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Foreword

The magnitude of the problem of driving—and seeing—safely at night is emphasized by the fact that death rates under nighttime conditions are substantially more than similar daytime rates. In urban areas, night death rates are almost three times day rates, while in rural areas, such night rates exceed day rates by two and a half times. Obviously, the special hazards of nighttime driving need extensive research, and application of such research where appropriate. The Committee on Night Visibility of the Highway Research Board for two decades has been focusing its attention on the research aspects of nighttime driving. Particular research findings as portrayed by recent papers are presented in this RECORD.

In the first paper, a California researcher reports a study of the correlation between poor vision and driving record. The research also presents the role of other variables such as sex, age, and annual mileage driven. The study also gives some practical applications of the findings to the screening of driver-license applicants.

Two Indiana researchers studied the effect of color of clothing, reflectorization, and driver intoxication on the visibility of a pedestrian at night. Since 20 percent of traffic deaths occur to pedestrians, and risk at night is several times that of daytime, the study is significant in revealing some dimensions of the problem.

A West Virginia and a California researcher have teamed up to develop a laboratory method of determining pavement reflectance and the third paper presents their study. The method of determining directional reflectance characteristics of pavement surfaces is described and data developed for a traffic-worn asphaltic pavement surface are presented. To design lighting systems properly, reflectance values are needed.

In the fourth paper, two Texas professors report on their study of roadway lighting systems. Various configurations of lighting systems were studied by photometric means. It was found that an increase in mounting heights and in longitudinal spacing between assemblies tended to increase uniformity of illumination over a wide range of values. If these preliminary conclusions are confirmed by more experimentation, significantly different lighting configurations may result.

The last two papers, both by four Michigan researchers, present substantive findings of their extensive research on sign visibility. The first study was concerned with measuring the effects of sign size and brightness and the effect of competing signs. Using simulation and experimental procedures, it was found that visibility of signs is enhanced by greater sign brightness, size, contrast, and letter-to-sign brightness. The other of these two papers is concerned with color and brightness facts used in laboratory simulation which were compared to a real life situation. A possible method of applying the experimental results to the estimating of sign visibility in actual traffic engineering situations is suggested.

Those concerned with the manufacture, design and maintenance of signs and lighting apparatus will find the material in this RECORD of extreme importance. Those interested in the problems of seeing at night will realize that significant new knowledge has been added. Those interested in aspects such as driver improvement and reduction of nighttime accidents will find considerable value in these papers. Highway department and government agency personnel responsible for pavement design, traffic devices, highway operations, and lighting should be able to reap valuable benefits from this research.

Contents

Vision and Driving: A Summary of Research Findings

ALBERT BURG, Institute of Transportation and Traffic Engineering, University of California, Los Angeles

To provide driver licensing adminstrators with heretofore unavailable information on which to establish effective vision-screening procedures for driver license applicants, a number of visual performance, personal, and driving habit characteristics of some 17, 500 volunteer California driver license applicants were compared with their 3-year driving records (accidents and convictions). The vision tests included those for dynamic visual acuity, static visual acuity, field of vision, lateral phoria, low-illumination vision, glare recovery, and sighting dominance. Of these, dynamic visual acuity was most closely and consistently correlated with driving record, followed by static acuity, field of vision, and glare recovery. All relationships were in the "expected" direction, i.e., poor vision was associated with poor record. As expected, among all variables studied, age, sex, and average annual mileage play the largest role in influencing driving record. Accident and conviction frequencies increase with increasing mileage, are lower for females than for males, and are highest for the young age groups. Accident and conviction rates per 100, 000 vehicle-miles decrease slightly with increasing mileage, are approximately the same for both sexes, and are highest for young drivers, followed by older drivers, with middle-age drivers having the lowest rates. The report gives recommendations for additional research and suggests practical applications of the present findings.

•IT HAS always been assumed, and logically so, that vision plays an important role in the driving task. While this assumption has been traditionally and universally accepted, and has been used by driver licensing agencies as the basis for incorporating one or more vision tests in their procedures for evaluating driver license applicants, there has been, in fact, no definitive experimental evidence relating visual ability to driving ability.

As was pointed out in a detailed survey (1), despite a reasonably large amount of published literature on vision in relation to driving, relatively little substantial research has been done and few, if any, basic relationships have been established. Attempts to determine such basic relationships have been largely unsuccessful for a variety of reasons, including the following:

1. Vision is only one of the many factors influencing driving performance, and thus it is extremely difficult to demonstrate a close relationship between a given vision characteristic and a measure of driving performance, such as number of accidents;
2. There may be a considerable disparity between the visual capabilities of the individual and the degree to which these capabilities are utilized in driving;
3. The tests used in the research may measure visual characteristics that are not closely related to the visual functions utilized in driving;

Paper sponsored by Committee on Road User Characteristics and presented at the 47th Annual Meeting.

4. The reliability of the specific vision test(s) and/or of the measure of driving performance (e.g., number of accidents) used may be low; and
5. The research study may have had methodological shortcomings, such as an unrepresentative sample of the driving population or lack of control over the many relevant variables (such as exposure).

Responsible officials have long felt the need for accurate and reliable information in this area, to permit establishing more effective procedures for screening driver license applicants on the basis of their visual abilities. Accordingly, early in 1962 the Institute of Transportation and Traffic Engineering, in conjunction with the California Department of Motor Vehicles, began a large-scale, long-range study of the relationship between visual ability as measured on several standard and nonstandard screening tests and driving performance as reflected in driving record.

The first phase of this study, comparing visual performance with 3-year driving records, has been completed, and the major findings are summarized in the present paper. The second phase, currently under way, involves:

1. Retesting a number of the original subjects, after a period of 2 to 3 years, to determine whether an appreciable change in visual performance occurs over this relatively short period of time;
2. Accumulating driver record information over a 6-year period, to provide a more valid and reliable measure of driving performance; and
3. In-depth analysis of the massive amount of data accumulated in the study, to evaluate such things as the relationship between specific types of accidents and specific types and degrees of visual degradation.

METHOD OF RESEARCH

The general sequence followed in the study was as follows:

1. Volunteers were solicited from among driver license applicants at DMV field offices throughout California.
2. Visual performance was measured, and personal and driving information (e.g., type and quantity of driving) obtained for these volunteer test subjects. (In addition, limited personal information was obtained about "non-test subjects," i.e., applicants who declined to volunteer for the study, to permit a check on the representativeness of the test subject sample.)
3. The information thus obtained was forwarded to DMV headquarters in Sacramento, where the immediately preceding 3-year driving record was examined for each test subject and non-test subject.
4. Whenever possible, each test subject's insurance record was located and examined, to provide a more complete picture of his driving record.
5. All accumulated information was coded and placed on IBM cards (and subsequently on magnetic tape) for computer analysis.

The vision tests utilized in the study measured the following aspects of visual performance:

1. Dynamic visual acuity (DVA)—the ability to perceive details of an object when there is relative motion between the observer and the object;
2. Static visual acuity—the ability of the observer to perceive details of a stationary object;
3. Lateral visual field—the extent of the observer's side vision when he is looking straight ahead;
4. Lateral phoria—the "aim" of the eyes in the horizontal plane, i.e., the degree of crosseyedness (esophoria) or walleyedness (exophoria);
5. Low-illumination vision—the amount of illumination required to perceive an object (also referred to as glarimeter threshold);
6. Glare recovery—the length of time required to perceive an object after having been subjected to glare; and

7. Eyedness, or sighting dominance—the individual's preferred eye, similar in concept to his hand preference.

The driving record variables studied include accidents incurred over a 36-month period, and convictions for traffic citations incurred over a 36-month period.

In addition, three variables of known influence on vision and/or driving record were controlled for age, sex, and average annual mileage (quantitative exposure).

Because of time considerations, that is, because an unlimited amount of time was not available for testing each driver, selectivity had to be exercised in choosing vision tests for inclusion in the study. As a consequence, only those tests were selected which are easily and quickly administered, and which, based on previous studies, also showed promise for "payoff." For example, "depth perception" and color vision were among those tests not chosen, because a summary of previous research (1) indicated these tests to be least likely to be related to driving performance. On the other hand, because a major visual requirement of the driving task is the perception of objects that are moving, relative to the driver, it was hypothesized that a dynamic test of visual performance, such as DVA, would be more closely related to driving performance than any static test of visual capability. It was on the basis of this hypothesis that the present study was conceived.

Driving record (accidents and convictions) was the inevitable choice as an indicator of driving performance or "driving ability," not only because it is the only indicator readily available, but also because it is the indicator of greatest practical value to the driver licensing administrator. Although driving record is at best an imperfect estimate of driving performance, at present no practical means exist for obtaining a reliable measure of driving performance for the large number of drivers required by this study. A 3-year driving record was chosen for evaluation because this is the length of time that records normally are kept by the California DMV. The use of age, sex and (quantitative) exposure as control variables also was inevitable, since all three have consistently been shown to be related to accident and conviction experience.

Because of the number and complexity of the variables chosen for evaluation, the use of a large sample of drivers was necessary to permit sufficient data for detailed statistical analysis. Consequently, a total of nearly 17, 500 drivers were tested over a 32-month period. These drivers ranged in age from 16 to 92; 62. 8 percent were male and 37. 2 percent female. Static visual acuity ranged from 20/13 to 20/200, corrected (subjects were tested with corrected vision, if they so drove). In addition, some 11, 793 non-test subjects were processed. Analysis of the composition of the test subject group reveals it to be adequately representative of California drivers as described in the 1964 California Driver Record Study (9).

Some 3143 of the subjects were new or out-of-state drivers, and hence had not accumulated a 3-year California driving record at the time the major data analyses to be described were conducted. These "hold subjects" were kept on file, and by mid-1968, 3-year records will have been accumulated for the entire sample of drivers, and the next set of major analyses will be conducted. In addition, some 121 subjects were eliminated from the analysis because for various reasons such as illness or absence from the state they had done little or no driving in California during the 3-year period prior to their vision-testing.

The findings described, therefore, are based on the 14, 215 drivers for whom 3-year records were available at the time of analysis. Table 1 shows the age by sex breakdown of both the total test sample and the analysis sample.

METHOD OF ANALYSIS

The primary statistical technique used to analyze the data was multiple-regression analysis, which is a technique for determining that combination of factors (the "independent" or "predictor" variables) that will optimally predict another factor (the "dependent," "predicted" or "criterion" variable). While the multiple-regression technique is based on known interrelationships among variables, i. e., simple correlation coefficients, unlike the correlation coefficient it permits the assessment of each independent variable's unique contribution in the prediction of the criterion variable. This type of

TABLE 1

DESCRIPTION OF TEST SAMPLE BY AGE AND SEX

Age (years)	Total Test Sample						Test Sample With 3-Year Record					
	Males		Females		Total		Males		Females		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Under 20	1185	10.81	736	11.30	1921	10.99	457	5.13	286	5.39	743	5.23
20-24	1388	12.66	780	11.98	2168	12.41	974	10.93	526	9.91	1500	10.55
25-29	1164	10.62	668	10.26	1832	10.48	896	10.06	529	9.97	1425	10.02
30-34	1124	10.25	633	9.72	1757	10.05	937	10.52	527	9.93	1464	10.30
35-39	1120	10.22	700	10.75	1820	10.41	993	11.15	618	11.65	1611	11.33
40-44	1125	10.26	723	11.10	1848	10.57	1016	11.40	661	12.46	1677	11.80
45-49	941	8.58	646	9.92	1587	9.08	859	9.64	595	11.21	1454	10.23
50-54	861	7.85	582	8.94	1443	8.26	819	9.19	542	10.21	1361	9.57
55-59	641	5.85	381	5.85	1022	5.85	606	6.80	370	6.97	976	6.87
60-64	499	4.55	275	4.22	774	4.43	473	5.31	270	5.09	743	5.23
65-69	410	3.74	216	3.32	626	3.58	393	4.41	212	4.00	605	4.26
70-74	280	2.55	108	1.66	388	2.22	266	2.99	105	1.98	371	2.61
75-79	144	1.31	45	0.69	189	1.08	139	1.56	45	0.85	184	1.29
80 and over	81	0.74	20	0.31	101	0.58	81	0.91	20	0.38	101	0.71
Total	10963	99.99	6513	100.02	17476	99.99	8909	100.00	5306	100.00	14215	100.00

analysis permits utilizing the multiple-predictor approach to the prediction of driving record, an approach which is most practical from the standpoint of driver licensing agencies.

In order to keep the size and complexity of the multiple-regression analyses within reasonable limits, not all of the many study variables were included for evaluation. (These same considerations dictated the use of a linear regression model instead of a curvilinear model, which would probably have been more appropriate.) For example, of the three tests for static visual acuity used in the study, only one (Ortho-Rater) is included in the analyses; similarly, only one of the four dynamic visual acuity target velocities was chosen to represent DVA. The dependent variables used in the regression analyses were (a) binocular Ortho-Rater static visual acuity (O-R); (b) 90°/second dynamic visual acuity (DVA); (c) total lateral visual field (FIELD); (d) lateral phoria (PHORIA); (e) glarimeter threshold (THRESH.); (f) glare recovery (REC.); (g) Age (AGE); (h) average annual mileage (MILEAGE); and (i) sex (M,F).

Separate regression analyses were performed for males and for females for each of two dependent variables: (a) number of convictions in three years (CONV.), and (b) number of DMV accidents in three years (DMV ACC.). Finally, for each dependent variable, the regression analysis was conducted two ways, once with the other dependent variable included as a predictor variable and once without. Thus, eight separate regression equations are under consideration.

In performing these regression analyses, the 14,215 analysis subjects (those with complete 3-year records) were randomly divided into two equal groups, one group for use in developing prediction (multiple-regression) equations, and the other group for use in validating these equations ("cross-validation"). An equation that indicates the relative contribution of each independent variable in predicting a given dependent variable was developed on the first half of the sample and then used to predict or estimate the magnitude of that dependent variable for the subjects in the second half of the sample. The degree to which these estimates correlate with the true values obtained for the second half of the sample is a measure of the predictive validity of the regression equations.

FINDINGS

Due to the massive number and variety of data analyses performed in the course of the study, only a brief summary of the findings can be given here. The reader is referred to the original report (5) for detailed results of the study.

Figures 1 through 12 graphically depict the simple interrelationships between several driving record variables and age and sex. The terms used in these figures are defined as follows:

Convictions—all convictions for traffic citations, regardless of type and regardless of whether connected with an accident, received by the DMV from the courts. A single

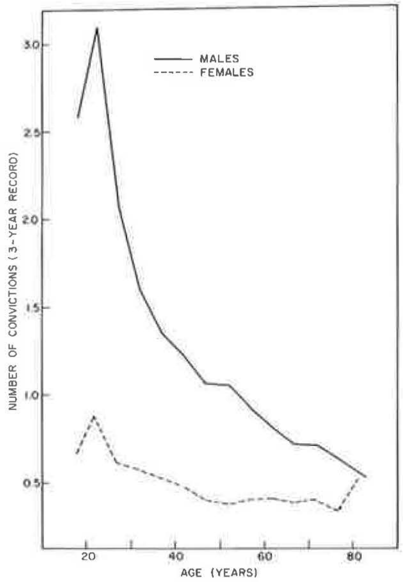

Figure 1. Conviction frequency by age and sex.

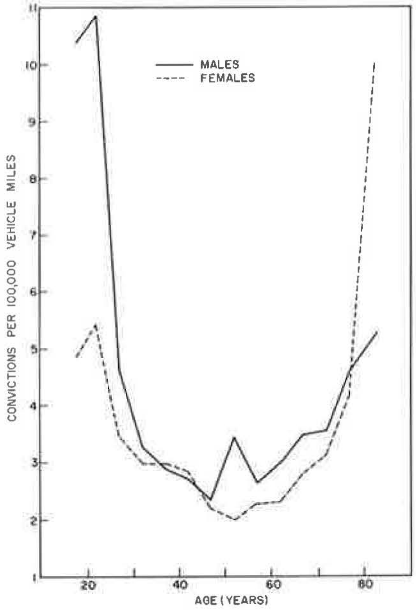

Figure 2. Conviction rate by age and sex.

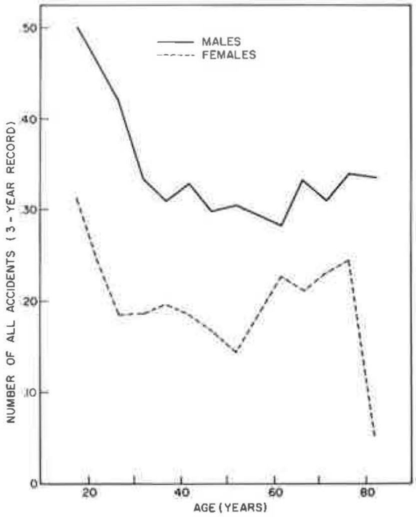

Figure 3. All accident frequency by age and sex.

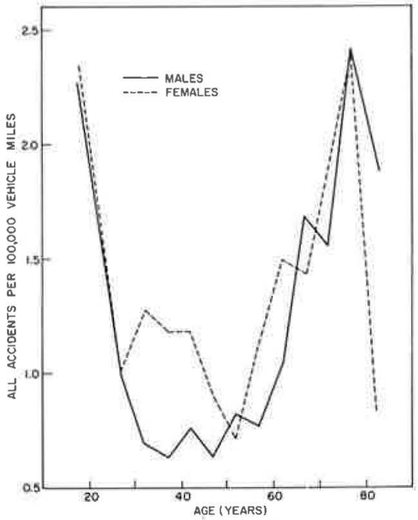

Figure 4. All accident rate by age and sex.

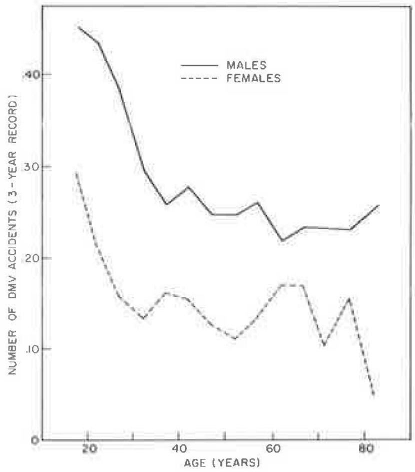

Figure 5. DMV accident frequency by age and sex.

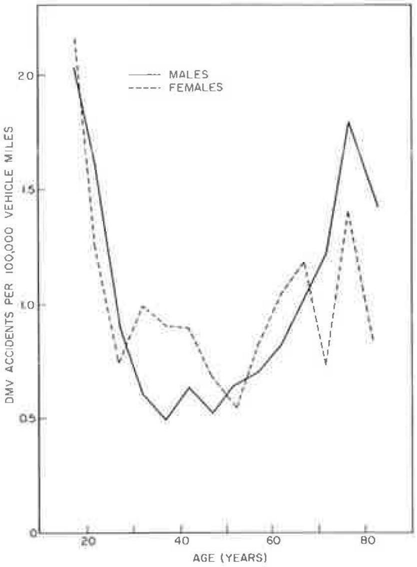

Figure 6. DMV accident rate by age and sex.

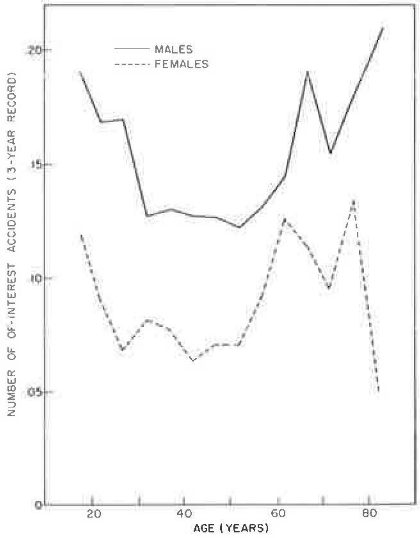

Figure 7. Of-interest accident frequency by age and sex.

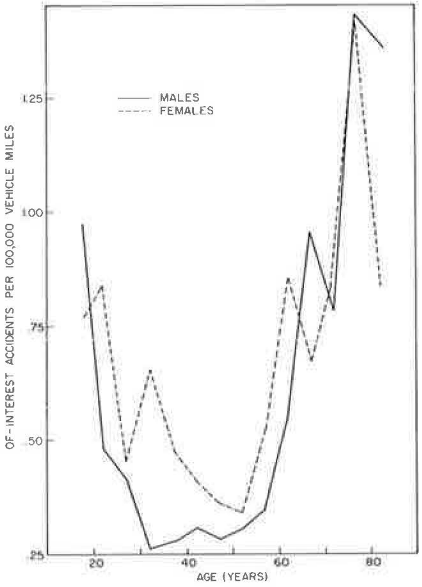

Figure 8. Of-interest accident rate by age and sex.

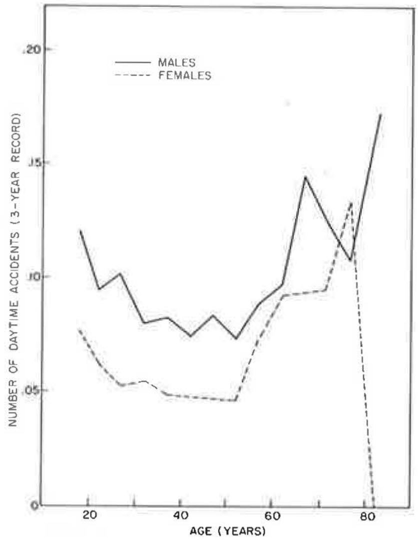

Figure 9. Daytime accident frequency by age and sex.

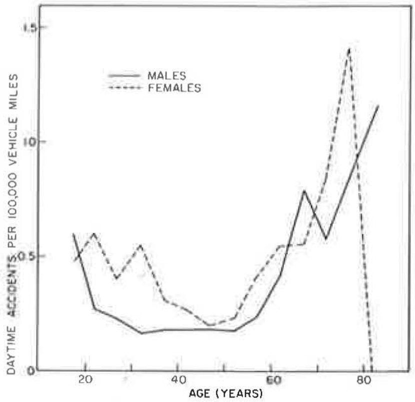

Figure 10. Daytime accident rate by age and sex.

conviction (or citation) may involve more than one violation of the Calfornia Vehicle Code. (No data analysis by type of violation has yet been conducted, although this information is available for each subject.)

