the form of relative visibility and visual comfort ratings, I am sure that in the future you will be able to make further improvements toward the rating of seeing effectiveness.

> T. W. Forbes, Assistant Director for Research, Highway Traffic Safety Center, Michigan State University: This paper is of much interest and importance in that it shows how factor ratings may be derived not only for the various factors in relative visibility but also for the comfort factors relating to glare. Veiling brightness has been widely recognized as of great importance because of its interference with visibility. The factor of discomfort has also been measured, but perhaps has not been thought of quite as much importance.

From the human factor and safety points of view, the comfort factor may be of as much importance as visibility. Reduced visibility from veiling glare, from spotty pavement brightness and all the other factors which have been so carefully analyzed are of primary importance, but visual factors leading to fatigue are also of major importance in the seeing task. Drowsiness may be induced by factors causing visual fatigue, or if present from previous lack of sleep, discomfort glare may enhance drowsiness and result in complete eye closure (32). The paper...suggests a method by which these various factors may be put together, including this highly important comfort factor, to produce a relative rating for roadway lighting...

But whether or not other and better methods of deriving such a rating are developed, the importance of such an undertaking seems very evident...demonstrating a procedure by which this may be done, thus laying the groundwork for further development.

Also it may be that with the increasing availability of electronic computers further developments along the line suggested will furnish a set of badly needed data for the mathematical simulation both of vehicle operation and separately of traffic flow under night driving conditions. Such simulation is being developed and when achieved will represent a scientific breakthrough which will facilitate highway and safety research of all sorts. For accurate simulation of night driving conditions as well as for valid rating of roadway lighting, combination of the different visibility and visual comfort factors into ratings of a mathematical type will be basic.

Charles W. Prisk, U. S. Bureau of Public Roads, and Director of the Highway Safety Study (June 12, 1959): I have only had time to examine the papers briefly, but I do feel that working toward the measurement of the relative seeing effectiveness of various systems is desirable.

Outdoor Laboratory Evaluation of Visual Comfort. Conducted at Hendersonville, N. C. Results reported at the I. E. S. National Technical Conference, on September 10, 1959, indicate that test data on visual comfort is consistent with computed (2, 4) relative visual comfort ratings. This conclusion is reached after two years of outdoor full-scale testing of a typical roadway lighting system using an evaluator developed on request by S. K. Guth (33, 34).

The selection of observer (3) data produced by the extensive outdoor studies was based on an indoor BCD "population study" conducted by J. S. Franklin in the Photometric Laboratory at Hendersonville. The latter data is in agreement with previous studies (35, 36). Figure 8 shows an observer making an outdoor relative visual comfort evaluation. The lighting-roadway system being observed is shown in Figure 9.

The Guth evaluator may be used to demonstrate and provide better understanding of the fundamentals involved in improving relative visual comfort. A driver-observer, sitting in an automobile, readily adjusts the brightness of the flashing comparison source to the BCD, borderline sensation between comfort and discomfort. By changing the lighting, the driver can observe and readily appreciate the fact that the BCD brightness for a roadway lighting system increases with appreciably higher field brightness, including the brightness of the pavement background against which the flashing comparison source is being viewed.

An increase in field brightness (including pavement) improves the relative visual comfort ratio unless accompanied by a corresponding increase in the combined brightness of the system luminaires. The latter may be increased within the limits of the relative comfort ratio without decreasing the relative visual comfort. The evaluator demonstrates that progress involves higher brightness at or near the pavement level with lower brightness up at the luminaire mountings.

Wilbur S. Smith, Consulting Engineer, has offered a discussion of the IES paper, which in addition to stating the fact that "comfort is a principal objective in all highway transportation," also includes the following excerpts:

> Certainly, highway officials and others are in dire need of a better means of objectively determining the optimum amount and type of lighting given for surface and traffic conditions. It is the desire of highway engineers to utilize roadway lighting as a means of improving traffic services and safety on major highways; yet, they do not have a method of evaluating different types of lighting and lighting installation by generally approved and accepted methods.
>
> ...Better means of objectively measuring highway lighting systems would probably be one of the most effective means of encouraging and justifying the more widespread use of highway lighting on expressways and other major highway facilities.

European Ratings and Studies. At the C.I.E. International Commission on Illumination, quadrennial meeting held at Brussels, Belgium, during June 1959, several reports (23, 24) were presented showing how their accelerated progress has brought about adoption of visibility and visual comfort criteria. An extensive full-scale demonstration of different roadway lighting systems, near Brussels, afforded the delegates visual proof that an effective and pleasant lighting installation combines adequate pavement brightness with a low cutoff of candlepower distribution.

More recently at Hendersonville, also at the I.E.S. Technical Conference, L. Gaymard (30), Street Lighting Chief Engineer for Electricite de France, reported on the widespread public enthusiasm for the continental European roadway lighting practice of low cutoff luminaire, 40-ft mounting heights and moderate spacings.