All Accidents—all accidents, regardless of type or culpability, on record in DMV and/or insurance files.

DMV Accidents—all accidents, regardless of type or culpability, on record in the DMV files. (This measure includes approximately 85 percent of All Accidents, and is the better measure to use when comparing subject groups since insurance information, which is included in the All Accidents measure, was available for only some 38.4 percent of the analysis sample of 14,215.)

Of-Interest Accidents—all accidents (regardless of culpability and from whatever source) except those types in which vision in all likelihood did not play a part, or those accidents whose type was undeterminable.

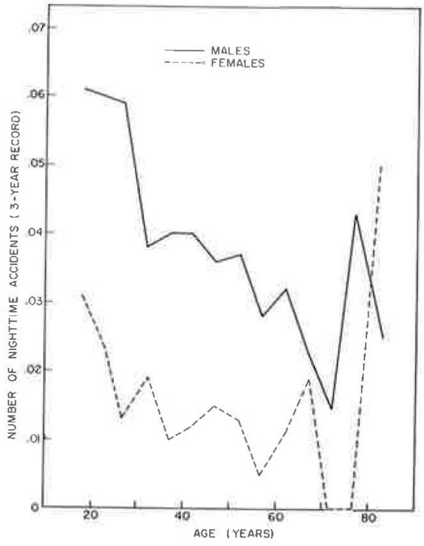

Figure 11. Nighttime accident frequency by age and sex.

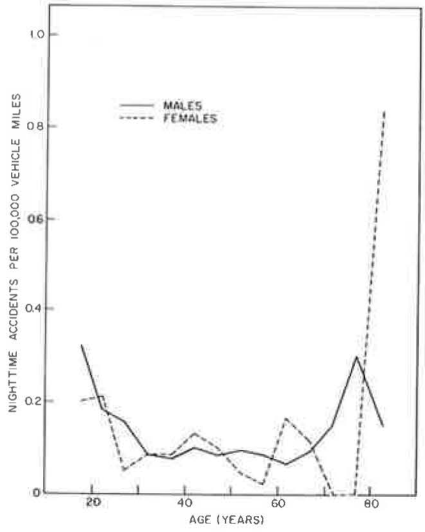

Figure 12. Nighttime accident rate by age and sex.

Daytime Accidents—all of-interest accidents that definitely occurred during daylight hours. (Dawn and dusk accidents are eliminated, and will be studied separately in future analyses.)

Nighttime Accidents—all of-interest accidents that definitely occurred during hours of darkness.

From inspection of the graphs it is obvious that, in general:

1. Young drivers tend to have poor driving records, whether frequency or rate is considered. Older drivers have poor driving records when rate is the consideration, but when frequency alone is considered, older drivers are generally only slightly worse than middle-aged drivers.
2. With regard to sex differences, males have poorer driving records than females in terms of frequency, but not in terms of rate (with the sole exception of conviction rate, for which the female record is slightly, but statistically significantly, better*). As a matter of fact, for all but nighttime accidents, accident rates for females in the middle age groups are significantly worse than those for the corresponding male age groups.
3. The graphs reflect the findings of other data analyses which show that older drivers drive proportionately less at night than do younger drivers, and women drive proportionately less at night than do men.

In addition, among the large number of product-moment correlations computed as part of the regression analyses, the following relationships are of interest (all statistically significant at the 0.05 level or better):

1. DMV accident frequency increases with increasing conviction frequency ($r = 0.292$).
2. DMV accident rate increases with increasing conviction rate ($r = 0.646$).
3. Both DMV accident and conviction frequencies increase with increased average annual mileage ($r = 0.154$ and 0.302, respectively).
4. Both DMV accident and conviction rates decrease slightly with increased average annual mileage ($r = -0.074$ and -0.057, respectively).

With regard to the multiple-regression analyses, space does not permit presenting and discussing the actual regression equations that were developed; however, it is possible to assess the relative contribution of the significant independent variables (i.e., those independent variables whose contributions to the prediction are statistically significant at the 0.10 level) to prediction of the dependent variable by comparing the squared beta coefficients of each variable in each equation. Table 2 presents this information for the eight half-sample equations developed.

Table 3 is a summary that presents, for each of the eight prediction equations, the multiple correlation coefficient (R), the "index of determination" (R^2)**, and the cross-validity coefficient (r). For purposes of comparison, Table 3 also includes the "terminal" multiple correlation coefficient (R_T), which is the R obtained when all of the independent variables listed earlier, regardless of the level of significance of their contributions, are left in the multiple regression equation. All correlation coefficients in Table 3 are significant at the 0.01 level.

Once the prediction equations had been generated on the first half of the subject sample, and validated on the second half, the same regression analyses were performed on the full analysis sample of 14,215 test subjects as a check on the consistency of the data. To provide a comparison with the half-sample data in Table 2, Table 4 shows the

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[*] It has been suggested that this finding may be the consequence of differential enforcement as a function of sex. No definitive information on this point is readily available.

[**] This represents the amount of variation in the predicted (dependent) variable associated with variation in the predictor (independent) variables.

TABLE 2

RELATIVE CONTRIBUTION OF SIGNIFICANT VARIABLES IN MULTIPLE-REGRESSION PREDICTION EQUATIONS (HALF-SAMPLE)
(Cell entry is beta coefficient squared × 100)

Significant Independent Variable	Predicting No. of DMV Accidents				Predicting No. of Convictions			
	Without No. of Conv.		With No. of Conv.		Without No. of DMV Acc.		With No. of DMV Acc.	
	M	F	M	F	M	F	M	F
CONV.			6.686	4.640				
DMV ACC.							4.964	4.440
MILEAGE	1.818	1.086	.604	.442	4.702	2.994	3.489	2.300
AGE	1.346	.785	—	.363	11.835	1.569	10.123	2.781
DVA	.332	—	—	—	1.010	.169	.768	—
O-R	—	.356	—	.312	—	—	—	—
REC.	—	.125	—	—	—	—	—	—

TABLE 3

MULTIPLE CORRELATION AND VALIDITY COEFFICIENTS FOR PREDICTION EQUATIONS (HALF-SAMPLE)

Coefficient	Predicting No. of DMV Accidents				Predicting No. of Convictions			
	Without No. of Conv.		With No. of Conv.		Without No. of DMV Acc.		With No. of DMV Acc.	
	M	F	M	F	M	F	M	F
R	.169	.144	.287	.253	.381	.210	.440	.294
R^2	.028	.021	.082	.064	.145	.044	.193	.087
r	.144	.087	.276	.234	.358	.280	.422	.347
R_T	.171	.148	.290	.256	.382	.214	.441	.297

TABLE 4

RELATIVE CONTRIBUTION OF SIGNIFICANT VARIABLES IN MULTIPLE-REGRESSION EQUATIONS (FULL-SAMPLE)
(Cell entry is beta coefficient squared × 100)

Significant Independent Variable	Predicting No. of DMV Accidents				Predicting No. of Convictions			
	Without No. of Conv.		With No. of Conv.		Without No. of DMV Acc.		With No. of DMV Acc.	
	M	F	M	F	M	F	M	F
CONV.			6.462	4.977				
DMV ACC.							5.059	4.511
MILEAGE	1.382	.952	.414	.267	4.411	4.197	3.369	3.385
AGE	1.361	.602	.109	.115	10.887	2.284	9.222	1.776
DVA	.234	.094	.070	—	.535	.109	.395	.070
O-R	—	—	—	—	.055	—	.050	—
REC.	—	.088	—	.069	—	—	—	—
FIELD	—	—	—	—	—	.102	—	.071
R =	.157	.121	.284	.247	.370	.244	.432	.322

squared beta coefficients of each significant variable (as defined in connection with Table 2) in the eight full-sample equations. Table 4 also includes the multiple correlation coefficients (R) attained with inclusion of these significant variables, for comparison with the half-sample R's given in Table 3.

All of the significant relationships expressed by the beta coefficients in Tables 2 and 4 are in the "expected" direction. That is, in every equation, driving record worsens with increasing mileage, decreasing age, and worsening vision.

From Tables 2 and 4 it is clear that, in general, the results of the half-sample and full-sample analyses are remarkably similar, indicating a relatively high degree of consistency in the data and thereby increasing confidence in the validity of the results. Also, as shown in Table 3, the cross-validity coefficients obtained in the half-sample analyses correspond quite well to the multiple correlation coefficients, again suggesting adequate consistency in the data and the lack of any major spurious elements. The small differences between the multiple correlations (R) and the "terminal" multiple correlations (R_T) demonstrate how little the non-significant variables contribute to prediction. It should be pointed out, of course, that no attempt was made to maximize prediction by utilizing all of the many variables involved in the study. The regression analyses performed were intentionally confined to specific vision variables plus the control variables of age, sex, and mileage. Based on the data summarized in all three tables, it may be said that:

1. Convictions are more predictable than accidents (due, no doubt, to their less complex causative structure).
2. Inclusion of a driving record variable in the equation for predicting another driving record variable substantially increases the validity of that prediction and, generally speaking, the driving record variable is the predictor contributing the most to the overall prediction.
3. Among non-driving record predictor variables, mileage, and then age, contribute the next most significant amounts to the prediction.
4. Among vision variables, the results support the original research hypothesis by showing that dynamic visual acuity is by far the most consistent contributor to prediction, followed (at some distance) by static acuity, glare recovery, and visual field. The two remaining vision variables (glarimeter threshold and phoria) do not appear to make a significant contribution to prediction of a driving record variable; this does not imply that they might not contribute significantly in prediction of specific accident types, a possibility that future analyses will examine. The relationship between sighting dominance and driving record has not yet been evaluated.
5. Major differences between males and females are noted; driving record variables are much more "predictable" for males than for females and, with rare exception, individual variables contribute less to prediction for females than for males.

Finally, it should be mentioned that exploratory regression analyses of different age groups strongly suggest the existence of major differences in the predictability of driving record variables as a function of age. Future analyses will investigate this in detail.

RECOMMENDATIONS

Need for Continued Analyses of These Data

While it is not expected that the major conclusions of the present study will be altered to any significant extent, important supplemental information will be gained when the following additional research is carried out utilizing data accumulated in the study:

1. Conduct detailed analyses of the total test sample (including the 3143 "hold" subjects) to determine more precisely the effects of age and qualitative exposure on driving record variables.
2. Conduct detailed analyses to determine the relationships between both vision and non-vision variables and specific accident types, as well as specific types of convictions.
3. Conduct detailed analyses of the relationships between driving record and the many variables which were not included in the analyses presented in this report, including such things as smoking habits, occupation, hours of sleep (in relation to vision performance), and so on.
4. Continue accumulating driving record information for all 17, 500 test subjects to provide a broader and more reliable indication of driving performance, repeating the analyses already conducted and adding new ones to ascertain such things as predictability of non-concurrent driving record, relationships between different 3-year driving record periods, relationship (if any) between driving records before and after testing, changes in driving record with age, and suggested criteria (e. g., cut-off scores for vision tests) for acceptance or rejection of driver license applicants.

Need for Additional Research

1. Efforts should be directed toward developing a more compact, less expensive and equally reliable test of dynamic visual acuity, in order to permit the use of DVA as a supplement to or replacement for static acuity testing for driver license applicants. Such a test should be designed to permit measurements under a range of illumination levels.

2. In conjunction with the preceding, basic research should be conducted to determine the primary components of DVA, to ascertain whether performance on a battery of simple, reliable, inexpensive and already standardized tests can be used as an adequate substitute for performance on a DVA test.
3. An attempt should be made to develop an accurate, reliable, and easily administered test of "night vision," for possible inclusion in the vision-screening procedure. Such a test should include threshold and glare recovery measurements as a minimum and, if possible, both form-recognition and acuity testing under both static and dynamic conditions.

Practical Applications of the Results of the Study

Based on information generated thus far, and until future research dictates otherwise,

1. The currently universal use of static acuity vision testing as a prime aspect of the driver licensing procedure is justified, and should continue at least until a DVA test is commercially available.
2. Consideration should be given toward more comprehensive visual evaluation for driver license applicants. Included in this visual evaluation should be tests of static and/or dynamic acuity, lateral visual field and, possibly, night vision as well. Well-standardized acuity and visual field tests are already available. Utilization of a DVA and night vision test must await development of the apparatus suggested earlier. Planned analyses of study data to be performed within several months will permit suggesting required performance levels on these tests to be included in driver licensing standards. (It must be emphasized that these suggestions are based solely on the research results; any decision to increase the scope of present vision evaluation procedures must, of course, be heavily influence by time and budget considerations that fall outside the province of this report.)
3. Based on the results of these comprehensive visual tests, issue appropriately restricted driver licenses. For example, applicants with very poor glare recovery and/or low-illumination vision could have their night driving restricted to the relatively better lighted urban areas.
4. Because of the rapid deterioration of visual capabilities with increasing age, a finding discussed in separate publications (3, 6, 7), consideration should be given to the institution of more frequent licensing (i.e., vision testing) and consequently, shorter term licenses, for older drivers. (Future analyses will permit more accurate recommendations as to whether this more frequent testing should begin at a certain age, or at the point where the individual driver's vision has deteriorated to a specified level.)
5. Based on the criterion of driving record (rather than visual performances), younger drivers (e.g., under 25) should be given shorter term licenses.
6. Based on the present results, as well as on the results of future analyses, consideration should be given to the feasibility of establishing differential renewal periods and degrees of license restriction based on predictive equations. Variables to be included in such predictions include those shown to be significant in the present study, as well as those that may be revealed as significant in future analyses.

In conclusion, it should be said that experience gained in conducting the study has made abundantly clear the strong desirability of having a complete, detailed and centrally located source of information on driver record. That is, it is felt that a central (state or, preferably, national) record file should be established containing basic details for every conviction, and every accident for which a report has been made (to whatever governmental or private organization or agency). This file should be maintained in such a fashion that ready access to driver record information can be provided for operational and research purposes.

ACKNOWLEDGMENT

This paper is a condensed version of a detailed, limited-distribution report published earlier (5); for more information concerning specific aspects of the study, the reader is

referred to the original report as well as to the other publications listed in the References. Data collection and analysis costs for the study herein described were partially borne by the U. S. Public Health Service and by the State of California and U. S. Bureau of Public Roads. The opinions, findings, and conclusions expressed are those of the author and not necessarily those of either the sponsoring agencies or the California Department of Motor Vehicles.

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The Ability To See a Pedestrian at Night: Effects of Clothing, Reflectorization, and Driver Intoxication

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In the United States, pedestrian deaths account for nearly 20 percent of all traffic fatalities. During darkness the pedestrian's risk is increased, and is further increased if a pedestrian is wearing dark clothing or must travel on a roadway concurrently with a driver who has been drinking.

In the laboratory phase of this study it was found that at low levels of illumination an individual's sensitivity to contrast decreases as his blood alcohol level increases. In the road test phase, visibility distances were found to be unacceptably short for "dummy" pedestrians covered with black or grey fabric. Dummies covered with white fabric were safely visible for a driver traveling at speeds up to 50 mph; however, only reflectorized dummies were safely visible above that speed. As blood alcohol levels of the observers increased, the visibility distance decreased for each of the simulated pedestrian conditions.

•IN THE United States alone an estimated 149,000 pedestrians are either killed or injured as a result of motor-vehicle accidents in a single year. The approximately 9,000 pedestrian deaths in the United States each year account for nearly 20 percent of the total traffic fatalities (1). Even though 65 percent of the pedestrian deaths occur in urban areas, if the density of pedestrian and motor-vehicle traffic is considered, the risk to the rural pedestrian may be as great or greater than that of the urban pedestrian. It has been reported that in urban areas 4 percent of the pedestrian accidents and only 0.7 percent of the non-pedestrian accidents are fatal. For rural areas 25.3 percent of the pedestrian accidents are fatal while 4.2 percent of the non-pedestrian accidents are fatal (2).

Darkenss increases the pedestrian's jeopardy. Pedestrian accidents occur more frequently during twilight and darkness, in spite of reduced pedestrian and motor-vehicle traffic during these hours. While overall pedestrian deaths represent slightly less than 20 percent of all motor-vehicle fatalities, in a three-year study of twelve U.S. cities with populations greater than 500,000, pedestrian deaths were found to account for 50 percent of the total nighttime traffic fatalities (2). In rural areas pedestrian deaths at night account for 10 percent of the traffic fatalities, even though pedestrian traffic is distinctly limited during this period.

There are several other prominent trends in pedestrian accidents: specifically, three-fourths of the pedestrian-involved accidents occur when the pedestrian is crossing or entering the roadway; children under 15 and adults over 50 years of age are more frequently involved; males account for about 70 percent of the total pedestrian deaths;

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within urban areas pedestrian accidents are more likely to occur away from built-up shopping centers; a major portion of involved pedestrians are not licensed to drive; socioeconomic factors influence pedestrian accident involvement (3, 4); and "alcohol is a significant factor (in accidents) for pedestrians as well as for drivers" (5).

To determine how the driver fits into the pedestrian accident complex, accident reports for 1965 in Indiana involving pedestrian fatalities were reviewed. Statements made by the investigating officer and the driver revealed that 87 percent of the drivers who hit a pedestrian at night claimed difficulty in seeing the pedestrian, while only 11.8 percent made the same claim for accidents occurring during daylight. In fact, 23.4 percent of the nighttime drivers claimed that they did not see the pedestrian until after the impact! Further, 50 percent of the drivers who killed a pedestrian during the twilight hours felt that poor visibility of the pedestrian was the major contributory cause. The majority of the drivers involved in pedestrian fatalities were driving within the posted speed limit and were not cited for other motor-vehicle traffic violations.

The "Grand Rapids Study" (6) has provided data on the characteristics of accident-involved drivers compared with a control group of drivers similarly exposed but not involved in accidents. It was found that drivers between the ages 15 and 24 and over age 70 were over-represented in accidents. Furthermore, it was found that for drinking drivers, blood alcohol levels of 0.04 percent and greater were associated with an increased accident involvement. The probability of accident involvement increases rapidly at alcohol levels of over 0.08 percent and becomes extremely high at levels above 0.15 percent. Recent estimates indicate that drinking may be a factor in as many as 50 percent of the fatal motor-vehicle accidents (1).

PEDESTRIAN ACCIDENT CAUSE

"The concept of 'cause' has little operational significance in the study of accidents. Traffic accidents are more meaningfully viewed as failure of the system rather than as failures of any single component. To a larger extent than usually appreciated, several factors simultaneously contribute to most accidents; changes made in any of these could have prevented the accident or at least moderated it" (5).

Pedestrian characteristics, environmental characteristics, and the characteristics of the driver and his vehicle compose the "system" of pedestrian motor-vehicle accidents. Within this framework one can imagine numerous unfavorable changes which could occur within each of the components of the "system." Any one change in and of itself could be sufficient to entail a pedestrian accident. Alternatively, individually innocuous system changes may in combination produce an accident.

The likelihood of an accident becomes greater as the number of pernicious changes increases. Thus, the action of a child running into the roadway in the presence of an oncoming automobile could lead to a pedestrian accident, particularly if there were concurrent detrimental changes in the characteristics of one or both of the remaining components of the system, such as environmental illumination or weather that was poor and a driver who had imbibed alcohol.

Three factors that appear to influence the likelihood of pedestrian accidents are nighttime, dark clothing, and an intoxicated driver. It is the purpose of this study to investigate these parameters of the pedestrian motor-vehicle accident system.

METHOD

The first phase was a laboratory investigation of the effects of ethyl alcohol on the brightness difference threshold of eight male graduate students, ages 22 to 39. The second phase was a series of road tests in which two of these graduate students and two additional graduate students served as observers (O's). These tests were designed to investigate the O's ability to detect simulated pedestrians (P's) with various clothing at night, and to study the effects of ethyl alcohol on this detection task. All O's selected for these investigations had normal binocular vision and corrected visual acuity of 20/20 or better.

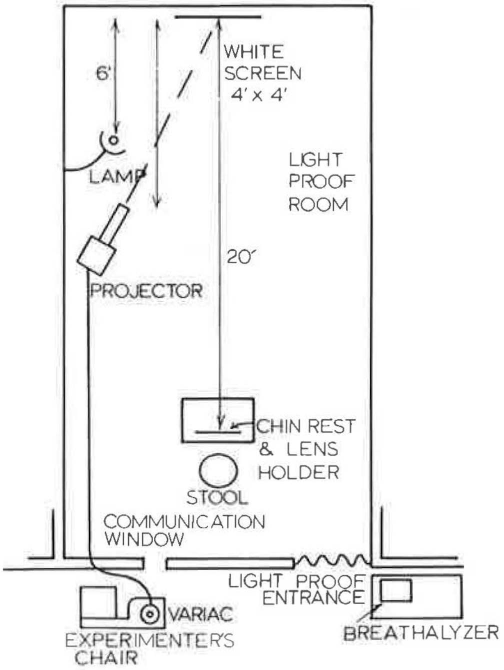

Figure 1. Light-proof testing room and apparatus.

Laboratory Experiment

Figure 1 is a diagram of the light-proof testing room. At one end a smooth-textured 4-ft square white screen was uniformly illuminated by a lamp 6 ft from the screen and powered by a constant voltage transformer. A projector superimposed a 17-mm spot of white light on the center of the screen. A Variac supplied by a constant voltage transformer was used to vary the intensity of the projected spot. The subject was located 20 ft from the screen in a head rest supporting auxiliary test lenses. A Breathalyzer[1] was used to measure the percent blood alcohol levels (BAL).

Two practice sessions were conducted on the days prior to data taking. Data were gathered on two evenings with four different O's being tested each evening. The day of the experiment the O's ate normal meals, but drank no alcoholic beverage. Each O performed 8 visual observation "blocks" consisting of 30 invisible to visible stimulus presentations. After each block O was given 66 cc of 100-proof vodka mixed with lime soda and ice. The O was allowed 5 minutes in which to drink the vodka, followed by 25 minutes free time. Each O was then given a Breathalyzer test and his percent BAL was recorded. After the Breathalyzer test the sequence was repeated. Prior to each block, O was allowed 2 minutes to seat himself and to adapt to the background luminance of the screen, which was 3.5 apparent ft-candles for the first four subjects and 0.15 apparent ft-candles for the second four. The task of the O was to say "now" when he first detected the superimposed spot of light. Ten trials were run for each of three different conditions in a single block. The O was rendered artificially emmetropic for the first condition. For the second condition O made the observations through additional -0.50 D lenses and for the third condition -1.00 D lenses were added. All observations were made binocularly and searching fixation was permitted. Each O was allowed to terminate his alcohol intake when he felt that he had reached his limit. However, each O was encouraged to complete 8 blocks of visual testing. The following day the O's returned to the laboratory for one additional block of visual observations without alcohol.

Dynamic Road Test

The apparatus for the dynamic road test consisted of two simulated pedestrians (P), a 1964 Mercury station wagon, four stopwatches, a Breathalyzer, and a straight 1400-ft test road. The P's were boxes 12 by 12 by 48 in. covered with fabric. One side was white fabric of 75 percent reflectance, a second was black fabric of 9 percent reflectance, and a third was grey fabric of 16.0 percent reflectance. The fourth side was covered with the same grey fabric and, in addition, had a strip of solver reflectorized tape (1 by 11 in.) placed horizontally 15 in. from the ground. The reflective strip had a candlepower reading of 50 candles/ft^2/ft-candle.

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[1] The Breathalyzer (designed by Robert F. Borkenstein, Department of Police Administration, Indiana University) instrument analyzes alveolar breath for alcohol content and yields an equivalent percent BAL reading. It is presently used by the Indiana State Police and other law-enforcement agencies.

Dynamic testing was conducted on two dark nights, and two O's were tested each night. The two P's were placed in alternating randomly preselected positions on or near the roadway for each test run. Each block consisted of 22 test runs, 18 of which contained 2 P presentations, 2 contained only 1 and there were 2 empty runs. Within a single block of trials the grey, white, and reflectorized sides of the P were presented 9 times each. The black side was presented 11 times. The headlight aim of the test vehicle was adjusted to the manufacturer's specifications. There was no opposing glare in any of the tests. Each test run was begun with the headlamps on low beam, approximately 1000 ft from the location of the P's. The two O's were in the front seat of the vehicle next to the driver. Each O held two stopwatches and was to start the watch held in his right hand when he saw the first P, and to start the watch held in his left hand upon seeing the second P. Both watches were stopped when the P's were reached. The vehicle approached the P's at a constant speed of 35 mph, and thus the elapsed time could be translated into distance. After the first block of trials the O's were given 66 cc of 100-proof vodka. Thirty minutes after finishing the first drink each O was given a Breathalyzer test and his blood alcohol level was recorded. Thereafter a Breathalyzer analysis was made midway through each block of trials and immediately following each block. An additional 66 cc of vodka was given at the midpoint of each subsequent block of trials. Each O completed four entire blocks. Only one declined to finish the entire allotment of vodka.

RESULTS AND COMMENT

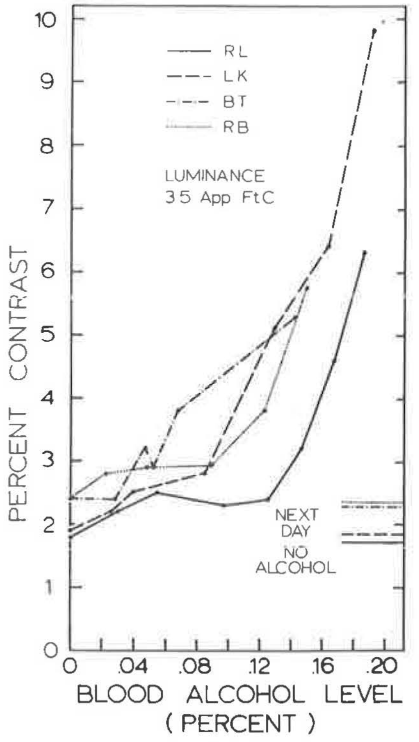

Figure 2. Percent contrast needed by four observers with increasing levels of blood alcohol to "just notice" a 17-mm spot of white light superimposed on a uniform white background of 3.5 apparent ft-candles luminance. Observers were allowed searching fixation.

Laboratory Tests

The formula for a brightness difference threshold is Contrast = $\Delta L/L$, where ΔL is the increment of luminance added to an area on a uniform background which is enough to make it just noticeably brighter than the remainder of the background L, O being adapted to L.

Results of the laboratory tests are represented graphically in Figures 2 and 3. In Figure 2 the ordinate is the percent contrast ($\Delta L/L \times 100$) needed to just notice the superimposed spot of light against the uniform white screen of luminance 3.5 apparent ft-candles. The abscissa is the percent BAL. Each of four O's is indicated by a separate curve representing mean values for emmetropia. The -0.50 D and -1.00 D conditions followed the same trend.

Subject B. T., who showed the most erratic decrease in contrast sensitivity, also showed the greatest subjective reaction to alcohol and became sick just prior to the 0.05 percent level. L. K. exhibited the least subjective effect from the alcohol and at the 0.18 percent level had good control of his faculties. Yet his overall decrement of contrast sensitivity, above the 0.09 percent level, was greater than any of the other four O's. B. T. and R. B. terminated their drinking just prior to reaching the 0.15 percent level of blood alcohol. (The legal limit accepted as "prima facie" evidence for being under the "influence" in most states is 0.15 percent.) L. K. and R. L. expressed dissatisfaction when the experimenters terminated their drinking at a considerably higher BAL.

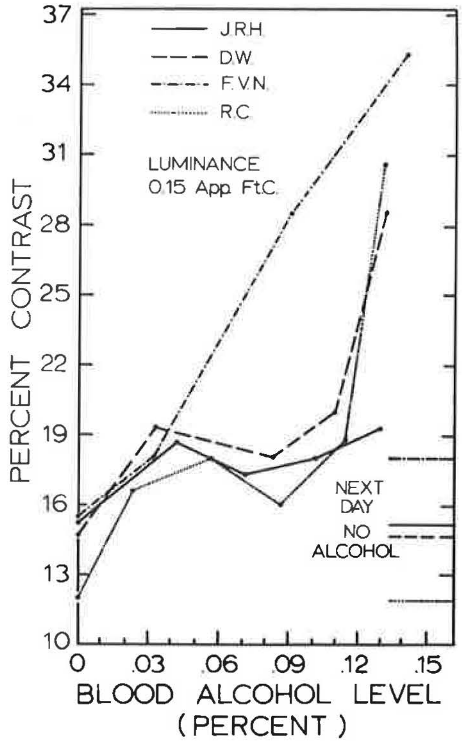

Figure 3. Percent contrast needed by four observers with increasing percentage levels of blood alcohol to "just notice" a 17-mm spot of white light superimposed on a uniform white screen of 0.15 apparent ft-candles. Observers were allowed searching fixation.

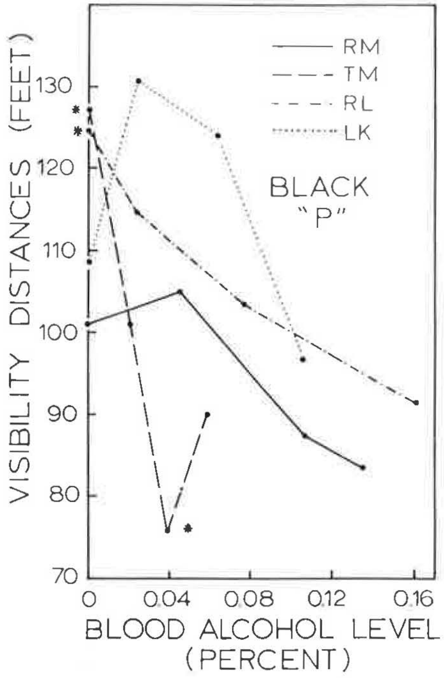

Figure 4. Mean visibility distances of black simulated pedestrian obtained by four observers at increasing percentage levels of blood alcohol. Asterisks represent visibility distance of zero for one observation (i.e., simulated pedestrian was not seen at all).

The following day the performance of every O returned to essentially the same level as that prior to the intake of alcohol.

Figure 3 is plotted in the same manner as Figure 2, but represents the responses of four new O's to the task with a background of 0.15 apparent ft-candles luminance. Individual differences were more noticeable in this set of observations with subject F.V.N. showing a steady decrease in sensitivity over the entire range of BAL from 0.00 percent to 0.14 percent. (He also appeared to be more intoxicated than the other four O's.) R. C. and D. W. did not exhibit a rapid decrement in performance until above the 0.08 percent level. J. R. H., who appeared to be the most sober of the four O's, did not show a major decrement in performance. All O's terminated their intake of alcohol before reaching 0.15 percent BAL. On the following day the performance for each O had essentially returned to its original level.

All O's except one, B. T., felt that their visual performance had not noticeably declined throughout the experiments.

Road Tests

An ample visibility distance must be greater than the combined reaction distance and braking distance. The "critical visibility distance" is just equal to reaction distance plus braking distance.

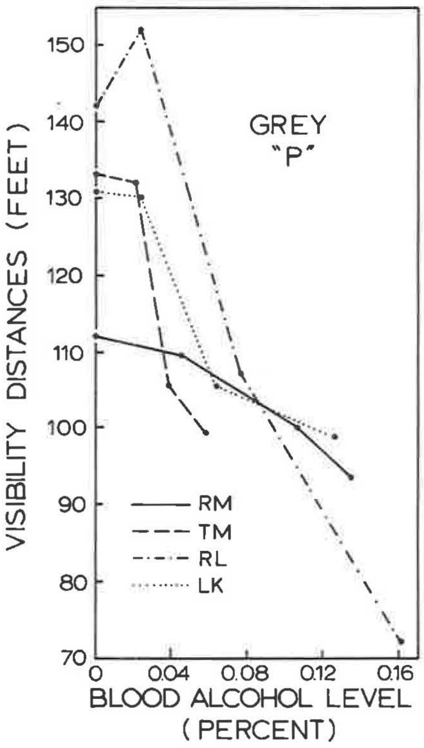

Figure 5. Mean visibility distances of grey simulated pedestrian obtained by four observers at increasing percentage levels of blood alcohol.

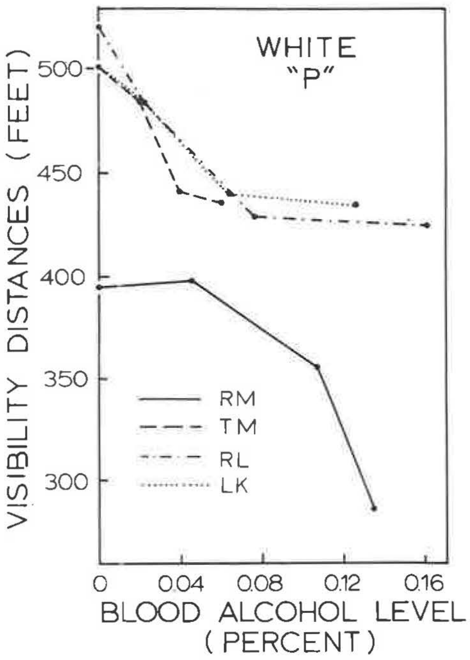

Figure 6. Mean visibility distances of white simulated pedestrian obtained by four observers at increasing percentage levels of blood alcohol.

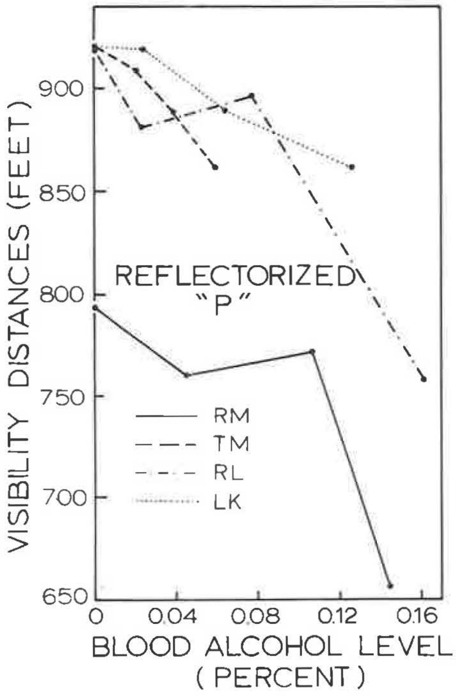

Figure 7. Mean visibility distances of reflectorized simulated pedestrian obtained by four observers at increasing percentage levels of blood alcohol.

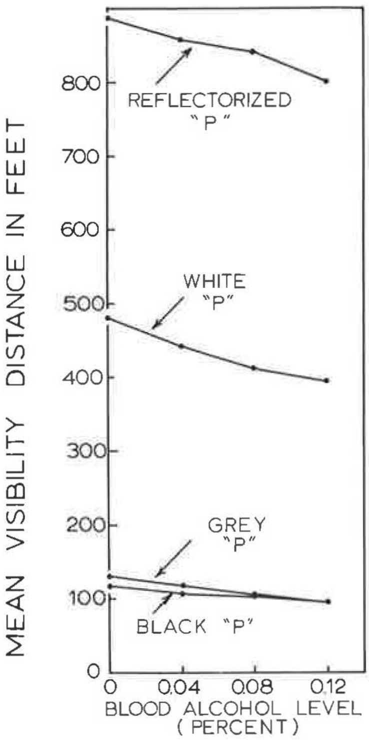

Figure 8. Mean visibility distances for black, grey, white, and reflectorized simulated pedestrian for all observers at increasing percentage levels of blood alcohol.

TABLE 1

CALCULATED CRITICAL VISIBILITY DISTANCES

Speed (mph)	Critical Visibility Distance (ft)
20	45
30	72
40	123
50	185
60	261
70	349
80	450

The results of the dynamic road test are shown in Figures 4, 5, 6, 7, and 8. In each graph the visibility distances are plotted against percent blood alcohol. Visibility distances found for both the black and the grey P's are shockingly short! Each data point represents the mean visibility distance for a given block of trials at the stated percent BAL. Although these graphs give an idea of the trends involved, there is doubt as to the appropriateness of using the mean when dealing with the topic of pedestrian safety. Although the mean visibility distance of the black P for all O's ranged from 115.2 ft with no alcohol to 90.4 ft at the high levels of blood alcohol, there were three of the black P's (out of the 176 presented to the four O's) that were not seen at all. Two were missed by one observer, and two of the three misses occurred before taking any alcohol. The visibility distance, for each test condition and for every O, generally decreased as the blood alcohol level increased. Learning no doubt took place as the tests progressed and the O's were in a high state of readiness for each trial due to group motivation; hence the measured visibility distances are probably greater than would be observed in the normal driving situation.

Table 1 gives the calculated critical visibility distances associated with 10-mph intervals of speed from 20 to 80 mph. Calculations were made for an automobile with safe tires and brakes traveling on dry pavement and driven by an individual with a reaction time of 0.75 sec.

TABLE 2

PERCENTAGE SAFELY VISIBLE BEFORE DRINKING

Type of P	Percent Visible at Given Speed (mph)						
	20	30	40	50	60	70	80
Black	86.4	68.2	45.4	15.9	0	0	0
Grey	100	100	47.2	13.9	5.5	5.5	0
White	100	100	100	100	97.2	91.7	52.7
Reflectorized	100	100	100	100	100	100	100

TABLE 3

PERCENTAGE SAFELY VISIBLE AFTER DRINKING

Type of P	Percent Visible at Given Speed (mph)						
	20	30	40	50	60	70	80
Black	90.8	63.6	15.2	0	0	0	0
Grey	97.2	73.2	14.2	2.7	0	0	0
White	100	100	94.4	88.9	80.5	61.1	25
Reflectorized	100	100	100	100	100	100	94.5

Table 2 gives the percentage of P's that were safely visible at distances greater than the critical visibility distance associated with the given speeds. The data are from four O's prior to the consumption of alcohol (BAL 0.00).

Table 3 gives the percentage of P's that were safely visible at distances greater than the critical visibility distance associated with the given speeds. The data are from four O's after the consumption of alcohol (BAL from 0.06 percent to 0.10 percent).

DISCUSSION

Visual Function During the Night Driving Task

The human eye is sensitive to a range of luminances of more than 10 billion to 1 (7). The adaptation level during night driving is within the mesopic or lower photopic range where contrast sensitivity is relatively poor (8). Glare, dark clothing, and the brief time available to see a pedestrian compound the problem. These visual disadvantages become more significant with age, lack of attention, the consumption of alcohol, etc.

Influence of Alcohol on Vision

Goldberg (9) reported that reduced fusion frequency begins at blood alcohol levels of 0.01 to 0.02 percent for abstainers, 0.02 to 0.03 percent for moderate drinkers, and 0.04 to 0.07 percent for heavy drinkers. Goldberg stated: "Alcohol has the same effect on vision as the setting of a grey glass in front of the eyes, or driving with sunglasses in twilight or darkness; a stronger illumination is needed for distinguishing objects and dimly lit objects will not be distinguished at all; when a person is dazzled by a sharp light it takes a longer time before he can see clearly again." This statement is supported by our findings.

Goldberg (10), Wayne (11), and Seedorff (12) report that moderate amounts of alcohol will induce nystagmus. Wayne (11) and Stewart (13) report a reduction in the visual field, while Colson (14) found no change in visual acuity or the peripheral visual field. A U.S. Air Force publication (15) states: "Alcohol in the system produces symptoms like those of hypoxia. The effect of alcohol in the blood is to make body tissues less receptive to the oxygen in the blood. Therefore, the oxygen that is present cannot do its work as effectively. Drinking reduces depth perception and ability to distinguish between different brightnesses, and it shrinks the visual field to some extent." Goodwin and his associates (16) have found that alcohol decreases visual acuity, increases esophoria for distance, decreases the amplitude of convergence and accommodation, and increases the increment threshold. They conclude: "The increases in the increment threshold which generally explain the decreases in visual acuity might have serious detrimental effects upon the detection of low contrast targets such as objects along the roadside at night." Our findings support this conclusion.

Pedestrian Visibility

"The word 'visibility' in common usage expresses the clearness with which objects stand out from their surroundings" (8). A pedestrian becomes visible either as a silhouette (negative contrast) or as an illuminated object against a dark background (positive contrast). Automobile headlamps create mainly positive contrast while most street lighting creates a negative contrast.

Rumar (17) of Sweden, in commenting on the visibility of pedestrians, states: "A frequent argument in discussions about night driving is that the silhouette-effects offer very long visible distances. Careful experiments have shown that, normally, these effects are of no help within 1 m from the near edge of the road. Certain conditions such as snowy or otherwise very bright roads, inside bends, light fog, etc., favor the effect. Drivers can never be sure, however, that the road is free because no silhouette effects have appeared." Pedestrians walking in well-lit areas are generally more visible, but well-lit areas combined with automobile headlights will produce both positive and negative contrasts and may obliterate a pedestrian!

Another factor influencing the safety of pedestrians is that they frequently overestimate their own visibility. Because they have adapted to a low level of ambient illumination and thus perceive an oncoming vehicle quite easily, they may fail to appreciate the difficulty of the driver's detection task.

Considering the low visibility distances found for the black and the grey P and the effects of alcohol on vision, it is fair to agree with Rumar (18) that the majority of nighttime pedestrian fatalities do not belong strictly in the category of "accidents." When a pedestrian is first seen at less than the critical visibility distance, a detrimental change has occurred in the "system" for which there can be little compensation. A disastrous result can only deceptively be termed an "accident!"

SUMMARY

1. Laboratory tests show a decreasing contrast sensitivity with an increase in percent blood alcohol level.
2. Roadway tests show a decreasing ability to detect pedestrian-sized objects with increasing percent of alcohol in the blood.
3. Roadway tests without alcohol show that with low-beam headlights in an automobile traveling at 40 mph an alert healthy driver looking for a pedestrian-sized object will not see it soon enough more than 50 percent of the time if the object is covered with black or grey fabric. Pedestrian-sized objects covered with white fabric or grey fabric and a 1 by 11-in. reflective material will be seen soon enough, but as alcohol is introduced only the reflectorized object remains safely visible for a 40-mph speed.
4. Three of the black simulated pedestrians (out of the 176 presented to the four observers) were not seen at all.
5. A review of the 1965 pedestrian accident records for Indiana showed that 87 percent of the drivers at night said they didn't see the pedestrian in time. Only 11.8 percent of the daytime drivers made the same claim. At twilight 50 percent of the drivers claimed poor visibility of the pedestrian. Further, 23 percent of the nighttime drivers did not see the pedestrian until impact, if then.

CONCLUSIONS

1. The literature and the results of this pilot study indicate that pedestrians are very difficult to see at night even under the best of viewing conditions.
2. Alcohol is indicated in the literature and in these results as causing an interference in the visual mechanism further compounding the visual task of night driving. The modern borderline highway lighting becomes significantly more inadequate to the driver who has consumed alcohol.
3. Pedestrian visibility distances could be increased and some of the losses of perception due to alcohol could be counterbalanced by either raising all roadway illumination or by increasing the positive contrast of the pedestrian himself. It was noted in these experiments that a small amount of reflectorization was detected in time even by the significantly intoxicated person. (No opposing headlight glare was present in these studies.)
4. Further study of the pedestrian visibility problem in the presence of headlight glare and alcohol is needed. The literature indicates that there is an increased hazard if opposing headlights are in the driver's field of view.

5. Further study is needed to evaluate the effectiveness of specific devices and environmental control techniques designed for the promotion of pedestrian safety.

6. The public should be further educated as to the importance of visibility in accident causation, and the hazards of alcohol need further emphasis.

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A Laboratory Method for Obtaining Pavement Reflectance Data

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Illuminating engineers have long known the importance of pavement luminance in roadway designs. It is also widely known that pavement luminance depends on the relative positions of the observer and the light source as well as the directional reflectance characteristics of the pavement surface. However, at present there is little information available that will permit the calculation of pavement luminance from an illumination specification. This paper describes the instrumentation and procedures associated with a laboratory method for determining the directional reflectance characteristics of pavement surfaces. In addition, data collected for one traffic-worn asphalt pavement surface are presented.

•THE general objective of this report is to describe a laboratory procedure for obtaining pavement directional reflectance data. Information of this nature, combined with appropriate methods and techniques for handling the data, needs to be made available to the illuminating engineer if roadway lighting is to be elevated from an art to a science. The need for directional reflectance data can be more readily appreciated by reviewing the difference between the two commonly used lighting terms, "illumination" and "luminance" (photometric brightness).