In addition to previous references to European practice and studies:

a. Much of continental European practice is based on extensive studies conducted on a full-scale outdoor laboratory provided by the Philips Company at Eindhoven, Netherlands.

b. Relative visual comfort (their terminology is discomfort glare) is evaluated in terms of pavement brightness, such as: "the average luminance (brightness) of the road surface necessary to reduce the discomfort glare to a satisfactory degree." This is similar to the preceding conclusion (2) regarding studies at Hendersonville using the Guth evaluator.

c. The visibility studies by de Boer and associates have been based on: "25 actual installations as well as in the outdoor laboratory. For test objects in these experiments Landolt-rings were used having a diameter of 0.16 M and a reflection factor of 9 percent."

These dimensions and reflectance values are quite similar to those of the target used in the computation (2, 4) of relative visibility. The dynamics of observers traveling along the test roadway in automobiles was included in the de Boer visibility studies.

d. Waldram's report for the International Committee on Street Lighting says: "In the U.S.A. the importance of luminance (brightness) is becoming recognized and the possibility of specifying it has been discussed."

e. The British Ministry of Transport has done considerable work on studies of pavement reflection characteristics and some studies of traffic operations, particularly from the standpoint of night accident prevention. They have been quoted as saying that United States accident data is not comparable in detail and engineering analysis with similar work that has been done in Britain.

The foregoing and the detailed reports of diligent accelerated foreign work on roadway lighting should be seriously considered by people in the United States, who are interested in, or affected by, night motor vehicle transportation.

New Requisite Visibility-Brightness Studies by H.R. Blackwell.—H.R. Blackwell and associates (Messrs. B.S. Pritchard, R. Schwab, D.F. Fisher, and J.G. Omhart) of the Institute for Research in Vision at Ohio State University have a very high quality scientific interest in contributing to the effectiveness of roadway lighting. At the September 1959 I.E.S. Technical Conference the Blackwell-Pritchard team presented an informal (22) paper reporting their preliminary studies of requisite roadway lighting. These studies were initiated during April 1958 and are expected to continue during 1960.

Blackwell's work on roadway lighting is being sponsored by the Illuminating Engineering Research Institute at the request of the IES Committee on Roadway Lighting. He has developed a system for evaluating the requisite brightness for seeing various objects on the roadway when the driver has a time interval of one-fifth second for perception under dynamic moving eye conditions. It is expected that a new scale of relative visibility and the visibility ratings required for representative night driving conditions is likely to be available during 1960.

The Blackwell studies use a new instrument called the Visual Task Evaluator (21) developed jointly by Blackwell and Pritchard.

It is hoped that the requisite level of brightness, and visibility which evolves from Blackwell's studies may be accompanied by a method for rating, relatively, the effectiveness of other lighting. The requisite level of visibility may be established as a datum or reference for comparison of less or more effective methods of producing visibility. Specific roadway lighting systems will provide visibility effectiveness which is higher or lower relative to the datum or requisite level.

Thus, relative-to-requisite ratings would be useful as a measure of how good lighting may be for visibility effectiveness. It is also hoped that the requisite level of relative visibility which evolves from the Blackwell roadway lighting studies can be correlated with the scale of the Luckiesh-Moss visibility meter which is relative to threshold or bare discernment.

It is obviously desirable to have and use a single number rating for net relative visibility instead of using two ratings, such as the factors: pavement brightness, and the percent visibility loss due to disability veiling brightness.

Additional Comprehensive Evaluations Are Desirable.—There are many indications as to the need for comprehensive evaluations of roadway lighting, including those pointed up by the Armed Forces, N.R.C. Committee on Vision (37), and the HRB Night Visibility Committee (38) as well as the Highway Safety Study.

Dynamics is a typical night driving condition involving high-speed movement of both the object to be seen and the driver-observer. The actual effect of dynamics on night visibility with or without roadway lighting should at least be estimated and included for rating purposes.

Fatigue, tension, preoccupation of the driver's attention and sense capacity with tasks other than seeing, typical of night driving with or without good roadway lighting, should be at least estimated. It is hoped that the $800,000 Harvard Medical Research project (39) on causes of accidents will provide some answers. Also the G.S.R. driver tension and similar studies by the U.S. Bureau of Public Roads might well be extended to include night driving conditions including good roadway lighting.

Factors involved (4, 22) in ratings for roadway lighting effectiveness should be measured, evaluated, interrelated, and conclusions published for general use. Relatively simple examples are percent loss of visibility due to typical fluctuations of DVB, full-scale measurements of pavement brightness, and reflection characteristics of representative pavement surfaces, evaluation of the effect of transitional brightness-adaptation, etc.

Instrumentation Recently Developed for Field Measurement of Seeing and Traffic Factors

New instruments for field measurement of the seeing factors in roadway lighting have been developed in the United States. These measurement devices should be put to use to provide additional data on the visual effectiveness of roadway lighting.

Action programs may involve measurements of existing roadway lighting installation, outdoor laboratory studies, and indoor simulator studies. Foreign instrumentation available for evaluation of roadway lighting should be investigated. Any that are adaptable to U.S. studies of roadway lighting effectiveness should be used even if the purpose involves only the correlations essential for an International Code or Recommended Practice for Roadway Lighting.

Recent United States developments include:

1. Pritchard brightness meter.

2. Fry-Pritchard meter for disability veiling brightness, (DVB).
3. Blackwell-Pritchard visual task evaluator (V.T.E.).
4. Finch visibility meter.
5. Comparison of visibility measurement systems.
6. Guth evaluator for rating the relative visual comfort of roadway lighting systems.
7. U.S. Bureau of Public Roads instrumentation for operations and driver response.

Pritchard Brightness Meter.—B.S. Pritchard has recently developed and made available an instrument which is suitable for the brightness measurement of small areas corresponding to the size of objects and surfaces when several hundred feet ahead of the driver-observer. This meter has the additional advantage of a physical scale reading, which does not require photometric balance by an experienced observer.

This instrument is being used for outdoor measurements (22) of the pavement brightness or object brightness factors in visibility, or discernment (as listed in Fig. 5), and described in Appendix A of A.S.A. Practice (9).

Fry-Pritchard Meter for Disability Veiling Brightness (DVB).—The DVB, or disability veiling brightness of roadway lighting systems, may now be integrated and measured using a new instrument developed by Fry (41) and Pritchard. Their work has been sponsored by the Illuminating Engineering Society Research Institute. Mounted at the driver's eye position in an automobile, the combined brightness in the field of view at successive driver positions in a lighting system may be readily measured by a physical scale reading similar to that of the aforementioned meter for pavement brightness.

Instrumentation or computation is essential for this purpose. The reduction in visibility due to DVB may be described as you-don't-see-as-well-as-you-think-you-do. Correlations should be provided in addition to those presented in previous papers (2, 4, 5, 6, 7, 14, 15). This percent loss data should include at least an estimate of the increase in loss resulting from the fluctuation due to the driver's movement along the roadway at representative speeds. As mentioned in the papers, the data used included an estimate by Reid-Chanon for 25-40 mph vehicle speeds.

Field brightness or the combined integrated brightness in the driver's field of view (2, 3, 4, 35, 36) should be measured for relative comfort evaluations (Fig. 5) using the basic instrumentation described under "Pritchard Brightness Meter" and "Fry-Pritchard Meter for DVB."

Blackwell-Pritchard Visual Task Evaluator (V.T.E.).—Crouch, Secretary of the Illuminating Engineering Research Institute, described (43) this instrument now being used for studies of requisite roadway lighting effectiveness (22) as follows:

> The Visual Task Evaluator is a portable piece of equipment built around a complex optical system. It is the function of the equipment to equate the visibility of a practical task to the visibility of a circular target for which illumination requirements have been established through research.
>
> To accomplish this, the practical object to be seen is placed within the instrument's view. The instrument is then adjusted so that the most important detail of the task object is at threshold—or just barely visible. Without changing the setting of the instrument, the image of the practical object is replaced by the image of a circular target, also reduced to threshold.

Finch Visibility Meter.—D.M. Finch of the University of California and the Institute for Traffic and Transportation at Berkeley has developed a readily portable visibility meter (40) which combines several features. This instrumentation has not been made available for use by others. However, one of the components used in the Blackwell V.T.E. resulted from the Finch meter development.

Comparison of Visibility-Measurement Systems.—It is obviously desirable to evaluate and correlate the features and/or data obtained using visibility meters available here and abroad. At the 1959 I.E.S. Technical Conference, Arthur A. Eastman and Sylvester K. Guth presented a paper (44) comparing the results obtained with the Luckiesh-Moss visibility meter (42) with data based on use of the V.T.E.

Correlations such as this should be extended to include roadway lighting visibility conditions and relative ratings pertaining thereto.

Guth Evaluator for Rating the Relative Visual Comfort of Roadway Lighting Systems.—The evaluator developed by S.K. Guth and J.B. McNelis is an aid to outdoor full-scale rating of effectiveness of roadway lighting systems in terms of relative visual comfort (2-4). Uses of the evaluator are shown in Figure 6 and Figure 7. This device is also valuable for indoor studies (33) and evaluation of simulated conditions (3).

The visual comfort rating is relative to the motorist-observer sensation which would be at BCD, the borderline between comfort and discomfort for the lighted roadway. The evaluator BCD brightness, $\bar{B}_L$, is on the observer's line of sight and excludes the combined brightness of the system luminaires. The brightness comparison providing the evaluator rating at each motorist-observer viewing position is:

$$\text{Evaluator Ratio at each position} = \frac{\bar{B}_L}{B_L}$$

in which $\bar{B}_L$ is the brightness of a source on the observer's line of sight which is at BCD sensation brightness with respect to the lighted roadway background excluding luminaires (fL) and B_L is the brightness of a comparison source on observer's line of sight which produces sensation equivalent to the combined brightness of the system of luminaires (fL).

This evaluator may be used to demonstrate and provide better understanding of the fundamentals involved for improvement of relative visual comfort ratings for roadway lighting systems. This may include an appreciable increase in pavement brightness.

U.S. Bureau of Public Roads Instrumentation for Traffic Operations and Driver Response.—The U.S. Bureau of Public Roads are congratulated for their development of the mobile Traffic Analyzer which records traffic operation field data in digital form. Also the GSR (galvanic skin reflex) meter is being used for measuring driver tension responses.

It is expected that these new instruments will be put to more extensive use in the immediate future. Such other instrumentation as may be required should be developed during 1960. The measurement of night traffic and human-driver factors is highly significant in evaluating the effectiveness of seeing factor improvement as produced by good roadway lighting.