Illumination is the measure of the amount of light flux falling upon a surface. Illumination is independent of the direction from which the light comes; the number of light sources or their positions; the type of light source; and the type of surface upon which it falls. A surface may be illuminated to a given level by one or several light sources placed normal or obliquely to the surface. The illumination is the same whether the surface is a photometric plate or a piece of black felt cloth. In roadway lighting, illumination is a useful quantity in the calculation of problems of lighting but has very little value in describing the observed situation.

Luminance is the measure of the amount and concentration of light flux leaving a surface and is the light by which an object is seen. It is the luminance which controls the magnitude of the sensation which the brain receives of an object. The luminance of a surface depends on all of the quantities of which illumination is independent, such as the direction from which the light strikes the surface, the direction from which the surface is viewed, and the reflective properties of the surface itself.

The amount of light falling upon a small area of a surface is measured as the illumination on that area. This incident light is generally reflected in all directions by the surface and its directional distribution is determined by the properties of the surface and the manner in which the light strikes the surface. The apparent luminance of the surface is determined by the amount of light reflected toward the observer's eye.

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Current roadway lighting design practice in the United States is sponsored by the Illuminating Engineering Society and approved by the American Standards Association (1). This standard states that one of the principal objectives of roadway illumination is "... to enhance the brightness of the pavement and uniformity of brightness along and across the full width of the roadway... ". However, the recommended design practice gives no further specific consideration to the concept of pavement luminance (brightness). Instead, the standard consists essentially of an average horizontal footcandle specification, measured on the pavement surface between two adjacent luminaires. This implies that the roadway brightness patterns are adequate if the average horizontal illumination is at the recommended level. But rather than rely entirely on the light incident on the surface to reveal the roadway scene, we should consider the amount of light reflected from the surface in the direction of the observer, since the information needed by the motorist to evaluate the visual scene is provided by the luminance patterns on the roadway (2). In this regard, the roadway ahead of the motorist should present an average luminance adequate to maintain eye adaptation, a minimum luminance to assure adequate visibility of any object on or near the roadway, and a uniformity sufficient to maintain continuity within the visual scene, to insure comfort, and to render frequent and rapid eye movements by the driver unnecessary. Many illuminating engineers have long been aware of the inadequacy of an illumination specification, and have frequently suggested roadway luminance as a substitute parameter for design purposes, but the latter has seldom been used in this country.

The "American Standard Practice for Roadway Lighting" (1) emphasizes the importance of the roadway surface in producing luminance patterns when it states: "The apparent brightness of the pavement depends upon the intensity and the angle of incident and reflected light and the pavement-reflecting characteristics (specular and diffuse) at typical angles of view." Perhaps this statement also gives a clue to the reasons that illuminating engineers continue to adhere to an illumination specification for roadway lighting, even though it is generally acknowledged that a luminance specification would be preferable. Whereas levels of illumination have been relatively easy to determine, either by measurement or calculation, the derivation of roadway luminance from photometric data has involved tedious measurement of pavement reflectance as well as a formidable number of calculations. Developments in recent years, however, have greatly simplified this task, a straightforward method for computing roadway luminance having been previously reported (2). The calculations, moreover, by their repetitive nature, readily lend themselves to computer programming. Nevertheless, the lack of reliable information concerning the directional reflecting characteristics of pavements is a retarding factor in this process. Past attempts to measure directional reflectance factors for representative roadway surfaces have met with limited success (3, 4, 5, 6). Both field and laboratory studies have produced only a meager amount of published data, and of this, only the field data appear to be usable. The collection of field data has generally employed either visual photometry or photographic techniques. While both of these methods offered advantages when they were used, the direct-reading instruments available today make a laboratory study both practical and desirable at this time.

EXPERIMENTAL EQUIPMENT

Reflectance is defined as "the ratio of the flux reflected by a surface or medium to the incident flux" (1). The quantity generally reported is the total reflectance, or the ratio of the total reflected flux to the total incident flux. This value cannot be used for pavement luminance calculations since, as pointed out previously, the incident and viewing angle affect the roadway luminance as perceived by the observer. For a particular incident and viewing angle, it is necessary to have a multiplying factor which relates the density of incident flux or illumination in horizontal footcandles (lm/ft^2) to the luminance or photometric brightness in footlamberts (π cd/ft^2). Then: Pavement Luminance = Directional Reflectance Factor x Horizontal Illumination.

The experimental equipment has been designed and calibrated in such a manner that the directional reflectance factor can be measured for many combinations of incident angles of luminous flux and observer viewing angles.

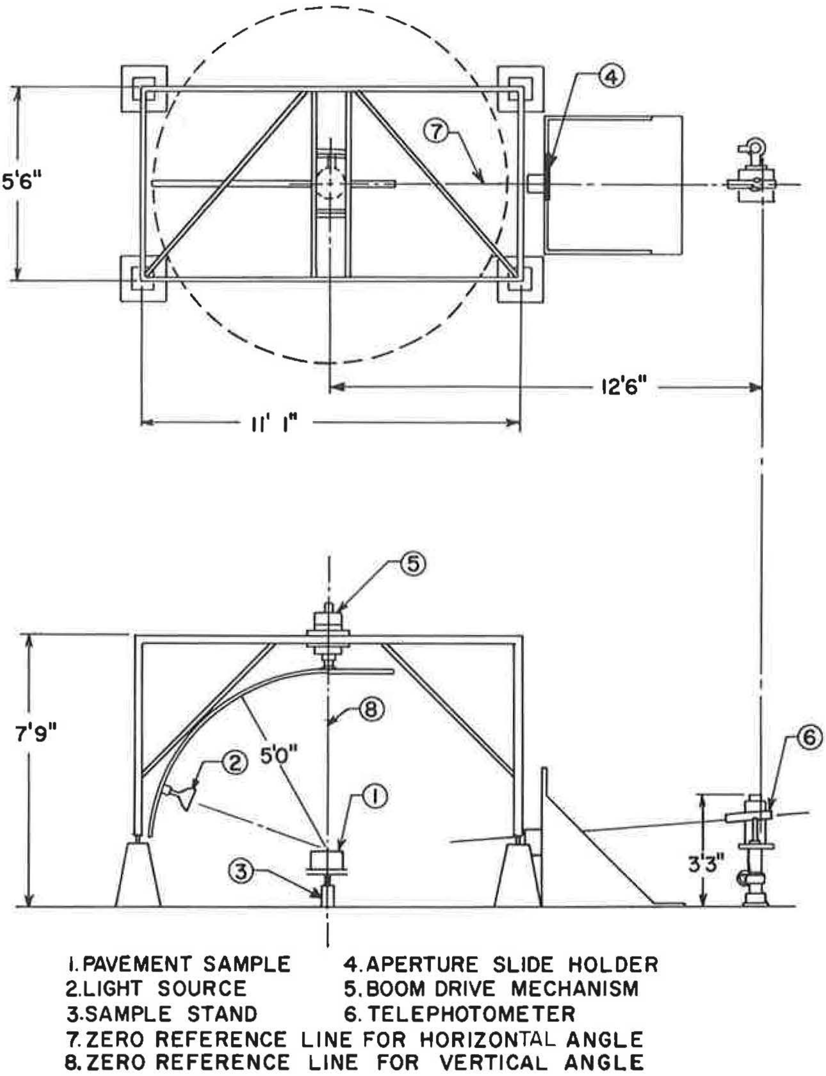

Figure 1. Directional reflectance goniometer.

The directional reflectance goniometer, shown in Figure 1 and hereafter referred to simply as the reflectometer, is basically a form of goniometer consisting of an incandescent lamp mounted on a curved rotating boom, a sample stand, an aperture slide holder, and a telephotometer. By means of detents in the boom, the lamp may be positioned so that it will illuminate the pavement sample from any of a number of vertical angles. The boom is motor driven and rotates the lamp through a 360-deg horizontal angle about the sample. The telephotometer is aimed and focused on the sample and its position can be adjusted to correspond to various driver viewing angles. At each viewing angle, an aperture of the appropriate size is placed between the sample and the telephotometer to insure that the telephotometer is, as nearly as possible, viewing only the surface of the sample.

The output of the telephotometer, which has been calibrated in terms of footlamberts, is amplified and fed to both a strip chart recorder and a digital recording system. The strip chart recorder provides a continuous trace of the telephotometer output as the boom rotates the lamp through 360 deg. The amplitude of the trace is directly propor-

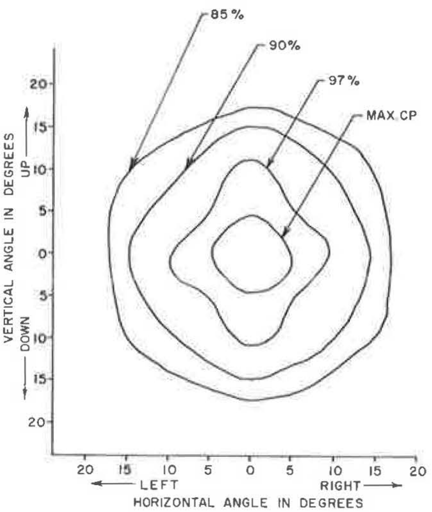

Figure 2. Isocandle diagram for light source.

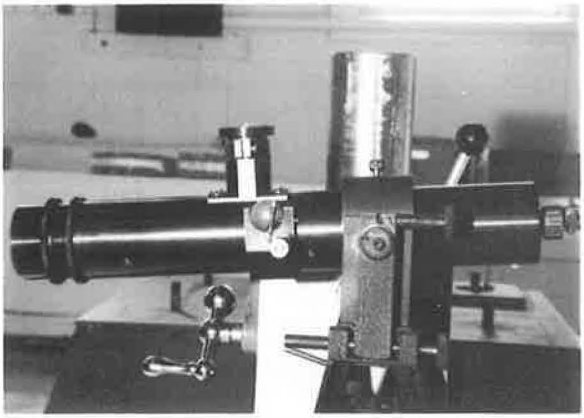

Figure 3. Telephotometer.

tional to the output of the telephotometer and previous calibration allows the determination of the directional reflectance factor for any combination of telephotometer and light source positions. The digital recording system converts the output current of the telephotometer, at 5-deg intervals, into digital form and records it on paper tape. Here, as with the strip chart, previous calibration allows the determination of the directional reflectance factor for any combination of telephotometer and light source positions.

The reflectometer boom has a 5-ft radius and is driven by a 115 VAC, 10 rpm, synchronous motor through a gear train salvaged from a radar antenna turntable. As the boom rotates, a microswitch is repeatedly actuated at 5-deg intervals. Each actuation places a mark on the strip chart recording and causes the digital recording system to read the telephotometer output at that instant.

The light source, a 120-volt, 300-watt, type R-40 inside-coated reflector lamp, is accurately positioned on the boom by means of a pin and detent arrangement. Locations corresponding to incident angles of 5, 20, 35, 50, 60, 65, 70, 75, 80, 82, 84, 86, and 88 deg are provided for. Adjustments are also provided for the alignment of the lamp. Figure 2 shows the isocandle diagram for the lamp in percentage of maximum candlepower. Note that the central 30-deg cone is quite uniform, the greatest deviation from the maximum being approximately 10 percent. This provides a uniform light distribution on the sample surface.

The telephotometer, shown in Figure 3, is mounted on a modified drill press stand, which in turn is bolted to the concrete floor. This provides a rigid and vibration-free mount for the instrument. A unique feature of the telephotometer is the adjustable slit, placed at the image plane, which provides for varying the vertical dimension of the area being viewed. The horizontal dimension may be changed by inserting circular apertures, of various sizes, immediately ahead of the adjustable slit. Figure 4 shows the stray light rejection curve for the aperture-slit combination used in this investigation. The telephotometer is desinged to have a symmetrical aperture. However, the combination of a 2½-deg circular aperture and micrometer vernier setting of 175 used in this investigation resulted in the asymmetrical aperture shown.

The color response of the DuMont type 6467 multiplier phototube has been corrected, by means of a Kodak No. 106 filter, to approximate that of the human eye.

The sample stand is composed of a hydraulic jack with a flat steel plate welded onto the lifting shaft. The sample rests on a second steel plate which is in turn positioned above the first plate by means of four cap screws, one at each corner. The sample is leveled by adjusting the cap screws in a manner similar to that used for leveling a

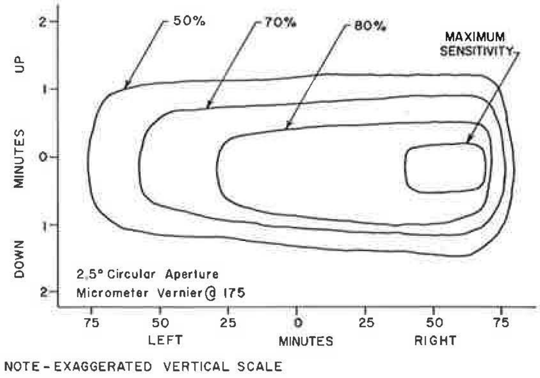

Figure 4. Aperture stray light rejection curve.

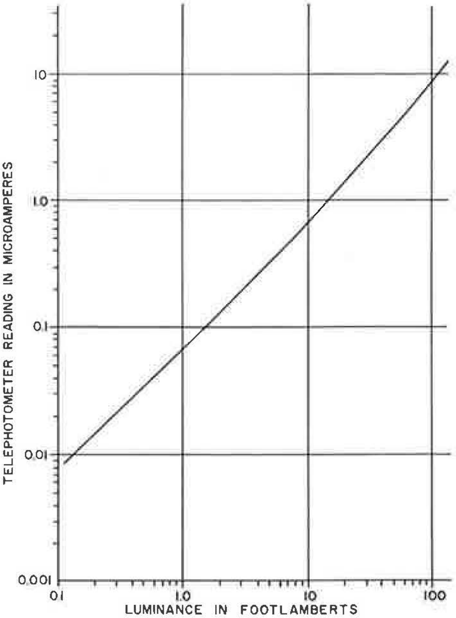

Figure 5. Telephotometer calibration curve.

surveyor's transit. In addition, the height of the sample can be changed by raising or lowering the hydraulic jack.

The aperture slide holder (Fig. 1), placed midway between the pavement sample and the telephotometer, is constructed of plywood, well braced and securely bolted to the floor. Aperture slides with openings corresponding to simulated driver viewing distances of 50, 100, 200, 400, and 600 ft were used in this investigation.

The reflectometer is housed within a virtually light-proof enclosure of opaque black plastic. This allows the reflectometer to be operated during any hour of the day with no interference from external sources of light.

An in-place calibration of the telephotometer was made with the aid of a uniform light source and a Spectra Pritchard Photometer. An elliptical cut-out, corresponding in size and shape to the sample surface when viewed from the simulated 50-ft distance, was placed on the uniform source. Both the telephotometer and the Pritchard Photometer were then aimed at and focused on this cut-out. As the luminance of the source was varied, it was recorded by the Pritchard and corresponding readings of the telephotometer were also noted. The resulting curve of luminance vs telephotometer output is shown in Figure 5. This curve is valid only for the simulated viewing distance of 50 ft for which it was derived. The curve may be used for other simulated viewing distances if suitable correction factors are applied to the telephotometer readings. These correction factors depend on the projected area of the pavement sample surface as viewed from each simulated distance, i.e., Factor = A_1/A_2, where A_1 = projected area at simulated 50-foot viewing distance, and A_2 = projected area at the simulated viewing distance in question.

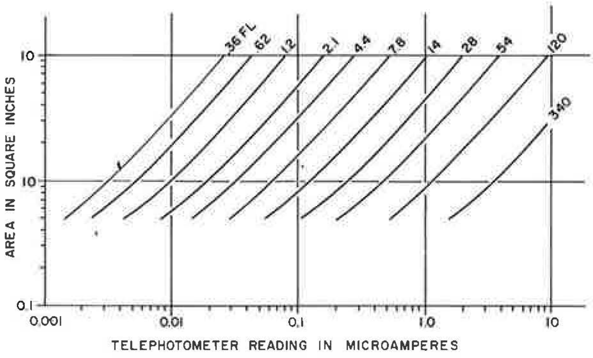

Figure 6. Area factor curve.

Using the distance of 50 ft as a base, the factors for distances of 100, 200, 400, and 600 ft would be 2, 4, 8, and 12 respectively. These factors were verified by masking off progressively smaller areas of the uniform source and recording the telephotometer output for several luminance levels. Figure 6 shows the data plotted as area vs output. Factors derived from this curve closely agree with the calculated factors.

Care was exercised in the design and construction of both the telephotometer and aperture slides to insure that only the light reflected from the surface of the sample would reach the telephotometer. However, analysis of the initial data indicated that these efforts had not been completely successful. Therefore, a set of "zero" curves was established for each of the five simulated viewing distances. These curves were made by recording a 360-deg sweep of the boom with no sample in the holder and a similar sweep with a sample in place but covered by a piece of black flock paper. This was done for each incident angle and each viewing angle. The final zero curves for each position were established by comparing the values of the initial two curves at 5-deg intervals and using the lower value of the two.

OPERATING PROCEDURE

The pavement sample is placed on the test stand and leveled with the aid of a spirit level. The sample is given the proper directional orientation on the test stand with the aid of a mark, indicating the direction of vehicle travel, placed on the side of the sample by the drilling crew. The sample is then raised, by means of the hydraulic jack, until its surface rests in the datum plane and the leveling is again checked. The datum plane is the plane corresponding to a 90-deg vertical angle for the light source and is established by stretching a wire between four previously determined points. The sample is then draped with a black velvet cloth to reduce light reflections from the sides. The light source is placed at the 5-deg vertical angle position and aimed at the sample. A reading of the illumination is made on the sample surface. Next the telephotometer is raised to its highest position, corresponding to a viewing distance of 50 ft. The appropriate slide is placed in the aperture slide holder and the telephotometer is aimed through the aperture at the surface of the sample. Final adjustments of the recording equipment are made and the photometer output for a single 360-deg rotation of the goniometer boom is recorded. Recordings for the sample under study are made with the goniometer lamp at each of its 13 boom settings until all of the previously mentioned vertical angles from 5 to 88 deg are covered. At this point the telephotometer is lowered to a new position simulating a viewing distance of 100 ft, the corresponding aperture slide placed in the holder and the whole procedure of aiming, adjusting, and recording is repeated. This is done for each of the 5 previously mentioned viewing distances.

DATA PROCESSING

Due to the large amount of data involved, the successful completion of this investigation depended upon automating the data collection and processing to the greatest extent possible. After automating the reflectometer as far as practical, attention was then focused on the data recording and processing system. Several means of recording the data were investigated and a combination of two methods was selected for final use. This consisted of a strip chart recorder and a digital recording system operating in parallel. The digital data processing system was chosen for speed and convenience of data processing and the strip chart recorder was incorporated into the system to provide periodic visual checks on the data being gathered. Frequent comparisons were made between the strip chart and digital system recordings. The digital system recorded the data on paper punched tape and the tape was then converted to cards, since one of the computers available for processing the data had no facility for reading the paper tape directly. A simple computer program was used to determine the directional reflectance factors utilizing the telephotometer calibration curve, the zero curves, and the data from the paper tape.

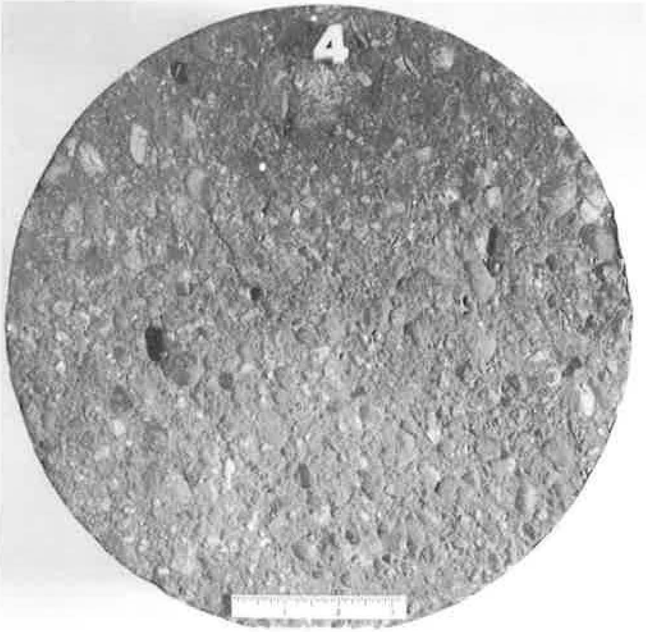

Figure 7. Traffic-worn asphalt surface.

TEST RESULTS

The results for one 12-in. core sample are shown in Figures 8 through 13. The sample is type B asphaltic concrete, $^3/_4$-in. maximum, medium graded aggregate, with 5 to 6 percent of 85-100 grade asphalt in the surface course. It was cut from an inservice pavement by the Materials and Research Section of the California Division of Highways. The sample had been exposed to 3 years and 8 months of traffic wear before its removal. Other than brushing any loose material from the surface, the sample was given no special preparation before testing. Figure 7 shows the sample as tested.

The directional reflectance factors for this sample are shown graphically as a function of horizontal and vertical angles in Figures 8 through 12. Each graph represents one of the simulated viewing distances. The curves are nearly symmetrical about the 180-deg horizontal angle, the

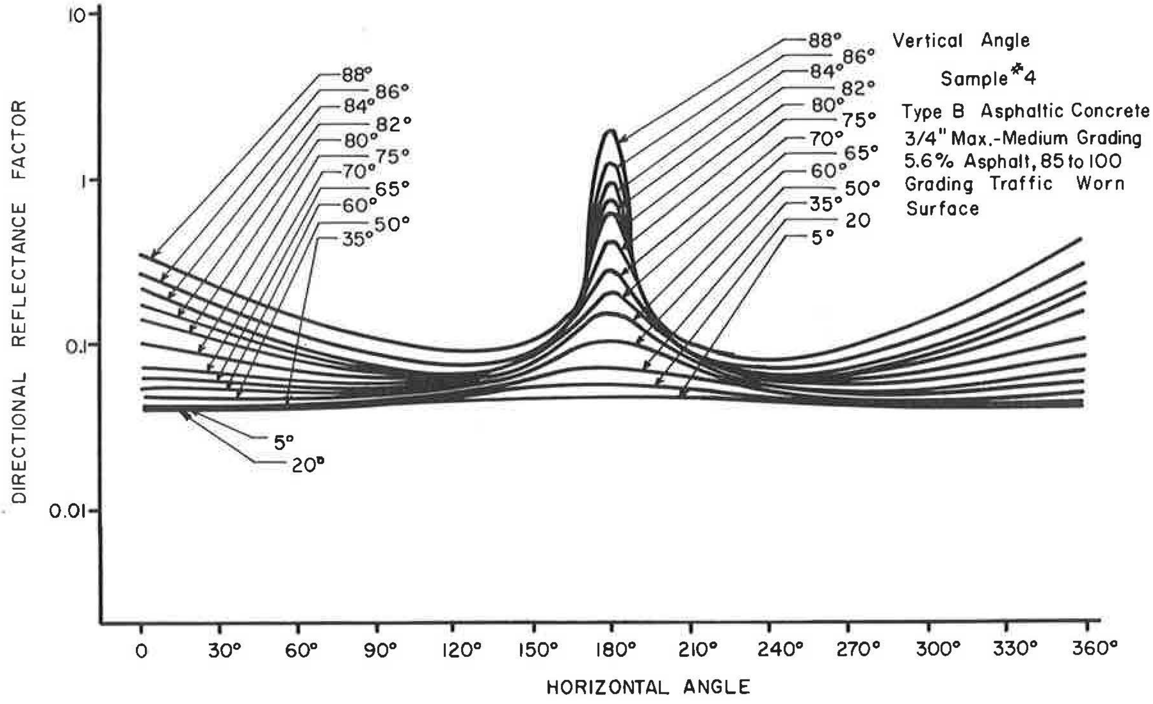

Figure 8. Directional reflectance factors for 50-ft viewing distance.