SUMMARY

Although some significant progress in roadway lighting developments is being made, it should be readily apparent that much more data accumulated and presented at a greatly accelerated pace is now essential. All those interested in, or affected by, night motor vehicle transportation should be vigorously initiating and supporting evaluations of the benefits of roadway lighting. The potential improvement in public welfare is an impelling obligation.

The night traffic benefits should be obvious; yet might well be further documented by engineering estimates, appraisals, and measurements where practicable. Ratings for night traffic benefit can now be based on seeing benefit ratings for the roadway lighting involved. Correlation of night traffic ratings with relative visibility and relative visual comfort ratings for the effectiveness of roadway lighting will indicate how good the lighting must be for the desired public benefit.

Visual benefit ratings will also implement attention to the technological details by which the seeing effectiveness of roadway lighting will be improved in the future. Additional visual data, studies, and presentations of knowledge are imperative.

Action by many people is urgent. Interest in accomplishment for improvement in night motor vehicle transportation is widespread in the United States and abroad. Freedom to drive at night with assurance, pleasure, and efficiency involves objectives which warrant the combined use of the best research, talent, facilities, and engineering skills.

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EXCERPTS FROM NETHERLANDS' RECOMMENDATIONS ON PUBLIC LIGHTING—MAY 1959

TABLE 2.1. Recommended values of road surface brightness and its irregularity

Road or Street		Average road surface brightness in cd/m²	(in) (footlamberts)	Highest permissible irregularity in the brightness pattern, expressed as the ratio of the greatest to the least brightness on any line across the road as well as the ratio of the average brightness to any minimum in the road picture. Ratio
Roads for fast traffic	Outside built-up area:			
	Road reserved for motor traffic	2	(0.6)	3
	Trunk road	1.5	(0.45)	4
	Important main road	1	(0.3)	4
	Inside built-up area:			
	Main thoroughfare	2	(0.6)	3
	Access road (Arterial road)	2	(0.6)	3
Street in industrial or dock area		1	(0.3)	5
Quay, wharve lock or bridge over important waterway		1	(0.3)	5
Shopping street with road traffic		1	(0.3)	5
Shopping street without important traffic		0.75	(0.22)	8
Residential street with road traffic		0.75	(0.22)	6
Residential street without important traffic		0.5	(0.15)	10
Fashionable square or promenade		0.5 to 2	(0.15 to 0.6)	-

"Cutoff luminaires, either low angle or medium angle, are generally used in the Netherlands."
(Note: Material in parenthesis added by C. H. Rex to put in terminology used in U. S. A.)

Appendix B

(FROM REPORT OF PROGRESS IN STREET LIGHTING 1955-1958, BY J.M. WALDRAM, CHAIRMAN COMMITTEE W-3.3.1 C.I.E. INTERNATIONAL COMMISSION ON ILLUMINATION)

"The following table indicates the ranges of mean illumination and mean luminance adopted in the various codes under review . . . . . . Nearly all codes pay special attention to glare, which is regarded as a particularly important blemish upon an installation, and in most cases advocate some form of cut-off lighting."

Table I

Country	Mean Illumination		Mean Luminance (Brightness)	
	Lux	lm/ft²	cd/m²	ft. L.
Finland	3-9 (mod. Pedestr. traffic)	0.3-0.9	0.3-0.85	0.09-0.25
France	2.30 (on dark surfaces)	0.15-1.5	Not less than 0.5-0.15	
Germany	0.5-16 or 20 (on dark surfaces)	0.05-1.6 or 2	0.03-1 or 1.3 (calculated)	0.01-0.3 or 0.4
Gr. Britain				0.2-0.7
Netherlands			0.5-1 or 2	0.16-0.31 or 0.6
Spain	0.5-0.8 to 9-12 (5 classes)	05-.08		
Sweden	3.7-5.1; max. 10	0.37-0.5; max. 1	0.35-0.5, max. 1 (calculated)	0.11-0.15, max. 0.3
Switzerland	Not less than 6	Not less than 0.6		
	Min. Illumination			
U.S.S.R.	0.2-6	0.02-0.6		

Explanatory notes inserted by Charles Rex:

(Luminance is our photometric brightness as we apply it to the brightness of pavement and objects.

"Not less than 0.5-0.15 footlamberts" as pertaining to the Code of Public Lighting for France should be of interest in revising our U.S.A. Recommended (ASA) Practice.

Suggest consideration of the phrase "not less than" instead of minimum, at any position on the traffic-used roadway and minimum in service at any time, etc.)

Appendix C

EXCERPTS FROM "THE FEDERAL ROLE IN HIGHWAY SAFETY," A REPORT SUBMITTED TO THE 86th CONGRESS, 1st SESSION, FEB. 27, 1959, by Lewis L. Strauss, U.S. Sec'y of Commerce

(House Document No. 93, available from Sup't of Documents, U.S. Government Printing Office, Washington 25, D. C., price - 60 cents)

This reports results of the Highway Safety Study conducted under the direction of Charles W. Prisk, U.S. Bureau of Public Roads.