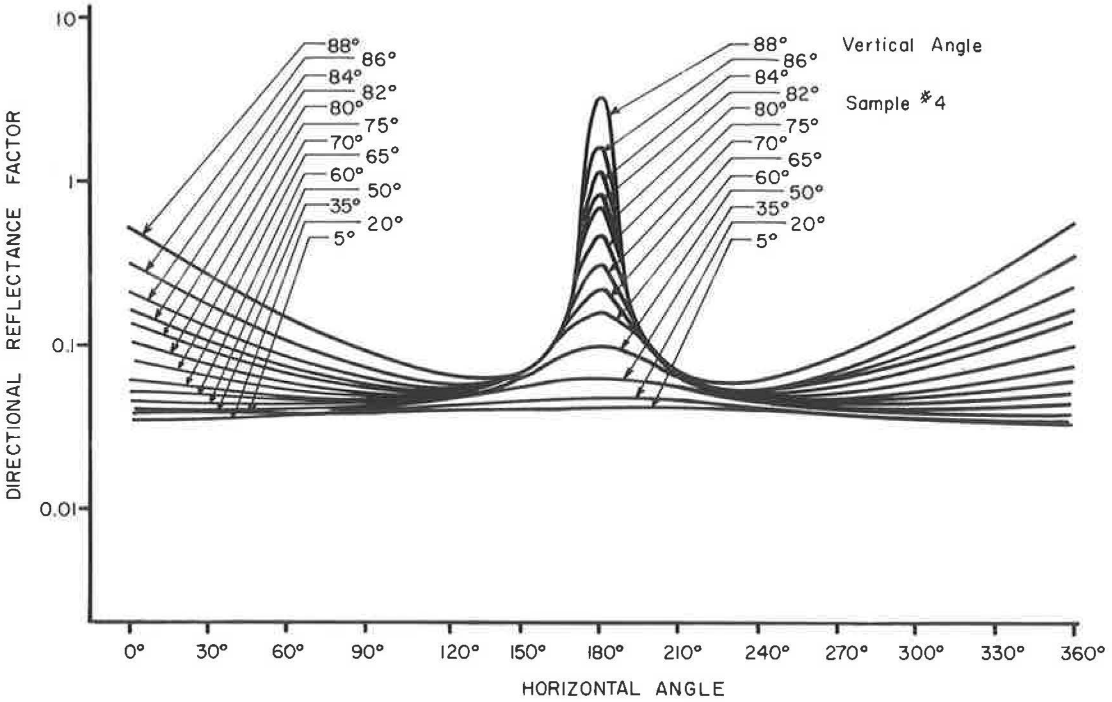

Figure 9. Directional reflectance factors for 100-ft viewing distance.

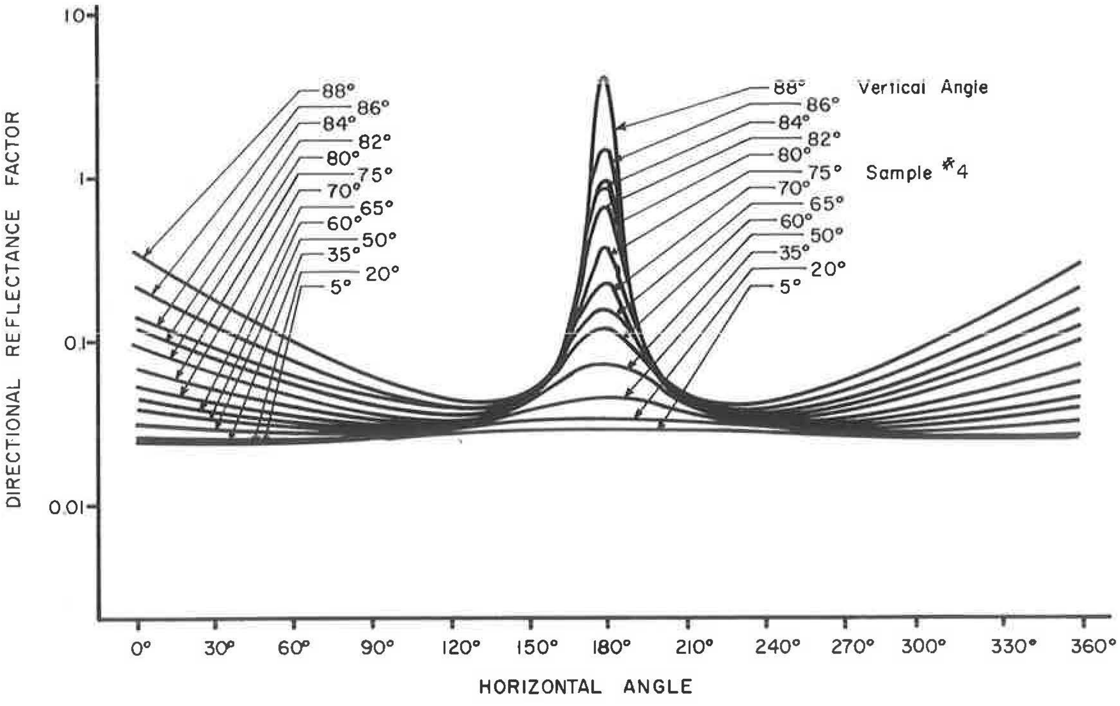

Figure 10. Directional reflectance factors for 200-ft viewing distance.

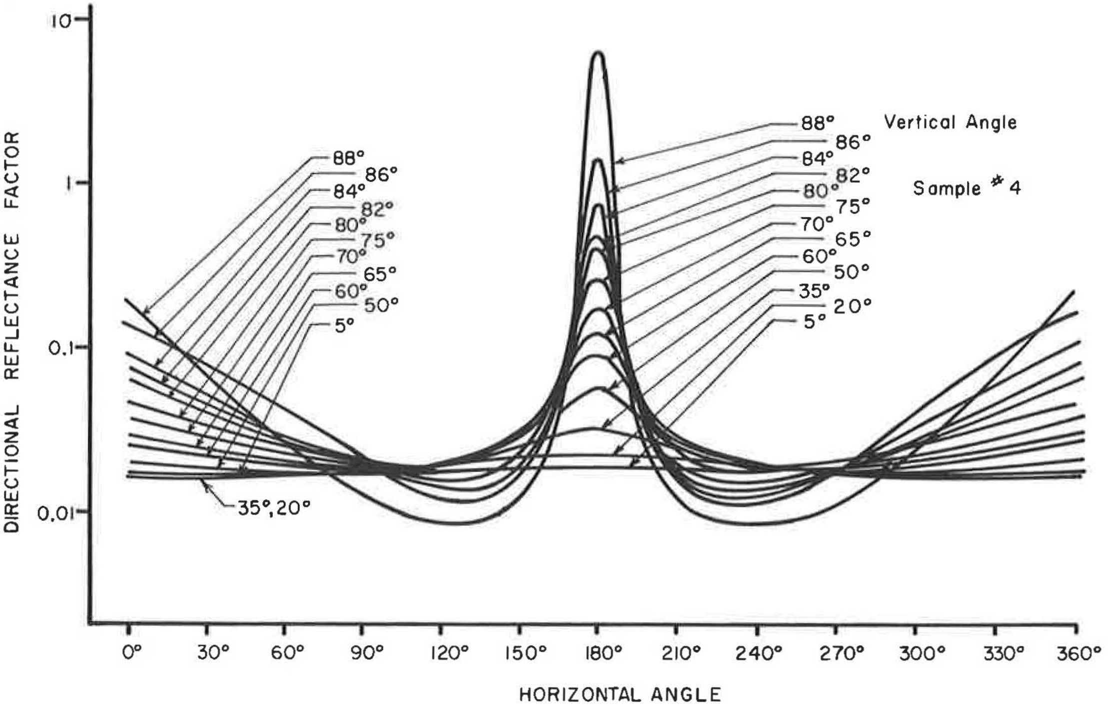

Figure 11. Direction reflectance factors for 400-ft viewing distance.

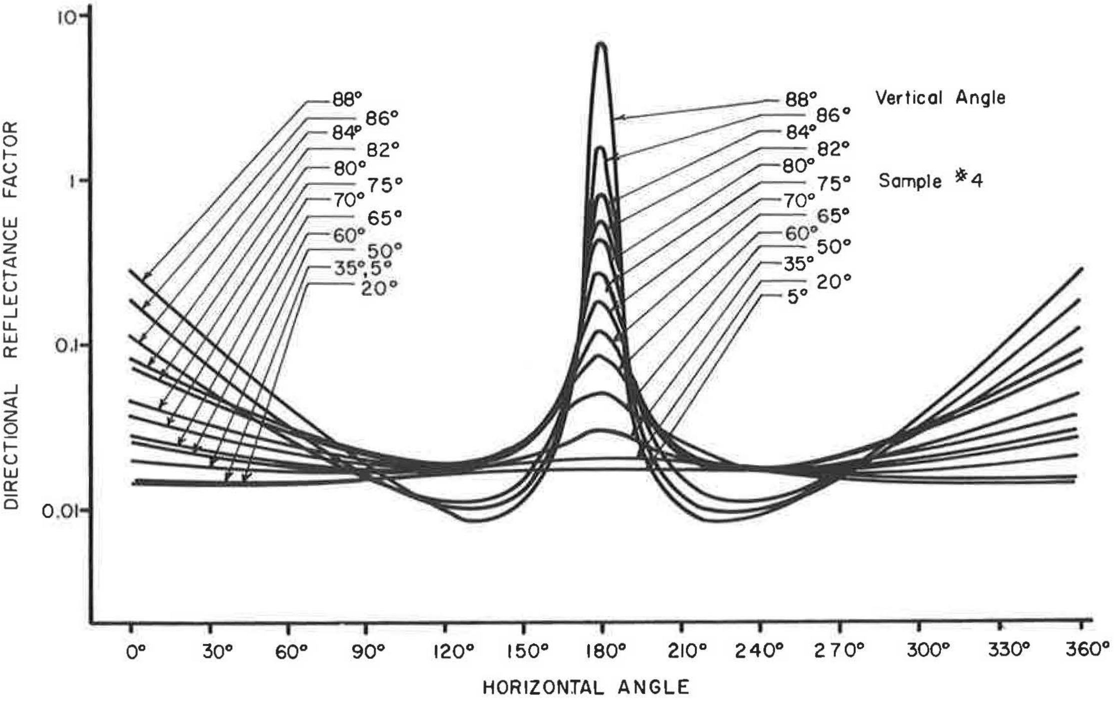

Figure 12. Directional reflectance factors for 600-ft viewing distance.

180- to 360-deg portion being almost a mirror image of the 0- to 180-deg portion of the graphs. The discussion here is limited to the 0- to 180-deg area.

The graphs show that the directional reflectance factors vary with changes in both the horizontal and vertical angles of the light source and with viewing distance. For each viewing distance the maximum value occurs for horizontal and vertical angles of 180 and 88 deg, respectively. The occurrence of the minimum value is greatly influenced by the simulated viewing distance. For a viewing distance of 50 ft, the minimum value is associated with the 5-deg vertical angle and is nearly constant for all horizontal angles. For the 600-ft viewing distance, the minimum value is associated with the 88-deg vertical angle and a horizontal angle of approximately 130 deg. For the larger vertical angles the factors are decreasing in magnitude in the 0- to 130-deg horizontal angle region. This is probably due to reflections from the faces of individual particles of aggregate.

As the source vertical angle increases from 5 to 88 deg, there is a marked increase in the directional reflectance factor for each viewing distance. For the 50-ft viewing distance the ratio of the factor at 88 deg to the factor at 5 deg is 44. The ratio is 73 at 100 ft, 148 at 200 ft, 333 at 400 ft, and 413 at 600 ft.

The effect of changes in viewing distance is shown in Figure 13. Here the directional reflectance factor is plotted as a function of vertical angle and viewing distance for a horizontal angle of 180 deg. The factors for the 50- and 100-ft viewing distances are very close at all but the greatest vertical angles. This is also true for the 400- and 600-ft distances. For vertical angles less than approximately 84 deg, the directional reflectance factors decrease as the viewing distance increases. However, due to the rapidly changing slope of the curves in the 84- to 88-deg region, the factors for this area increase with increasing viewing distance.

Further study and comparison of Figures 8 through 13 indicates that the directional reflectance properties of this sample could be characterized by only three graphs,

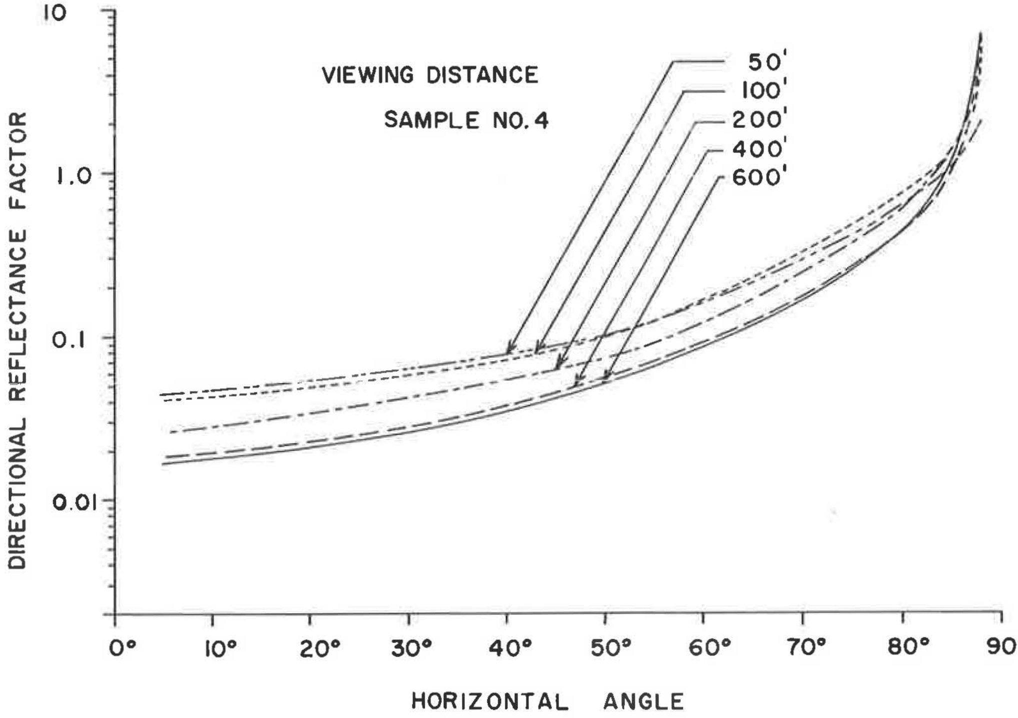

Figure 13. Directional reflectance factors for 100-deg horizontal angle.

rather than the five presented here. The 50- and 100-ft viewing distance curves could be combined into a single set of curves, as could the curves for the 400- and 600-ft viewing distances.

SUMMARY

A directional reflectance goniometer has been developed for use in the laboratory in conjunction with 12-in. pavement core samples. Measurements made with this reflectometer have proven to be both accurate and repeatable. The directional reflectance characteristics of several pavement surface samples have been recorded and the data for one sample have been reported here. Data of this nature, combined with appropriate handling techniques, provide the illuminating engineer with a means for calculating roadway luminance from a horizontal footcandle specification.

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Optimization of Roadway Lighting Systems

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•ROADWAY lighting has long been used on city streets where it serves a number of functions in addition to providing for safety and efficiency of traffic operation. Only in recent years have highway departments and municipalities realized the benefits that could be had by lighting heavily traveled high-speed arterials such as freeways and major streets in outlying areas. This new concept in roadway lighting embraces a single-purpose function, namely, to light the roadway for the express purpose of improving the safety and efficiency of traffic operation.

There is no doubt that illumination of principal roadways can be justified on the basis of safety. This is well documented in the Congressional Record (1), where the Honorable Charles Farnsley, Representative from Kentucky, reported on the benefits of roadway lighting and presented documentary evidence.

As substantial mileage of the Interstate System was completed in Texas, the state highway department recognized the need for lighting these facilities, especially in the urban areas. However, officials were greatly concerned that the design criteria for roadway lighting had not changed to meet the challenge of the new generation of modern highways. Because of this concern, a research project in roadway lighting was initiated in 1964 by the Texas Transportation Institute and the Texas Highway Department in cooperation with the U. S. Bureau of Public Roads. The objective of the first phase of this research was to determine the optimum geometric configuration of lighting systems that would provide functional and economical roadway lighting for freeway-type facilities. Prior to this research, the Texas Highway Department specifications for roadway lighting called for luminaires to be mounted at a maximum height of 30 feet and a spacing generally not to exceed 160 feet. These specifications were typical of many throughout the country.

Lighting systems designed on the basis of these early specifications left much to be desired for traffic operations on high-speed roadways. A "puddle of light" was spilled onto the roadway immediately under the luminaire. This bright puddle of light completely overshadowed the effectiveness of a lower intensity of illumination that could be directed to the fringe of the lighted area. The environment resulting from this system of illumination was that of extreme variations. The driver, passing from the puddle of light into the area of relative darkness was continually experiencing changes in his environment and rapidly becoming a victim of fatigue without realizing it. The human eye adapts from light to dark and dark to light conditions quite rapidly and thus, with this system, the driver's eyes are in a continuous state of adaptation, causing fatigue during prolonged exposures. Therefore, one of the major objectives of the research was to improve the uniformity of illumination systems.

THE STUDY

The purpose of this study was to determine the optimum height and spacing of luminaries in lighting systems for access-controlled facilities. Considerations in determining the optimum geometric configuration were (a) obtaining a more functional system; (b) reducing glare; (c) reducing the overall cost of installation, operation, and maintenance; and (d) reducing the number of poles to reduce fixed-object hazards.

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Figure 1. Full-scale illumination facilities.

A full-scale laboratory approach was taken in this study to facilitate subjective as well as objective evaluation of lighting systems. Engineers and researchers felt that there would be considerable merit in being able to observe the illumination produced by various geometric configurations and make collective or team decisions based on these observations. Further, objective evaluations were necessary to be able to describe these systems analytically, to make objective comparisons, and to substantiate the subjective evaluations.

Facilities

Full-scale illumination laboratory facilities were developed at the Texas A & M Research Annex. Ten trailer-mounted portable lighting towers were constructed to provide luminaire mounting heights up to 60 ft. Since the towers were trailer-mounted, the selection of longitudinal spacings between luminaires was unlimited.

A large concrete paved area, approximately 500 by 3500 ft, was striped for 12.5-ft traffic lanes and marked in a 10 by 12.5-ft grid pattern for photometric studies. Figure 1 is an overall view of the test facilities.

A GE SL 480-A Street Lighting Meter was used to measure light intensity in horizontal footcandles. This meter was later modified to facilitate measurement of vertical footcandles. Also, a Pritchard Spectra Photometer, with a glare lens, was obtained later for studies of brightness and glare.

Experimental Procedure

The study of photometrics phase of the research included studies of 400-watt and 1000-watt Type III mercury-vapor luminaires. Three 400-watt luminaires from each of four manufacturers and three 1000-watt luminaires from each of three manufacturers were obtained for the tests. To reduce the influence of the lamps on the test results, only one make of clear mercury-vapor lamps was used, with rated outputs of 21,500 and 57,000 lumens, respectively.

In order to give adequate consideration to the various geometric configurations of freeway lighting systems, the following systems were selected for the investigation:

A. System Type
   (1) One-side or house side lighting.
   (2) Median lighting, transverse spacing of 10, 20, and 30 ft.
B. System Configuration
   (1) 400-watt units
      (a) Mounting heights of 30, 40, 45, and 50 ft.
      (b) Longitudinal spacings of 100, 120, 140, 160, 180, 200, 220, 230, 240, and 250 ft.
   (2) 1000-watt units
      (a) Mounting heights of 50 and 60 ft.
      (b) Longitudinal spacings of 240, 260, 280, 300, 320, 340, and 360 ft.

These systems represent a large number of possible combinations for both 400-watt and 1000-watt luminaires. This number is increased when different manufacturers and the variability among individual units are considered. Each combination would constitute a field study and would require several hours to obtain photometric data, so it was apparent that some means to expedite data collection was needed. Various sampling techniques were considered but finally a means of generating synthetic systems from basic illumination measurements was selected because it could be performed rapidly and economically by electronic computer.

The synthetic approach involved taking photometric data for each luminaire at each mounting height. Then, for each mounting height the data from the three luminaires of the same manufacturer were averaged at each grid point. Further, the data at "mirror" points on opposite sides of the transverse axis of the luminaire were averaged to give a symmetrical pattern. The synthetic systems were then generated by arranging the resultant light distribution patterns in the desired geometric configuration and summing the overlapping illumination values at each grid point of the system.

Assuming the luminaire to be mounted over the edge of the roadway, the computer was employed further to determine the following photometric variables for each lane of each of the lighting systems:

1. Average illumination on each lane;
2. Maximum illumination on each lane;
3. Minimum illumination on each lane;
4. Ratio of maximum to minimum illumination on each lane; and
5. Ratio of average to minimum illumination on each lane.