P. 3 " . . . . new knowledge in highway construction is benefiting safety."

P. 4 "Modern design practices can also bring permanent gains in safety."

P. 5 " . . . , the most hazardous period in cities and rural areas alike is during the hours of 2 to 4 a.m. when the effects of natural fatigue, intoxication, and drowsiness are compounded by the lack of light. Nationwide, the fatal accident rate in these early morning hours is substantitally above that of the most of the other dark hours throughout the night and is at least six times that of the more favorable daylight hours."

P. 6 "Cost of traffic accidents

(a) Total cost.--The total cost of traffic accidents, including property damage, wage loss, medical expense, and the overhead cost of insurance, is estimated at up to 1 cent per mile of travel, an approximate equivalent of 12.5 cents on each gallon of gasoline consumed for highway purposes. The total economic loss to the Nation is estimated by the National Safety Council at $5.4 billion for 1958. Other estimates are higher.

(b) Direct cost.--An intensive study in one State disclosed that direct out-of-pocket cost is 0.43 cent per vehicle-mile. Especially conspicuous among the major findings from this study reported is the division of the direct-accident-cost dollar ($0.05/gal. gas): 40 cents is incurred for property-damage accidents, 57 cents for injury accidents, and 3 cents for fatal accidents. While human loss through fatal accidents cannot be adequately measured in cold terms of dollars and cents, the fact that fatal accidents account for but 3 percent of the total direct economic loss clearly shows that consideration of the total accident problem should not become obscured by attention to this aspect."

P. 8 " . . . . The nature and proportions of the highway safety research need are such that the required work cannot be readily undertaken and supported by private interests, universities, or to more than a limited extent by the States and cities."

P. 9 " The Board should coordinate all official Federal traffic-safety programs and all research activities of the Federal Government in the field of traffic safety. It should seek the advice of State and local highway and traffic officials in carrying out its responsibilities and should encourage the application of the results of research in the safety programs of State and local agencies by cooperation directly with those agencies or through their official organizations . . . . "

P. 29 "Most presentations on the cause of the highway accidents assign responsibility for 9 out of 10 accidents to the driver . . . "

"This assignment may have some value in the promotion of safety consciousness, but it is of doubtful validity in any broad study of the traffic-accident problem. If responsibility for cause is interpreted to mean any amount of contribution, then the driver becomes 100 per cent involved since obviously no action takes place on the highway except of his instigation. . . . . . "

"Thus the driver is often believed to be the principal medium for the improvement of highway safety and yet there is less critical knowledge about him than is known about either of the other two elements. It has been stated that vast sums have been spent on vehicle development, and that highway research though less than adequate has been impressive, but that the real gap in our knowledge is in the understanding of human factors."

P. 30 ". . . . Thus, there is a very fundamental interrelation between driving and the driver, and the ways in which the demands of the task are adapted to the characteristics of the human being will be a determinant of the safety and efficiency with which the highway-transportation system will function. It is, therefore, very artificial to view the human factors as something distinct and independent of the system in which they must operate."

"In contrast to the effort expended on such things as reaction time and eye tests, relatively little experimental research has been done on the more fundamental factors of perception, judgment, analysis, decisionmaking, etc. . . . . . ."

P. 31 "Thus, it is well known that the human being has definite limits in the amount of information he can utilize per unit of time. . . In all of these areas of fundamental importance to highway safety, little research has been carried out. It does seem apparent, however, that the very nature of the driving task often forces the driver to the very limits of his capacities, thereby increasing the possibility of accident - producing responses."

". . . . In long-distance driving, loss of vigilance may become an important factor in driving errors. "

"Fatigue is also a common consequence of extended durations of driving, and may contribute as much as monotone to loss of vigilance. Fatigue has not been clearly defined, especially with reference to highway safety, but it usually
P. 32 refers to the decrement in performance due to depletion of energy reserves--either physiological, psychological, or muscular. . . . . ."

". . . . Although little work has been done on automobile drivers, skill fatigue may be a fundamental contributor to accidents."

P. 52 "The investment involved in the planning, design, and construction of a highway dictates that it serve traffic for a substantial period of time. The highway itself is the one permanent structure of highway safety, working 24 hours a day every day in every year to fulfill its public-service function. Obviously, this has both advantages and disadvantages. The highway hazards that are built in, without sufficient regard for human engineering principles, endure in their effect as persistently as do the features that improve safety. . . . . ."

P. 53 ". . . . but because the States recognize that these standards are based on the results of extensive research and sound engineering judgment gained through long years of experience."

"These new standards are the nurtured product of long experience and research, including countless observations and analyses of traffic performance and driver behavior, key factors in safe highway design."

P. 55 "Comfort, convenience, and safety are considerations of importance equal to a consideration of capacity, in today's highway planning. This concept of adequate facilities requires modern techniques for handling traffic with clear unmistakable signing, marking, and other controls so that all highway facilities, old and new alike, will function properly. . . . "

P. 64 "STREET and HIGHWAY LIGHTING"

"The use of street lighting is a widely accepted practice in urban areas, especially where traffic congestion and pedestrian movements are heavy. Non-traffic benefits are also readily appreciated. These include a sense of public comfort and convenience and the deterrence of crime."