In addition, values of the following variables were obtained for roadways of two-lane, three-lane, four-lane, and five-lane widths:

1. Average illumination;
2. Maximum illumination;
3. Minimum illumination;
4. Largest of the ratios of maximum to minimum illumination on each lane; and
5. Ratio of average to minimum illumination.

The final step in the analysis performed by the computer was to produce iso-footcandle charts for the single luminaire and for each of the systems. In the first attempts to produce machine plots of these charts a Calcomp X-Y plotter was used, but due to excessive time requirements, an alternate technique known as the U-M Plot routine

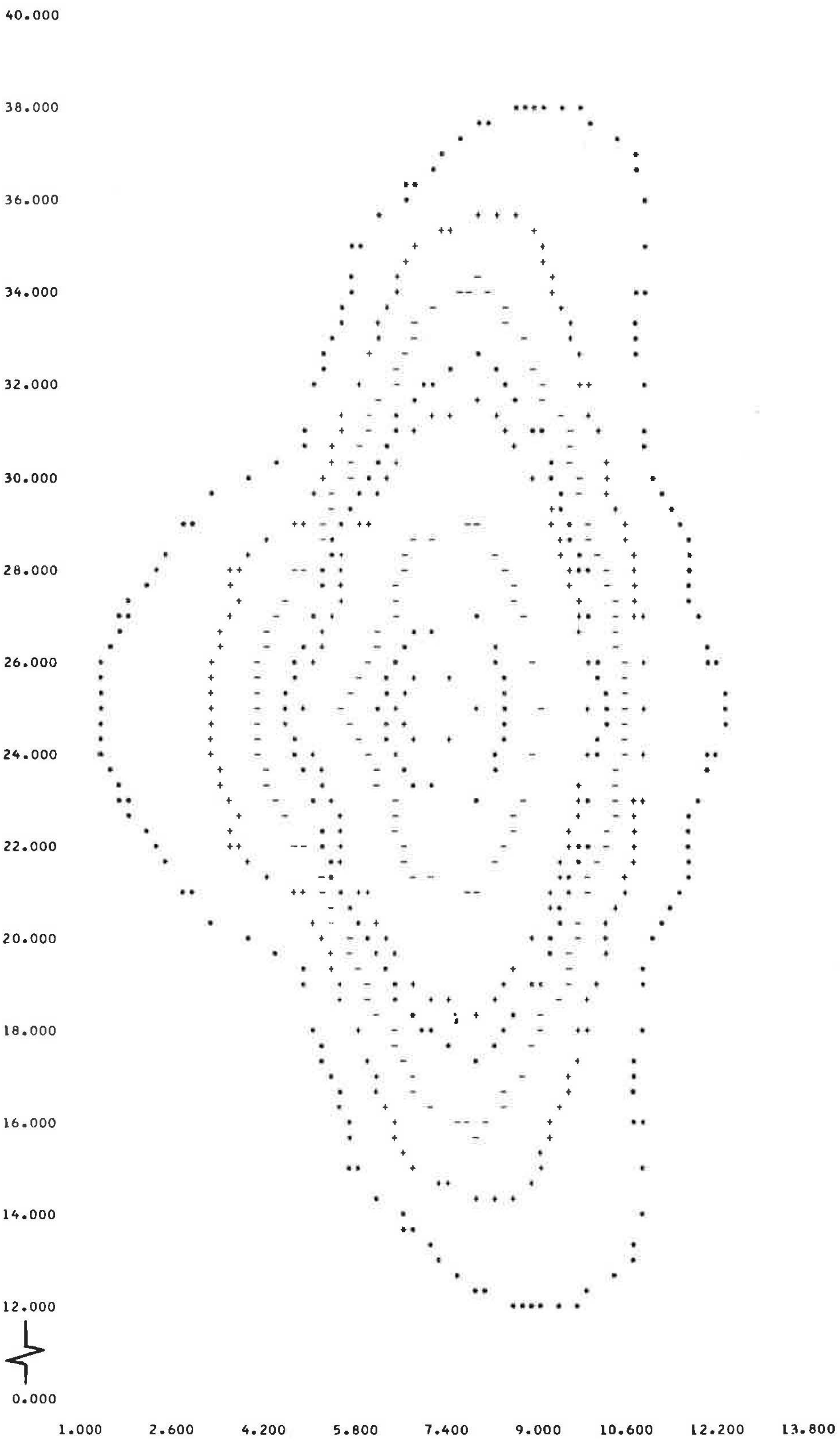

Figure 2. Iso-footcandle chart prepared by U-M Plot method.

was substituted. This technique utilized a standard IBM printing machine to provide graphical representation of data. The cost of plotting the iso-footcandle charts by the U-M Plot technique was only a fraction of the cost of plotting by the X-Y plotter. Figure 2 shows an actual plot using the U-M Plot technique.

The entire computer analysis procedure of building the synthetic systems, determining the photometric variables, and plotting the iso-footcandle chart was repeated for both 400-watt and 1000-watt units from each manufacturer at each of the mounting heights tested. Then a series of field studies were conducted on a random sample of the possible systems in order to ascertain the reliability of this technique. The data from the field tests were compared with those of the corresponding synthetic systems and it was found that the differences were not appreciable.

The photometric characteristics of the various lighting systems determined in the computer analysis were compared and the photometric variables were related by graphic interpretation to roadway lighting system parameters to illustrate the relationships between luminaire mounting height and spacing and the resultant system photometrics.

DISCUSSION OF RESULTS

As stated previously, the purpose of this study was to determine the optimum height and spacing of luminaires in lighting systems for access-controlled facilities. Considerations in determining the optimum geometric configurations were

1. Obtaining a more functional system;
2. Reducing glare;
3. Reducing the overall cost of installation, operation, and maintenance; and
4. Reducing the numbers of poles to reduce fixed object hazards.

In this discussion, primary attention will be devoted to results pertaining to a more functional system.

Functional Systems

A freeway lighting system should adequately illuminate the roadway so that safety and efficiency of traffic operation will be achieved. Therefore, it is necessary to relate this function to illumination variables. However, the main difficulty that has been experienced for many years in illumination research is our inability to relate visibility and the roadway environment to illumination variables. Consequently, one of the oldest problem-solving techniques was used to produce results in this study, that is, observation and subjective evaluation. However, lighting systems cannot be designed using subjective evaluation as criteria, and therefore it was necessary to compliment this research approach with objective or analytical studies.

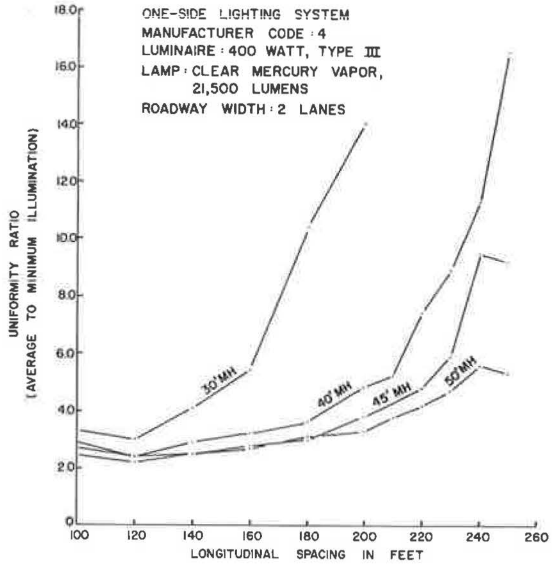

Figure 3. Uniformity ratio vs longitudinal spacing for different mounting heights.

400-Watt Luminaires—Many nights were spent by the research staff and the study team observing various system configurations of 400-watt luminaires. It was the consensus of the study team that higher mounting heights provided a more acceptable illumination system. This was based on two observed phenomena: (a) the discomfort from glare was reduced, and (b) the "puddles of light" were spread, re-

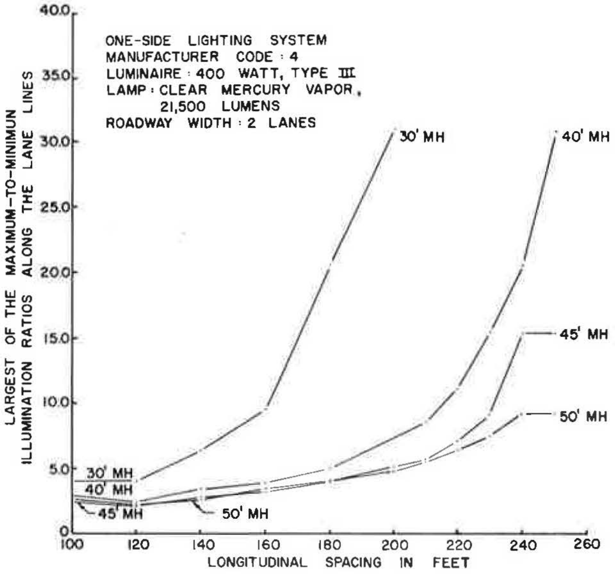

Figure 4. Ratio of maximum to minimum illumination vs horizontal spacing for different mounting heights.

ducing the maximum intensity and improving the uniformity of illumination. By observing illumination systems at mounting heights of 30 to 50 ft and at various longitudinal spacings, it was found that the 40-ft mounting height and 200-ft spacing produced the most desirable results. The visual discomfort was eliminated and the glare levels were no longer objectionable. The team did not feel that any additional benefits were derived by extending the 400-watt luminaires to the 45- and 50-ft mounting heights.

There are objective or analytical reasons for the apparent improvement produced by the higher mounting height, and for the decision reached by the team. There was a measurable variation in uniformity as the mounting heights and spacings were varied. Figure 3 illustrates this variation. It may be noted that the most significant variation occurs between 200 and 220 ft for the 40-ft mounting height. This is the "optimum" configuration arrived at by the observation team. Note also that for the 30-ft mounting height the variation in uniformity as related to spacing is much more severe and spacing must be limited to 160 ft to achieve reasonable average to minimum uniformity. Figure 3 also substantiates the team observation that

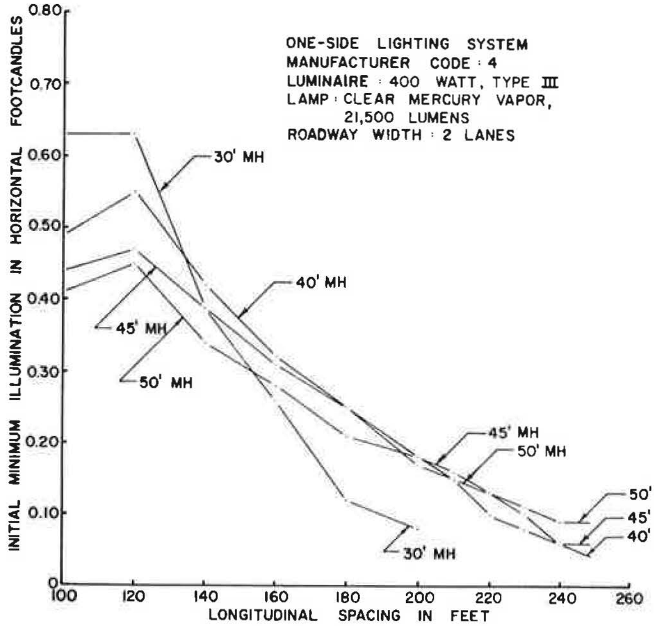

Figure 5. Initial minimum illumination vs horizontal spacing for different mounting heights.

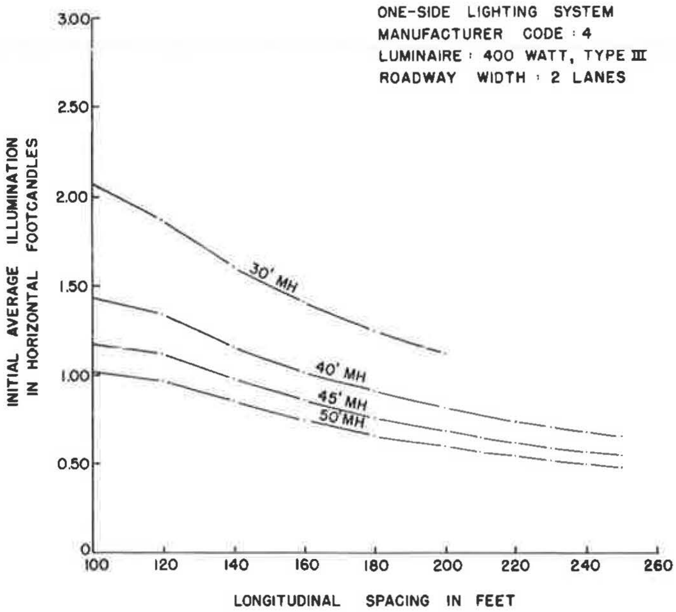

Figure 6. Initial average illumination vs longitudinal spacing for different mounting heights.

there is very little added benefit of extending the heights to 45 and 90 ft. Even more significant in the control of uniformity is the relationship shown in Figure 4. This represents the ratio between maximum and minimum illumination as related to height and spacing and it is this relationship that gives the true measure of uniformity. It is not the average to minimum ratio that the driver evaluates, but the bright and dark

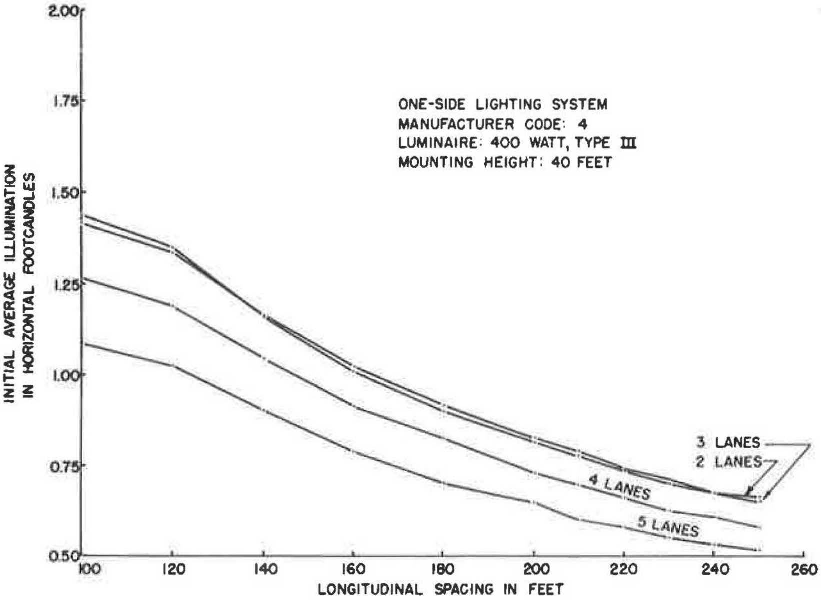

Figure 7. Initial average illumination vs longitudinal spacing for different roadway widths.

spots, or maximum and minimum areas of illumination. Note that the "optimum" ratio again occurs at the 200- to 220-ft spacing.

Further objective substantiation of the team's observation is shown in Figure 5. This illustration of minimum illumination as related to height and spacing shows a substantial increase in minimum illumination between the 30- and 40-ft heights. It is this minimum illumination that eliminates the apparent dark spots experienced with the lower mounting heights.

One other objective variable that must be considered is average illumination. Figure 6 shows the initial average illumination and height-spacing relationships. Upon first observation, it would appear that too much is sacrificed in average illumination by going to the higher heights. Remember, however, this average covers a much larger area and serves to eliminate the extreme bright spots that occur at the lower heights.

The illustrations that have been given are based on roadway widths of two to three lanes for a one-side system and four to six lanes for a median or two-side system. During the subjective tests, the study team observed that the 400-watt units mounted in a one-side geometric configuration would not adequately illuminate more than three lanes. It is appropriate then to discuss limitations of the 400-watt systems.

Figure 7 shows the significant reduction in average illumination that occurs between three, four, and five lanes. In addition, similar reductions were measured for minimum illumination. As a result, the uniformity ratio (average to minimum) did not show a substantial change for the wider roadway widths. However, the maximum to minimum illumination ratios, the most critical measures of uniformity, were found to increase very rapidly between three, four, and five lanes. These relationships serve well in substantiating the team's observation that the 400-watt units cannot adequately illuminate more than three lanes (six lanes with a median or two-side configuration).

Other factors that were found to influence the photometric variables are illustrated in Figures 8 and 9. These figures are specific illustrations of variations for various manufacturers and for transverse spacing in median systems and represent only two of the photometric variables, average illumination and uniformity. Complete tabular values and diagrams for all possible geometric combinations and photometric variables have been published and are available upon request from the authors.

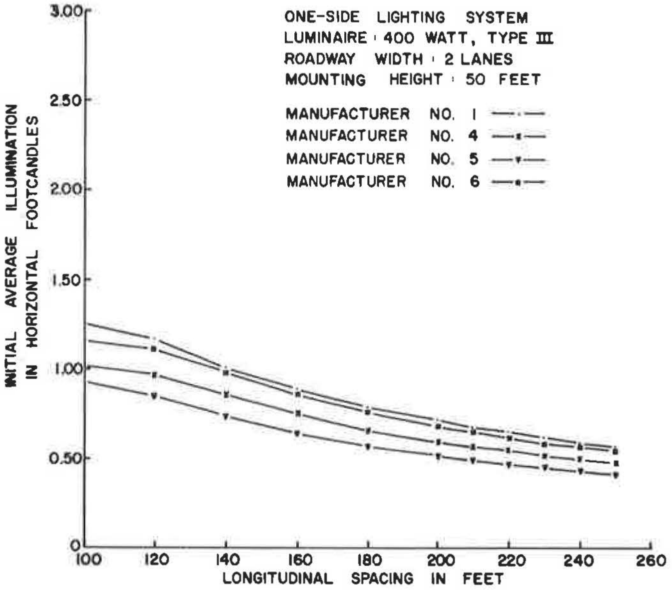

Figure 8. Initial average illumination vs longitudinal spacing for different manufacturers.

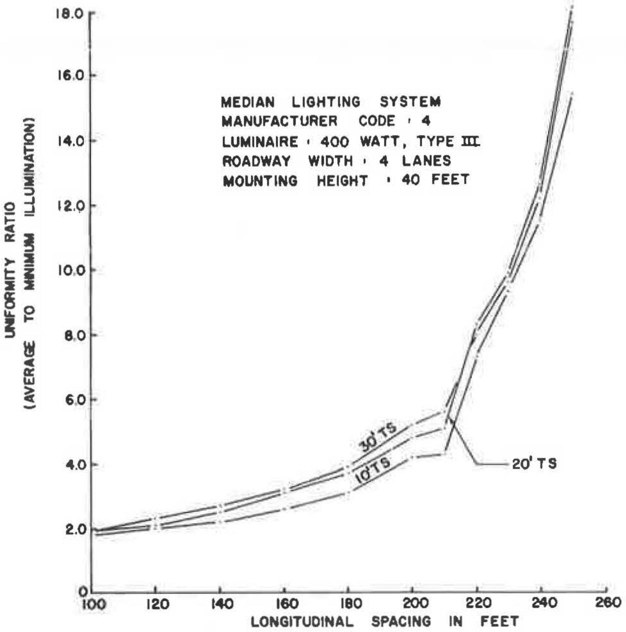

Figure 9. Uniformity ratio vs horizontal spacing for different transverse spacings.

1000-Watt Luminaires—Most of the earlier freeway lighting systems utilized 400-watt mercury vapor luminaires. However, recent years have seen the development of 1000-watt mercury vapor luminaires, which are being used more and more in freeway lighting design. This development comes at a very opportune time, because most of the newer freeways are more than six lanes, which was stated previously as the maximum effective width for 400-watt luminaires. It will be illustrated subjectively and objectively that the 1000-watt units pick up nicely where the 400-watt units stop.

At the test facility, 1000-watt units were observed at heights of 40, 50, and 60 ft. It was immediately concluded that 40 ft was too low because of glare and extreme intensity; thus, no further consideration was given to that height. However, many combinations of the 50- and 60-ft heights were observed and the study team concluded that the most desirable system consisted of 50-ft mounting heights and 300-ft spacings. This combination led the team to observe that the system was "comfortable" and that "visibility" was superior to any other configurations observed Again, there are objective or analytical reasons to substantiate these observations.

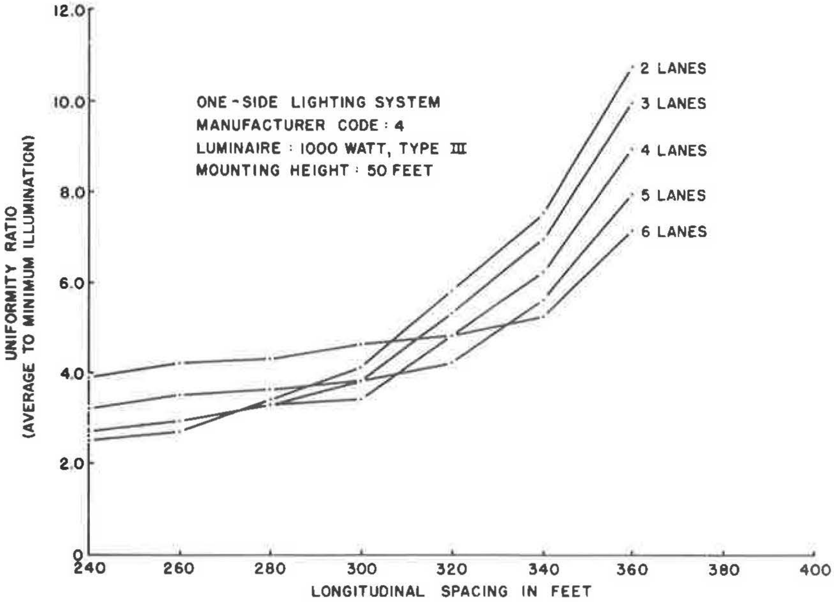

Figure 10. Uniformity ratio vs longitudinal spacing for different roadway widths.

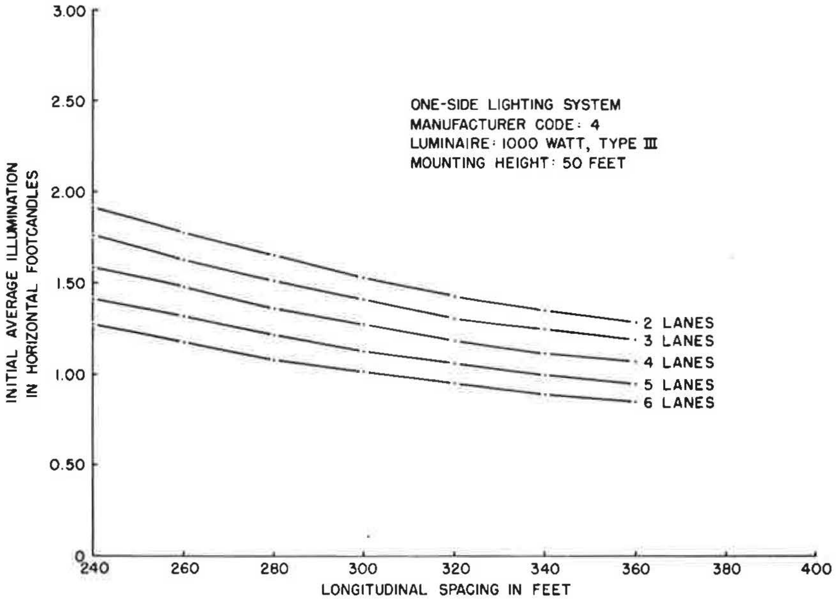

Figure 11. Initial average illumination vs longitudinal spacing for different roadway widths.

As with 40-ft mounted 400-watt units, the 50-ft mounted 1000-watt units produced excellent uniformity for up to six lanes, as illustrated in Figure 10. Note the "optimum" uniformity that occurs at or near a longitudinal spacing of 300 ft. The "optimum" maximum to minimum ratio also occurs at the 300-ft spacing and is low when compared with the other configurations.

Also, in terms of initial average illumination, the 50-ft mounting height was shown to be effective for six lanes, as illustrated in Figure 11. With 300-ft spacings the average illumination over six lanes is a little over 1.0 footcandle.

The other variables associated with 1000-watt systems, both photometric and geometric, that were discussed for the 400-watt units, were shown to have approximately the same relationship as those for 400-watt systems.

Reduced Glare

The ideal seeing conditions exist when the whole field of view is as uniform in brightness as possible. When viewing a bright field, some of the light entering the eye is reflected, causing stray light within the eye. The effect of stray light in the eye is to superimpose a veiling brightness upon the visual field of view and decrease the brightness contrast needed for discernment. For nonuniform light in the field of view, the stray light in the eye increases and the veiling brightness is directly proportional to the intensity of the glare source. The effects of two or more sources are additive. For nonuniform fields of view as found in roadway lighting with large glare sources present, the stray light produces disability veiling brightness (glare) which can adversely influence visibility and comfort.

In the subjective observations it was noted that the glare was decreased as the mounting height of luminaires increased. This decrease in glare for increased mounting heights follows from the expression for glare:

$$B_V = \frac{10\pi E \cos \theta}{\theta (1.5 + \theta)}$$

where

B_V = equivalent veiling luminance produced by disability glare, in footlamberts;
E = illumination striking the plane of the pupil of the eye in lumens per ft^2, measured normal to the incoming ray; and
θ = the angle between the line of sight and the source of glare.

When the mounting height is increased the angle θ is increased for any glare source and for any position as long as the line of sight is the same. In subsequent studies of glare for various system configurations it was shown that glare does decrease as the mounting height increases (2). Further studies (3) showed that glare from 400-watt Type III (medium distribution) luminaires mounted at 40 ft approximates that from 400-watt cutoff luminaires mounted at 40 ft. The same relationship is true for 1000-watt Type III (medium distribution) luminaires and 1000-watt cutoff luminaires when mounted at 50 ft.

Reduced Cost

Substantial savings can be realized by taking advantage of the higher mounting heights. The 40-ft mounting height of 400-watt units, as compared to 30-ft mounting heights, allows an increase in longitudinal spacing of approximately 20 to 25 percent. This means that the initial installation cost can be reduced accordingly. There is a slight increase in per-pole cost because of the added length. However, this is far outweighed by the reduction in total number of poles and luminaires. This reduction in number of poles and luminaires also reflects substantial savings in cost of operation since 20 to 25 less power consumption will be required.

It is also expected that the cost of maintenance will be reduced accordingly. One objection that many administrators have voiced against the higher mounting heights is the need to purchase service equipment capable of maintaining the greater heights. This objection is ill-founded since, on practically any lighting project, the higher mounting heights will produce sufficient savings to purchase the necessary service equipment.

As an example of the economy of the higher mounting heights, two of the 42 lighting projects in the State of Texas using the higher mounting heights have resulted in savings sufficient to cover all costs of a 5-year lighting research project still under way in Texas. The cost of the research project: $250, 000.

Improved Safety

Two immediate safety benefits are derived from the higher mounting heights. First, the reduction in number of luminaires reduces the total number of glare sources and these glare sources contribute much less glare due to their greater height. Second, and of great importance, is the significant reduction in fixed-object hazards due to fewer luminaire supports. This reduction is very significant where the light sources can be mounted in a median configuration.

Median vs House-Side Lighting

The subjective and objective studies have indicated that 400-watt and 1000-watt luminaires have applications in median and house-side lighting configurations. However, each has limitations that must be recognized. For example, it was observed that 400-watt units may be used in a median-mounted configuration for a four-lane roadway but not for a six-lane facility. The units do not provide sufficient illumination for the auxiliary lanes and ramp connection points that are beyond the three main lanes. On the other hand, the 400-watt units mounted on both sides of the facility, rather than in the median, provide adequate illumination for all traffic lanes of a six-lane facility since the luminaires can be placed in close proximity to the ramp connections.

The 1000-watt luminaires are generally applicable to facilities of six or more lanes and are most economically located in the median for the wider facilities. However, it is possible and practical to use these units in a side-mounted arrangement. For example, where the median is too narrow to accommodate the supports, the 1000-watt units can be used effectively and economically in a staggered side-mounted arrangement and illuminate roadway widths up to approximately 100 ft.

SUMMARY OF RESULTS

The principal objective of this research was to determine the optimum geometric configuration of roadway lighting systems to produce a satisfactory driving environment for freeway-type facilities. To accomplish this, both objective and subjective studies were made using full-scale roadway lighting laboratory facilities.

This research showed that a more economical and functional lighting system can be obtained by increasing the mounting height of conventional Type III (medium distribution) mercury vapor luminaires. It was found that 400-watt luminaires mounted at 40 ft and spaced 200 ft apart produced the most functional system for roadways with two and sometimes three lanes in each direction. Type III 1000-watt mercury vapor luminaires mounted at 50 ft and spaced 300 ft apart produced the most functional lighting system for roadways with three to six lanes in each direction.

The benefits derived from higher mounting heights are

1. Reduction in discomfort due to glare;
2. Improved uniformity of illumination; and
3. Greater safety and lower cost of installation and operation due to fewer luminaires per mile.

RECOMMENDATIONS

The results of this research suggest that, in order to design the most efficient and functional lighting system, consideration must be given to the relationships between the geometric parameters of roadway lighting systems and the photometric variables to be used as criteria. Careful evaluation of roadway geometrics must be exercised to assure the proper application of lighting system design.

Based on this thought and the results of this study, the following design applications are recommended for consideration.

Design No. 1

Roadway Description—Controlled-access facility, four lanes excluding auxiliary lanes, normal median width.

Lighting System Description—
Luminaires: Type III, 400-watt mercury vapor
Mounting Height: 40 ft
Longitudinal Spacing: 200 ft
Placement of Supports: Median, dual-mounted luminaires

Design No. 2

Roadway Description—Controlled-access facility, six lanes excluding auxiliary lanes, normal median width.

Lighting System Description—
Luminaires: Type III, 400-watt mercury vapor
Mounting Height: 40 ft
Longitudinal Spacing: 200 ft
Placement of Supports: House-side, both sides

or

Luminaires: Type III, 1000-watt mercury vapor
Mounting Height: 50 ft
Longitudinal Spacing: 300 ft
Placement of Supports: House-side, both sides, staggered

Design No. 3

Roadway Description—Controlled-access facility, six lanes excluding auxiliary lane, one-way, no median.

Lighting System Description—
Luminaires: Type III, 1000-watt mercury vapor
Mounting Height: 50 ft
Longitudinal Spacing: 300 ft
Placement of Supports: House-side, one-side

Design No. 4

Roadway Description—Controlled-access facility, six to eight lanes, restricted median width.

Lighting System Description—
Luminaires: Type III, 1000-watt mercury vapor
Mounting Height: 50 ft
Longitudinal Spacing: 300 ft
Placement of Supports: House-side, both sides, staggered

Design No. 5

Roadway Description—Controlled-access facility, more than eight lanes, restricted median width.

Lighting System Description—
Luminaires: Type III, 1000-watt mercury vapor
Mounting Height: 50 ft
Longitudinal Spacing: 300 ft
Placement of Supports: House-side, both sides

Design No. 6

Roadway Description—Controlled access facility, six to twelve lanes, normal median width.

Lighting System Description—
Luminaires: Type III, 1000-watt mercury vapor
Mounting Height: 50 ft
Longitudinal Spacing: 300 ft
Placement of Supports: Median, dual-mounted luminaires.

In addition to these recommendations, it should be pointed out that the light source may be mounted over the outside edge of the roadway, or as much as 12 to 15 ft from the roadway. When using 400-watt units on wider facilities, the light source should be mounted as closely as possible to the outside edge of the roadway. However, when using 1000-watt units, the light source may be mounted 12 to 15 ft from the roadway edge without affecting the efficiency of the luminaires. It appears desirable to tilt the luminaire upward toward the roadway as far as the mounting assembly of the luminaire will permit (approximately 3 degrees).

The longitudinal spacing of the recommended designs may also be varied to fit certain geometric features of the roadway. For example, the longitudinal spacing may be increased or decreased to balance the lighting system on each side of overpassing structures without seriously impairing the efficiency of the system. However, these spacing adjustments should be limited to 160 to 240 ft for 400-watt units and 260 to 340 ft for the 1000-watt units, and should be used only when necessary.

SIGNIFICANCE OF RESULTS

These results and recommendations are significant because they are immediately applicable in the design of improved roadway lighting systems for access-controlled facilities. The Texas Highway Department has developed new specifications for roadway lighting systems based on this research, and more than 40 jobs have been designed using these specifications. In addition to the improved illumination, these jobs have resulted in immediate savings on the order of one million dollars. Other states have shown considerable interest in this research, and many are revising their specifications accordingly.

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Letter and Sign Contrast, Brightness, and Size Effects on Visibility

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•AN earlier report (1) provided results of experiments on sign position and brightness variables, and was preceded by an annotated bibliography (2), and a paper describing the research program (3). This paper deals with experimental results on sign size and brightness and letter-to-sign brightness ratio.

The experimental procedure was the same one used earlier. A typical highway scene for day or night conditions was projected continuously on the screen in front of the subject. From time to time under automatic control, keyed by his own responses to an auxiliary task, four simulated "interstate green" highway signs were flashed on the screen superposed on the previous highway scene. Thus visual adaptation was maintained constant. The auxiliary task was to relight one to four small red lights which went out in random order from a matrix of 12 lights located just below the highway picture on the screen.

This report gives the results of four additional experiments which used this same general experimental procedure. The objective of this series of experiments was to measure (a) the effects of sign size, brightness, and letter-to-sign brightness ratio, and (b) the effects of competing signs on highway sign visibility. The laboratory approach enabled the use of many combinations and better control of conditions than would be possible in outdoor, full-scale experiments. No attempt was made to measure legibility of the legend, but a combination of letters and symbols gave an indication of the effect of the letter-to-sign brightness ratio.

The purpose of Experiment 6 in the series was to investigate size and brightness combinations with the brightness of the letters and symbols held constant. To explain effects found in Experiment 6, Experiment 7 used blank simulated interstate green signs (of the same size and brightness combinations but without letters or symbols). Experiment 8 further investigated effects of letter brightness with the same simulated sign brightness and size combinations but with the letter-to-sign brightness ratio maintained more nearly constant. Experiment 10 employed signs of one size only, viewed against a night background to measure the effect of competing advertising signs.

RESEARCH PROGRAM

The laboratory simulation procedure was the same as that used in the five experiments previously reported. A highway scene in color was projected on a screen in front of the subject, who responded to simulated signs flashed on the same background for 1-second intervals. The subject indicated which of the four signs was seen "first and best" by pushing the appropriate button under his right hand and also the one seen next best.

An auxiliary task consisted of relighting one, two, three, or four small red signal lights in a matrix of 12 by pushing the appropriately numbered button under his left hand. Automatically controlled circuits randomized the number of lights turned off. At unpredictable intervals, the subject's response activated the next stimulus sign combination presented. The setup was illustrated in Figures 1 and 2 of the earlier report (1).

Paper sponsored by Committee on Night Visibility.

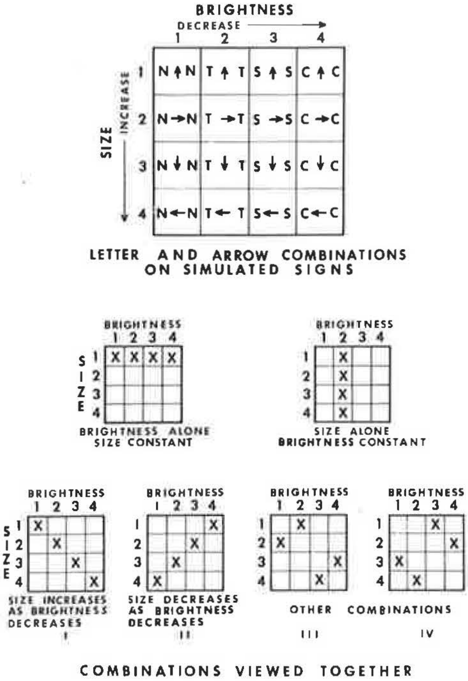

Figure 1. Size and brightness stimulus combinations.

Subjects were given practice with the auxiliary task and also with a partial series of simulated sign combinations. They were instructed to continue relighting the small signal lights and, when a set of simulated signs appeared, to give their immediate reaction as to which sign was "seen first and best" and which next best. Each group of subjects saw the test signs against only night or only day highway backgrounds. This eliminated the possibility that having seen an earlier series against a different background might influence the subject's responses.

A darkened laboratory was used for the experimental work. The practice period furnished over five minutes of visual adaptation to the particular highway scene. This adaptation was maintained constant by continuous projection of the background scene alone when the simulated signs were not showing. In making the colored stimulus slides, the plain background always was made at the same time and under the same conditions as the stimulus slides carrying the simulated signs.

The number of first responses to each of the simulated sign combinations was scored from the paper tape of a multipen recorder actuated by the subject, and summated for each group of subjects. Significance of differences was tested statistically by use of the sign test, or the "t" test of mean differences.

Effects of Size and Brightness With Constant Letter Brightness

Experiment 6 was designed to measure the combined effects of brightness and size on sign visibility. The experimental design used the same four brightnesses used previously and a series of four sign sizes, the smallest being that used in previous experiments. Balancing out the effect of different sign positions, brightnesses, and sizes was necessary for a good experimental design. However, all possible combinations would have required 578 stimulus slides which probably would have introduced fatigue effects. As a compromise, a series of 24 presentations each for day and for night series was developed to give a total of 48 stimulus slides. Each simulated sign carried an arrow and two capital letters designed to be well within legibility range, since it was not desired to measure legibility. Figure 1 shows the letters and arrow directions used, one of the four letters for each brightness, and one of the four arrow directions for each size of sign.

A total of 46 subjects viewed the signs. Half saw the randomized series of slides against the day-snow and the other half against a night background. The 24 stimulus slides included four different orders of the following: (a) four brightnesses of the same size sign, (b) four sizes of the same brightness sign, (c) one diagonal in which size and brightness increased together, (d) one diagonal in which one increased and the other decreased, and (e) a folded diagonal so as to include all combinations in one of the series.

The subjects were instructed to ignore the particular letters and arrows and to record their immediate reaction as to which of the four signs was "seen best and quickest." They were then given practice with the auxiliary task and finally with a practice series of the simulated slides. There were 50 practice trails with the relighting task and a series of 24 practice slide presentations.

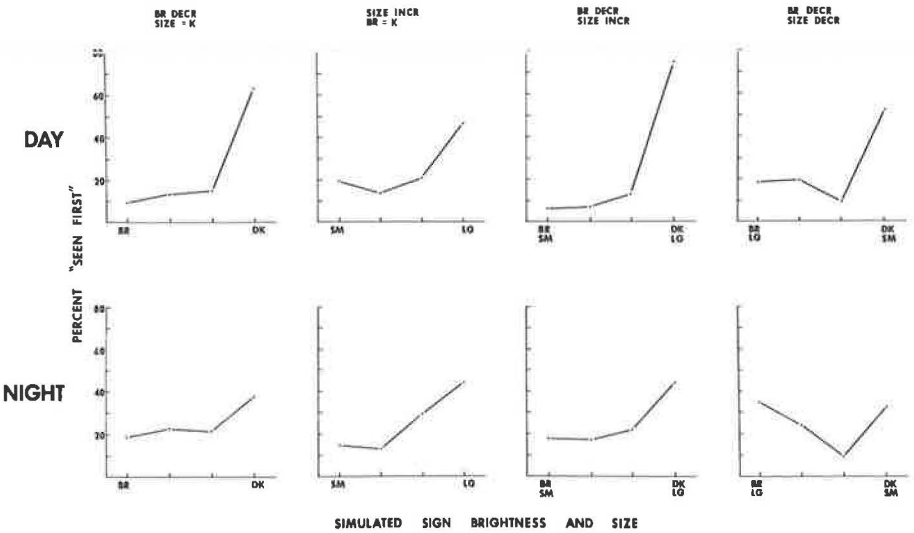

Figure 2. Results of Experiment 6—bright letters and arrows.

Scoring of the paper tape record from the multipen recorder showed which of the four simulated slides in each presentation was indicated by the subject to be seen best. The record for each subject was scored and tabulated. The sum of the scores for each of the possible combinations was entered in one box of the matrix.

These scores were then summated for each of the combinations of four brightnesses, sizes, or diagonals. Analysis could not be carried out across all combinations because every size and brightness was not seen in combination with every other.

Results are shown in Figure 2. The upper row of figures shows that, against the day-snow background, the darkest and the largest signs were seen best with the other variable held constant. When brightness decreased as size increased, darkest and largest signs were seen best. When size and brightness decreased together, dark-and-small signs were seen best more frequently than bright-and-large. Against the night background, somewhat similar relationships occurred, except that there was less additive effect of dark-and-large together and a larger percent of bright-large and dark-small being seen best.

The day relationships were similar to those found in earlier experiments. However, the night results showed the expected advantage of the largest sign, but an unexpected advantage of the darkest sign. This was contrary to results in the earlier experiments in which the brightest sign was seen best against night backgrounds.

It was hypothesized that the bright letters and the arrow symbol on each sign had influenced the night results. This hypothesis arose from the consideration that the letters were larger than those used in earlier experiments and that as the simulated sign was made darker the constant letter brightness resulted in a higher letter-to-sign brightness ratio.

Effects of Size and Brightness Without Letters

Experiment 7 tested the hypothesis from Experiment 6 that the letter-to-sign brightness ratio had enhanced the effect of the dark sign against the day background and had also caused it to be seen best against the night background as well. The same combinations of size and brightness and groups of four signs were used as in Experiment 6 except that the simulated signs were blank, i. e., carried no letters. If the unexpected results were due to the bright letters, it was hypothesized that we should obtain results consistent with the earlier experiments using blank signs.

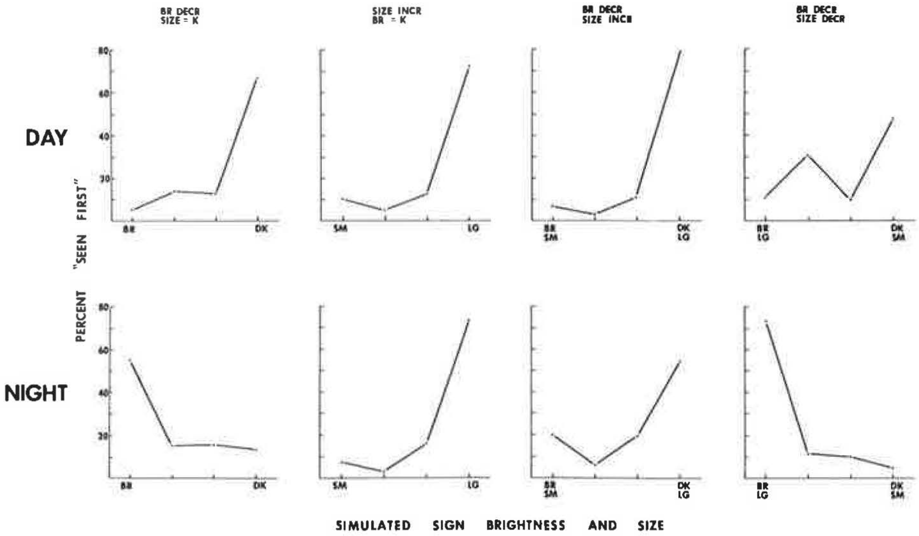

Figure 3. Results of Experiment 7—blank signs.

The results depicted in Figure 3 show that this hypothesis was confirmed. When seen against the day-snow background, dark-and-large were seen best, the two variables enhanced each other where size increased as brightness decreased, and opposed each other when size and brightness decreased together, i.e., bright-and-large, and dark-and-small were seen best more than other combinations.

When seen against the night background, the brightest sign was seen best in the majority of cases as it was in earlier experiments. When brightness was constant, the largest sign was seen best. Where brightness and size increased together, the bright-large sign was also seen best. When brightness decreased as size increased there was a trend toward opposing effects, i.e., neither the brightest sign nor the largest sign was seen as frequently as it had been when the other variable was constant.