"Comparative studies in numberous cities have shown that urban lighting tends to produce highway safety gains. Often the comparisons have been limited by a lack of scientific controls and by the fact that the lighting was installed as a part of a larger improvement program. Considering all advantages to the driver and the other social advantages, it can be concluded that modern street lighting, adequately designed and operated, does improve safety in most city situations. By present standards, many urban street-lighting systems are outdated, inadequate, and poorly designed. Modernization programs are active, and the progress is geared principally to the availability of funds, as well as to the relative importance attached to street lighting as against that of other public works."

"The continuous lighting of rural highways has not been undertaken on an extensive scale since no substantial facts are available to show that the cost is justified. Lighting for a specific purpose and usually at specific locations is more common and has proved definitely beneficial to safety. Typical advantages cited include the identification for the motorist of critical roadway features farther ahead, minimization of headlight glare, and improved driver judgment of speed and direction of travel of other vehicles."

"Lighting of rural highways has not been as generally accepted as for city conditions because the benefit-cost ratio has not been established to be as high as that of other needed improvements. In this connection, more intensive studies are warranted to understand better the safety effects and economics of rural highway lighting. A recently opened freeway, continuously lighted over a substantial mileage, has furnished the first opportunity for such research. The Bureau of Public Roads has initiated appropriate cooperative studies with State authorities

P. 72 . . . An accident involvement, very simply, is one driver or one vehicle involved in one accident. The accident involvement rate, then is the number of involvements that occur for every 100 million miles of highway travel . . . . . . "

P. 75 Note Figure 7.

P. 79 Note Figure 10.

P. 80 Note Figure 11.

P. 81 "It is significant that passenger cars had a nighttime involvement rate nearly three times as great as their daytime rate . . . . . "

P. 84 " . . . Enthusiasts for highway illumination often ascribe the difference chiefly to darkness, per se, but this is a misleading oversimplification . . . . "

"Fatigue, intoxication, higher speeds of travel, and other factors probably all contribute to the extremely high fatal-accident rate during the hours shortly after midnight, although darkness presumably compounds some of these difficulties for nighttime drivers. Only carefully planned research can determine and measure the contribution of the factors involved and point the way toward night accident reductions."

P. 85 Note Figure 15. (P. 84-"Figure 15 presents evidence based on travel miles of exposure and suggests that additional factors are involved."

P. 93 "... To fulfill the primary aims of the study looking toward identification of bona fide accident causes, wholly new techniques for scaling and isolating the basic variables must be developed or adopted. Thus, the intensive investigation of accidents is being expanded to include development of measures and criteria for a new series of factors. As an example, driver vision is customarily measured by a static test, which has not reliable association with the visual demands upon a driver or object in motion at the time of accident. Means need to be found for improved measures of dynamic visual acuity, of meaningful components of the perceptual fields, and of the driving process."

P. 108 "Vision problems... Dynamic visual ability has been identified as having special significance for safe driving."

"....Similar research on lighting of highways, bridges, and tunnels, and other light adaption problems has been or is being conducted by the Bureau of Public Roads in cooperation with State Highway Departments and others as a means of developing adequate policies for the facilities new in construction."

P. 114 "Other work planned, --In addition to current research in highway safety, the Bureau of Public Roads is considering plans for new research aimed toward selected areas where more knowledge is critierically needed. Proposed projects include investigation of monotone and fatigue problems in expressway driving, more intensive analysis of the driving process, application of human engineering principles to highway design and operation, improved units for accident exposure, development of more complete and accurate accident reporting, and improved means for communication from the highway to the driver and among drivers."

P. 169-171 Note participation of Automotive Safety Foundation.

P. 173 Note questions.

P. 198 Note in "Table I--Classification of elements characterizing the accident process

1. Road situation: Physical environment within which the man and vehicle operate.
   Factors and their operation
   Stable - #3. The lighting on road in terms of such factors as appropriateness, intensity, color, and patterning.
   Variable-#2 Visibility as influenced by night and day cycles.

Excerpted by Charles H. Rex - 5/27/59

Vision at Levels of Night Road Illumination

V. Literature 1959

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For a number of years, literature on vision with information applicable to the problems of night driving seeing has been reviewed (55). This paper continues the project and endeavors to cover material on vision of interest to the Night Visibility Committee. A considerable part of the Atlanta Symposium was published (4). Current knowledge on vision is included in the new Handbook of Physiology (21), Gebhard's review (29), and the chapters on dark adaptation of (12). Colored light signals is a current CIE report (6).

MOTORIST'S VISION

Both Porter (51) and Nisemboim (46) have described requirements of motorist's vision for safe driving, including the American Optometric Association material. A series of papers by Platt (50) gives an operations analysis of the driving situation and Forbes (23) summarizes and emphasizes the psychological factors concerned in driving. Platt's contribution is too lengthy for ready review. Forbes calls attention to the time necessary for seeing and reacting to visual stimuli, that judgment may be more important than speed, and the importance of appropriate responses to hazards. The relation of optimal stimulation efficiency is discussed by Lauer (43). The use of alcohol was reported to be a significant factor in some one-vehicle accidents (34).

Proposed Canadian driving standards would require 20/30 vision for both eyes with or without glasses and 120-deg fields for drivers of heavy transport vehicles of 3 ton or more. For light vehicles of less than 3 tons, 20/30 in one eye, 20/60 or better in the other and the same field is recommended. For private vehicles, 20/40 in one eye and better than 20/200 for the other eye are the limits proposed. When one eye is not better than 20/60, the person should be limited to daylight driving. With a one-eye deficiency the use of a mirror should be required on the deficient side (58). A survey in Australia (3) discovered that 31 percent of the drivers failed one or more tests; the major deficiencies were: inadequate acuity in one eye (15 percent), both eyes (8 percent), inadequate dark adaptation (9 percent). They estimate that 0.3 to 0.6 percent of a large cross-section of people cannot be corrected to 6/12 (20/40) in the better eye. Less than 20/20 vision is uneconomical for taxi drivers (57). This may point the way toward higher standards for motorist's vision.

In Iowa, the basic information (beam candlepower of the headlights, the reflection factors of view or luminance, atmospheric conditions, glare effects, and the visual acuity of the driver) have been used to establish night driving speed limits, and these limits have been tested and supported by the Iowa Supreme Court (61). This is a good example of the integrated use of vision data.

ILLUMINATION

Night luminance levels for summer and winter terrain with varying degrees of moonlight and starlight are brought together (Cibula, 15). A series of papers by Finch (22) and his associates (14, 30) describe a measuring instrument and the importance of the brightness factor (the ratio of the foot-candles in the direction to the foot-candles normal to the surface), which may be different from the reflection factor, ρ, when specular and diffuse reflection are not directly involved. The importance of controlling contrast by properly adding light is stressed and charts are given to show how light can be added to improve contrast. Tinker (63) questions the use of threshold measurement data for the formulation of specifications for illumination. Dreyer (18) presents information on just perceptible and just imperceptible stimuli. His results seem to depend on a decrease in sensitivity of the area stimulated being greater than the slower rise in sensitivity that follows a corresponding stimulus, of luminance less than that of the background.

GLARE

The report of Fry's committee of the Illuminating Engineering Society gives formulas for the specification of glare, a nomogram, and discussion of the calculation of glare with respect to comfort and discomfort (27).

Guth and McNelis (33) describe their glare evaluater and Hopkinson and Bradley (37) have formulated a scale for the magnitude of the glare sensation. Glare discomfort is stated to be equal to a constant times the source brightness raised to the 1.23 power. Luminance changes in retinal acuity, by Johnsen et al., show significant effects of glare on adaptation (40). Unfortunately, the levels used in the experiment did not extend into the night driving range; such work could be useful.

Highway lighting is a subject of lively disagreement, judging from the discussion following Fowle and Kaercher's (26) endeavor to set theoretical bases and Waldbauer's (64, 65) discussion on glare-free lighting. Some of the difficulties depend on seeing distance defined as the perception of an object of given size and contrast, or to include "...be detected in order to take proper action to deal with it" (26). Either method should be useful provided it is made clear which is being considered. When one uses reaction-seeing distances, these then have to be large enough to permit the required action at that time for the actual condition of the roadway. It would seem preferable to use perception seeing distances and weight these as required when driver response is also involved. Rex (54) proposes a method for the analysis of roadway lighting in terms of relative visibility and disability from veiling brightnesses.

VISION

Too little attention is being given to problems of the total time involved between the appearance of some object and the necessary action for safe driving. Some of these responses take time, and a high-speed vehicle may cover considerable distance during the interval. The problems of evasive action are far less with automobile driving than flying of superspeed airplanes, though some of the data from the latter are of use in highway problems. Stereo threshold times indicate that aviators can start an evasive action in about 2.5 sec (Diamond, 17). Similar conditions may be involved when passing vehicles on the highway. The stereoscopic threshold increases with increased illumination and shows a break at the rod-cone transition and unequal illumination of the eyes causes variation in depth perception (44).

When steadily viewing an object, the accommodative focusing mechanism of the eye shows short fluctuations from 0 to 0.5 cycles per second, and with large pupils other fluctuations near 2 cycles per second. When the eye is viewing an empty field, the higher frequency components diminish and lower frequency components increase (Campbell, 13).

Ocular movements of 15 to 90 deg were studied by Hyde (38). Short saccade movements tend to overshoot and long saccades tend to undershoot the target. With 30-deg movements, inward movements of the eyes to the primary position are faster than outward movements. With long eye movements, the rate speeds up and then slows down. There are more corrective movements at the primary point (straight ahead view) than from more peripheral targets. The information on time factors is useful. Small eye movements cover from the center of the highway to a sign on the shoulder. Longer movements are required when looking down approaching roads. Moving the eyes continuously over large areas is desirable, but also takes time.

Goodson and Miller (31) report that dynamic visual acuity begins to deteriorate with eye movements of 20 deg per second, though not appreciably until eye movements of 30 deg per second are reached. Measurements made in the air proved similar to those made in the laboratory. The rate of decrease in acuity was linear for two targets, but curvilinear for one target. Deceleration has a marked effect on the performance, both from the change in speed and the change in configuration of targets. The placement of signs along the highway should be such that the eye does not have to move more rapidly than 20 deg per second for the time needed to perceive what the sign says.

The decrease of acuity as the image falls away from the very center of the fovea, is shown again to fall off rapidly in the first 5 deg. Held (36) has combined a study of acuity from center to periphery together with the effect of blurring the acuity with positive lenses. There is a slight improvement from the blur from a +0.50 diopter lens. A slightly out of focus image can aid resolution.

The easier seeing of small objects aligned at 90 and 180 deg to the horizontal is explained by Weymouth (66) in that rays from the images add in these directions, but not at oblique directions (45 and 135 deg). Amblyopic and some defective eyes seem to work better with lower intensities than with high intensities and this may be a fortunate compensation which should be kept in mind in establishing the ability of such an individual to drive (47). A similar finding, and also that the proper spacing of letters markedly improves vision, is reported by Prince (52). Contrast is important in visual search (42). The incorporation of some of this information in the design of signs might improve legibility. Eastman's new chart for testing astigmatism is proving useful (9).

The response of the pupil of the eye to changed illumination is stimulated by both rods and cones, although the cones were a more efficient stimulus (1). The pupil response is greater with photopic than with scotopic vision (45). Studies on dark adaptation by Baker et al. (7) and Sweeney (62) indicate a rise in the threshold before adaptation progresses, and that up to two log units the energy in the test flash does not affect dark adaptation significantly. Neural factors may be concerned in monocular dark adaptation (8).

In experiments with flickering light, and also in some conditions of photometric measurement, Kelley (41) has found that the edge enhancement behavior, where the observer response is mainly to the edge gradient while the experimentor is controlling only a large area of luminance, is important. Peckham (48, 49) finds a time summation in critical flicker fusion. Analysis of averages and normal curve fits shows that there is a 25:1 decrease in retinal sensitivity with old (51-80) as compared with younger (32-50) eyes. This is another measure of senility that needs further analysis. Projector (53) gives formulas for comparing the efficiency of flashing and steady lights and Ives (39) discusses visual signals of short duration. Alternating flicker duration studies are reported (24).

A case of night myopia is presented by Fulthorpe wherein the night myopia was mainly due to the spherical abberation accompanying large pupils (28). Space myopia is an active topic (20) altho probably not a factor in motoring.

Visibility from automobiles is more restricted as manufacturers reduce the height of the cars. Both Sutro (60) and Fosberry (25) discuss problems of design with respect to vision. This information should be helpful to the designer of automobiles. Motorists dependent on glasses for vision, especially truck drivers, are urged to carry a spare so that they can still see in case of damage to their spectacles (5).

COLOR

The Council of Industrial Health, American Medical Association, has again opposed tinted glasses and windshields for night driving (2). "The use of any 'night-driving' lens or windshields, whether tinted, reflecting, or polarizing, reduces the light transmitted to the eye, and renders the task of seeing at night more difficult. The source of glare in night driving is the contrast between the headlights of oncoming cars and the darker surroundings. The use of tinted lenses or windshields does not reduce the contrast but reduces the intensity of illumination from both the headlights and the surroundings, thereby impairing vision. There is no scientific evidence to support any claim that the use of tinted lenses or windshields improves night vision." Yellow glasses reduce recovery time after glare by about 12 percent and the seeing time in the presence of glare about 29 percent according to Davey (16).

Recent proposals for tinting highways with various colors and for use of fluorescent color markings for night driving suggest careful study as to the effect these will have in seeing after dark. Heath and Schmidt (35) have examined color recognition by those with defective color vision. The recognition of colors is improved when both white and red are seen in the same field of view. They report that bluish-green tends to be called green, and yellowish-green tends to be called red. In general, the limits for signals proposed by Judd were approved. Breckenridge (10) has given a check list of the conditions affecting the probability that a signal light will be recognized, and discusses color signal standards. An international report on colors of light signals is available (6).

From a study of low contrast, Ronchi (56) proposes that for perception of low contrast, it is essential that one should eliminate with suitable filters either the blue or the green, as the presence of both blue and green impairs the perception of contrast at low luminances. This may be another factor contributing to the difficulty of seeing at dusk. Noise, according to Grognot and Perdriel (32), of 100 decibels decreases the size of visual fields and color perception, although not producing visual acuity.

With regard to Land's recent contributions to color vision, Wolfson (67) indicates that Land's observations are explainable by color constancy and gives computations to show compatability with the Young-Helmholtz theroy. Brown (11) calls attention to the Fechner colors obtained from black and white pictures.

RESEARCH

A considerable amount of money is granted to the Division of Optometry of Indiana University to (1) determine the visual demands of night driving, (2) for determination, measurement and appraisal of normal and abnormal skills and responses which relate to these demands, (3) for the derivation of reliable tests and instruments, and (4) for the publication of the results (19).

At the Chicago 3rd Annual Conference on Motorist's Vision (unpublished) the following topics were proposed for research: task analysis and time motion study, correlation with the total time the attribute of driving is used in actual driving, dynamic side visual acuity, the intercorrelation of tests of acuity (Snellen-Orthorater, etc.), an efficient test for acuity against glare, and coordination of the research people with those who must apply the results on the highway. Most of these suggestions were made by B.H. Fox.

A preliminary report of the California Research Project (59) suggests that drivers with good vision outdrive their seeing, those with normal lateral vision have fewer signal violations, drivers with better side vision are more involved with speeding and less for not stopping at thruways, those with better vision on the right side have fewer accidents and other interesting correlations. The completion of the project should provide much interesting material on motorist's vision.

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