Effects of Sign Size and Brightness With Reducing Letter Brightness

Experiment 8 was designed to check in another way the hypothesis that letter-to-sign brightness ratio, because it increased on the darker signs, was responsible for the apparent advantage of the darkest sign against the night background in Experiment 6. In Experiment 8, simulated signs were used having the same size and brightness and the same size letters and arrows. However, the neutral overlay used to reduce the brightness of the simulated sign was placed over the letters as well on signs 3 and 4. Thus, the brightness of the letter was reduced with that of the sign. Sign 1 (in which the background was lightened by a transparent white overlay) in itself reduced letter-to-sign brightness as compared with that of sign 2, which used the most saturated green material available. Thus, brightness sign 2 contained the highest letter-to-sign brightness ratio and the greenest (most saturated) green. Sign 1 was lighter and with a lower letter-to-sign brightness ratio, and signs 3 and 4 (increasingly darker) had proportionally reduced letter-to-sign brightness ratios.

If the hypothesis was correct, the size effect against the day background should occar with less advantage for the darkest sign. Because of the now reduced letter-to-sign contrast, against the night background relations more like those of Experiment 7 should result. The procedure was the same as in the two previous experiments.

The results tended to confirm the hypothesis. The upper row in Figure 4 shows results with the day-snow background. Brightness sign 2 was seen best with size constant. With brightness constant, the largest sign was again seen best most frequently.

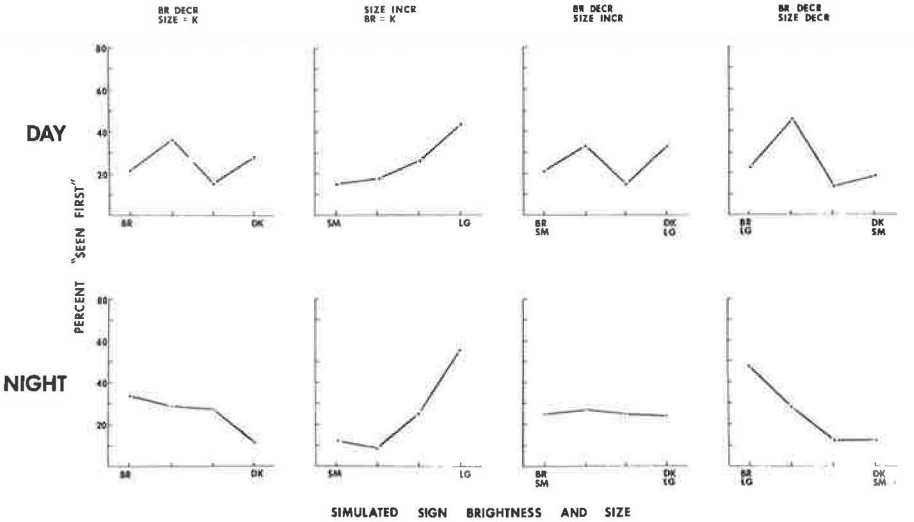

Figure 4. Results of Experiment 8—reduced letter-to-sign brightness.

When brightness decreased as size increased, there was an advantage for the darkest, largest sign and for the second brightest sign, i. e., the highest letter-to-sign brightness and most saturated green. When size decreased and brightness decreased together, the combination of second brightest and second largest was seen best most frequently. Thus, the influence of the letter-to-sign brightness overcame to some extent the advantage of the dark-large sign in the third and dominated the response in the fourth series of combinations.

The lower row of Figure 4 shows the results when the simulated signs were seen against the night background. With size constant, the previous advantage of the lightest sign was equalized with the second and third brightest. With brightness held constant, the dominant advantage of the largest sign remained. When brightness decreased as sign size increased, the opposing effects canceled each other, giving almost a horizontal line. When brightness and size decreased together, the bright-large was seen most frequently, but the second brightest (high letter contrast and saturated green) sign combined with the second largest was seen best more frequently than in Experiment 7.

Conclusions from Experiments 6, 7, and 8

It was concluded from the three experiments that the expected advantage for the largest of four signs was found consistently when the simulated green signs were seen against either day-snow or the night background. An advantage for the brightest of four blank signs was consistent when seen against the night background. Also, for night blank signs, brightness and size enhanced each other where both variables increased together and opposed each other where brightness decreased and size increased.

The bright letters resulted in an increasing letter-to-sign brightness ratio as sign brightness decreased. Against the day background this enhanced the advantage of the dark signs against the day-snow backgrounds. When letter brightness was reduced with sign brightness, the advantage of the darkest sign lessened and the second brightest (greenest, high letter-to-sign brightness) was increased. Against the night background, to reduced letter brightness tended to equalize the advantage of the two brightest signs and to balance the opposing effects of size and brightness.

Thus, it is clear that an advantage for visibility was enhanced by a combination of (a) greater sign brightness, (b) greater relative sign size, (c) contrast of sign against background, and (d) letter-to-sign brightness. These effects either enhanced or opposed each other, depending on the background against which the simulated signs were seen, and whether the letter-to-sign brightness ratio increased as sign brightness decreased.

Effect of Sign Size and Brightness and Competing Illuminated Signs

The purpose of Experiment 10 was to measure the effect of sign brightness against night backgrounds with competing illuminated advertising signs. Two night background scenes were used. One had a profusion of brightly illuminated advertising signs and the second somewhat fewer and less brilliant competing signs.

The stimulus slides were made using the same four brightnesses of simulated green signs carrying the same five nonsense letters as Experiment 3 (smaller than those of Experiments 6 and 8). Again, these were photographed in color against the two background scenes to produce the stimulus slides.

To increase the range of competing brightnesses, two different camera exposures were used one-half stop apart. This resulted in two presentation series against each of the background scenes, one darker than the other. A total of 40 subjects viewed the slides, 10 viewing each combination of background, advertising signs, and normal or darker exposure.

Both position of the sign, sign brightness, and relation to the background affected visibility. The results when the simulated signs were viewed against the brighter surround are shown in the upper part of Figure 5, and the darker surround in the lower part of Figure 5. The solid line represents the background scene made with normal exposure (brighter), the dashed line with reduced exposure (darker).

Against the brighter night surround, the darkest of the four signs was seen best more frequently for the brighter exposure and for the right-hand position. This position was next to a large, bright advertising sign. The brightest of the four simulated signs, on the other hand, was seen best against the slightly darker exposure and the left-hand position where competing signs were not as bright.

In location B, which included street lighting but fewer competing signs, the right position was seen best the least and the darkest sign the most frequently. However, the brightest of the four signs was seen best against the background with darker exposure and the darker against the background with the normal or lighter exposure.

Thus, on the whole, the brightest sign was seen best more often against darker backgrounds and the darkest of the four signs against lighter backgrounds and brighter surround. This does not mean that the signs were more legible, since there was no reading of the nonsense letters on the signs involved.

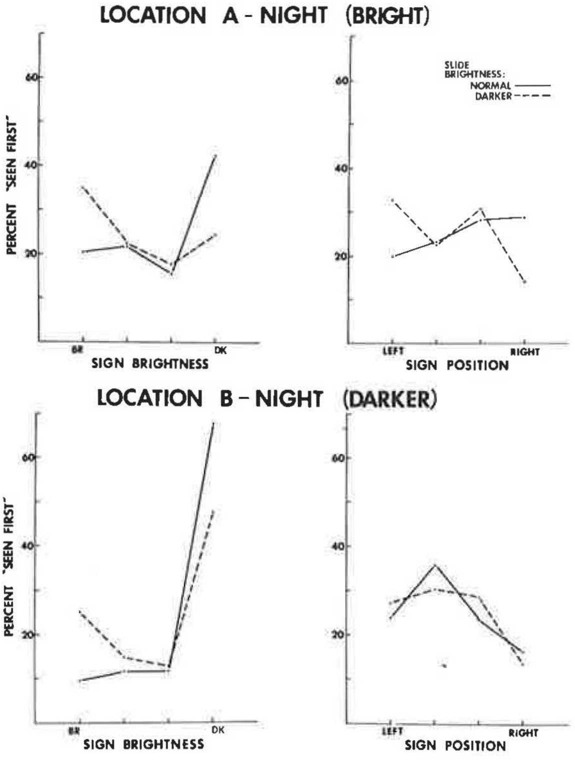

Figure 5. Results of Experiment 10—competing signs in background.

DISCUSSION

The first three experiments confirm previous results indicating that the darkest of four signs was seen best by most observers against a bright background, such as the day-snow background. The brightest of four blank signs also was seen best against a dark night background most frequently.

Adding large, bright letters and symbols to the simulated signs introduced a third influence on visibility or attention value, which depended on letter-to-sign brightness. Constant brightness letters had the effect of increasing brightness ratio as the simulated signs became darker, and this enhanced the attention value of the darker signs. Higher letter-to-sign brightness, therefore, opposed the effect of greater sign brightness against night backgrounds and added to the effect of a dark sign against a bright day background. By reducing letter brightness along with sign brightness the letter-to-sign brightness effect on visibility was reduced. The results with competing advertising signs also showed the advantage of the darkest sign against bright and the brightest sign against darker backgrounds.

These findings suggest that silhouette seeing is of importance for visibility or attention value where signs are seen against a bright background. Consistently, where they were seen against a dark background, the brightest sign showed a definite advantage. It is evident that letter-to-sign brightness ratio is another important variable. Letter-to-sign brightness and contrast also is known to be important for legibility. Therefore an optimum combination of these three variables must be found to obtain best attention value and best legibility.

A further factor being studied is color contrast. This factor may also affect highway sign visibility and attention value.

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Color and Brightness Factors in Simulated and Full-Scale Traffic Sign Visibility

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•THIS is a report of the last three experiments of a four-year study of traffic sign requirements, the objective of which was to study characteristics yielding optimum sign visibility and effectiveness. A review of earlier studies showed that much research had been on legibility but relatively little on visibility factors (1, 2). Accordingly, this project emphasized the study of factors affecting visibility and attention value. Observations were obtained from a total of 499 subjects in 13 laboratory experiments using simulated signs and highway scenes, and from an outdoor, full-scale set of observations as a check of the laboratory results.

Two previous reports described the laboratory simulation method and the results obtained. The first five experiments (4) showed that when four simulated green signs were presented briefly while the subject was engaged in an auxiliary task, overhead mounting position was favored over side mounting. To equalize this factor, later comparisons were therefore all in the overhead position. Use of blank green signs indicated an advantage for the brightest sign against night and the darkest sign against a day-snow background. Introduction of white letters on the signs modified these relationships.

Another series of experiments (5), in which size and brightness of the simulated signs were varied, showed that bright letters on the sign gave contrast effects which tended to oppose the advantage of the bright signs against the night background and to enhance the advantage of a darker sign against a day-snow background. When this effect was reduced or eliminated, the advantage of the bright signs against the night background increased.

The present report gives the results of Experiments 12, 13, and 14. Experiment 12, in which the four simulated green signs were seen against three colored backgrounds, showed contrast of sign-to-background to be important. Experiment 14 measured the effects of seven different colors of simulated signs in pairs when seen against four different colored backgrounds. Finally, Experiment 13, in which outdoor observations were made by subjects riding over a standardized course, is reported. Mathematical models based on known visual and logical relationships were tested against each set of laboratory results. A model which fitted the laboratory results best is reported, along with another which gave good correspondence with average outdoor observations. Suggestions are made as to application of the results for estimating highway sign effectiveness, although the results must be viewed as tentative until further research confirms and refines them.

RESEARCH METHODS

Laboratory Simulation Method

Previous reports have described the laboratory simulation procedure (1, 3, 4, 5). Essentially it required the subject to relight with buttons under his left hand whatever number of lights were extinguished in a matrix of small red lights. The matrix appeared

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Paper sponsored by Committee on Night Visibility.

below a projected highway scene. This auxiliary task thus "loaded the operator" to some degree and assured fixation at road level.

An appropriate highway scene was projected continuously in a darkroom laboratory from a 35-millimeter colored slide to maintain the proper visual adaptation for the day or night background being used. At unpredictable times and keyed by the response to the light matrix (the auxiliary task), a set of test signs appeared for one second on the same highway scene. The subject was asked to give his immediate reaction as to which of the four signs was seen "first and best" and which second best. He recorded his reaction by pushing one of four buttons under his right hand, then continued with the auxiliary task. From 15 to 20 subjects viewed the simulated signs against each different background, giving for Experiments 12 and 14 a total of 105 different people.

Outdoor Observation Method

Outdoor observations were made by 41 subjects, 22 under night and 19 under day conditions. Each observer rode beside the driver in a station wagon and reported all signs as soon as they were seen. The 40-mile standardized course included both city and freeway driving in and near Lansing, Michigan.

A speed and delay recorder in the car showed the position at which each sign was reported. The observer indicated a highway or an advertising sign by pushing one of two buttons which activated recording pens. Mileposts and locations of selected experimental signs were identified by the experimenter on the paper recording tape.

Approaching five multiple overhead sign locations (at freeway interchanges), the subject was instructed while the signs were not yet visible to raise a cardboard screen to cut off his view. On signal, about 200 feet from the signs, he dropped the screen and reported the sign he saw first.

ANALYSIS OF THE DATA

From the laboratory records, the number of times each sign (of the four) was "seen first" was tabulated for each subject, and the total for all subjects was converted into percent "seen first." Resulting figures were plotted.

Outdoor observation distance was measured from the paper tape and recognition distances plotted for each experimental sign. Average, 25, 50, and 75 percent values were determined.

For each sign of the installations viewed suddenly by use of the cardboard screen, the number and percent reported as "seen first" were tabulated and percents computed.

TERMINOLOGY

In dealing with stimuli for color perceptions and achromatic visual responses, terminology is sometimes confusing in spite of attempts to standardize it. One system uses the terms "hue," "chroma," and "lightness" for the three basic characteristics of colored surfaces viewed under reflected light. On the other hand, "hue," "saturation," and "brightness" may be properly used for colored light stimuli.

In our study, projection of the colored highway scenes and simulated signs on a reflective screen gave a result somewhere between that of highly reflectorized materials and ordinary surfaces seen in reflected light. Fairly good simulation of day and night viewing of signs was obtained, but terminology must be arbitrarily selected. We have used the term "brightness" throughout to indicate the "Y" or "brightness" values measured with the Spectra Pritchard photometer (which includes a correction for the average brightness sensitivity of the human eye). Similarly, we have arbitrarily used the term "brightness" for this characteristic of signs outdoors under both day and night conditions, again referring to the same photometric measurement.

EXPERIMENTS WITH COLORED BACKGROUNDS AND COLORED SIGNS

Experiments 6, 7, and 8 investigated effects of four sign sizes and four brightnesses of simulated green signs (5). Experiment 6 used white letters and arrows of the same

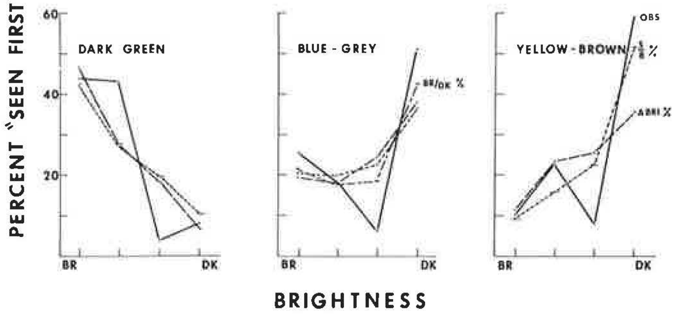
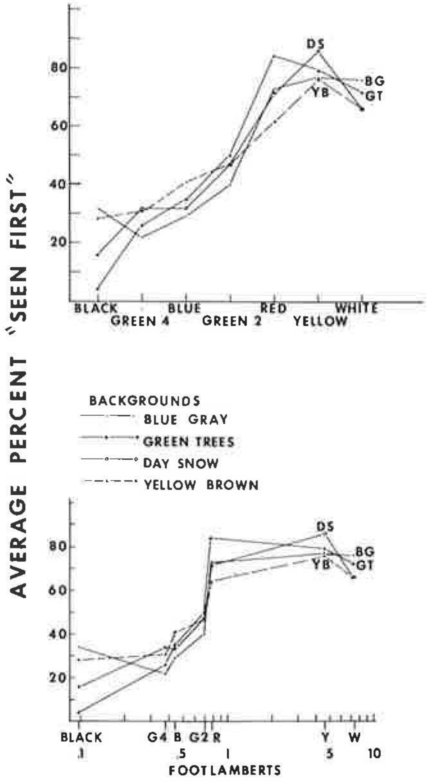


Figure 1. Results of Experiment 12—green signs and colored backgrounds (observed values shown by solid lines, calculated values by broken lines).

brightness on all signs. Experiment 7 used blank signs (no letters or arrows). Experiment 8 used letters and arrows of reduced brightness on the darkest two signs. The results showed an advantage for the bright and large blank signs against the night background and of the dark and large against day-snow. White letters and arrows contrasting with the signs enhanced the advantage of dark signs against snow and reduced the advantage of bright signs against night backgrounds.



SIMULATED SIGN COLORS PRESENTED IN PAIRS

Figure 2. Results of Experiment 14—colored signs and colored backgrounds.

Colored Backgrounds

Experiment 12 investigated the effect of seeing the four simulated green signs against three colored backgrounds. Dark green trees, a yellow-brown hill, and a blue-gray cliff were the backgrounds against which the green, blank simulated signs (of four brightnesses) were seen by the subjects. A total of 45 subjects viewed these signs while carrying on the auxiliary task as in the original procedure.

Figure 1 (solid lines) shows that the brightest sign was seen best against the green trees, the darkest against the yellow-brown hill, and there was a combination effect against the blue-gray cliff background. This last effect apparently resulted from a difference in brightness from left to right in the background scene. The other two consistently show an advantage for signs contrasting in brightness with the background.

Colored Signs and Colored Backgrounds

Experiment 14 investigated the effect of seven different colors of simulated signs seen against four different colored backgrounds (dark green trees, yellow-brown hill, blue-gray cliff, and the day-snow scenes). The signs were black, dark green (with 30 percent overlay), blue, the saturated green, a brilliant red, yellow, and white.

A total of 60 subjects, 15 for each background, saw the simulated signs in pairs and indicated which of the pair was "seen best." The pair-comparison technique in this case was effective in deriving a scale. The scale is based on the average percent of the total observations in which each color of a pair was selected when seen against all four backgrounds.

Figure 2 shows that when the colors were arranged in general order of brightness (top figure), the brighter colors were "seen best" more frequently. When plotted against the logarithm of brightness of the simulated sign (lower figure) the average percent "seen best" increased nearly linearly with the log of brightness as might be expected if the different contrast against the four backgrounds of the seven colors averaged out. The exceptions were the red and the yellow and black signs. Here hue contrast apparently added to the effect of brightness contrast and modified the result. This was especially noticeable for the red, which was a brilliant, slightly bluish-red contrasting well with the four backgrounds when projected in the darkroom laboratory. The spread of plotted points for black and for red indicates the effect of sign-to-background contrast.

Outdoor Observations

Experiment 13 was a full-scale outdoor check series in which each subject rode in a car over a standardized course and viewed regular street and highway signs against backgrounds of sky, trees, grass, concrete bridges, buildings and other city backgrounds, and competing signs. As noted earlier, a standard route of some 40 miles included freeway driving and city driving in and around Lansing, Michigan, in about equal proportions. From a total of over 400 highway and advertising signs, 82 highway signs were used as test signs.

The subject called out each sign as soon as he noticed it, indicating color and location (right, left, or ahead), and pushed one of two buttons to indicate whether it was an advertising or a highway sign. A group of 19 subjects made day observations and 22 others made night observations.

Figure 3 shows examples of the range of distances recorded for pairs of different sizes of signs—large, medium (4 to 6 feet in height), and small. Each pair illustrates

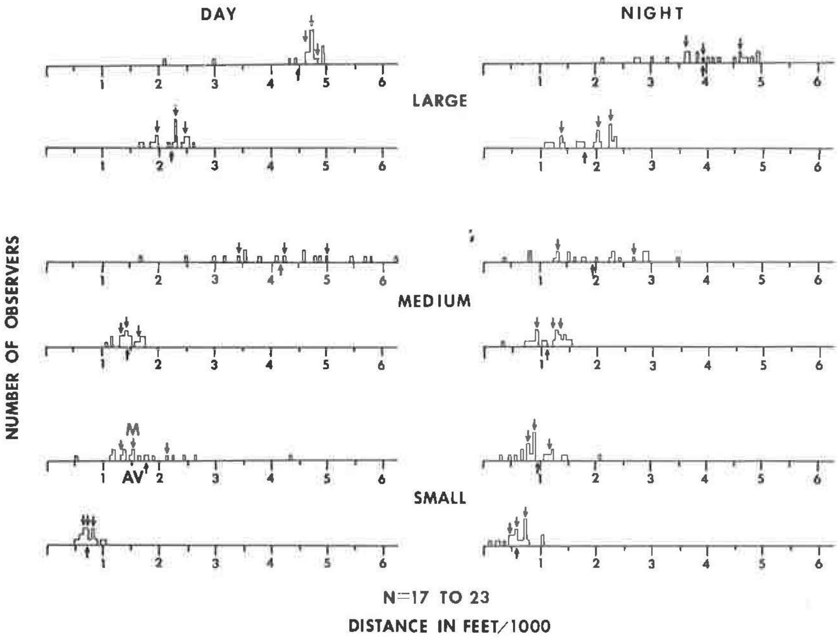


Figure 3. Results of Experiment 13—three sizes of sign with restricted and unrestricted sight distance (arrows indicate 25 and 50 percentile and arithmetic mean).

records from a sign with unrestricted sight distance and another where viewing distance was limited. Most signs were reported well beyond the legibility distance of their largest legend, but clear vision distance often limited recognition distance. Large overhead multiple installations, when viewed with sudden exposure, showed an advantage for the left-most sign in daylight and the straight-ahead sign under night conditions.

TEST OF MATHEMATICAL MODELS AGAINST OBSERVATIONS

In experiments of the type used here for measuring visibility and attention-getting characteristics, a relatively large number of factors had to be varied. But possible fatigue of the subjects and effects carrying over from one series of sign presentations to another limited the number of combinations which could be used in any one experiment. The results were in percentage form and the number of points determined was limited.

Under such circumstances, one practical method of analyzing and explaining the results is to test calculated values obtained from a mathematical model against the observed values from the series of experiments. The mathematical model must be based on proper assumptions from known characteristics of human vision with regard to color, size, and brightness and allowable logic from other known relationships. The models should fit the essential results from both the laboratory experiments and the outdoor experiment. For this purpose, laboratory Experiments 6, 7, 8, and 12 were the most clear-cut in control of conditions and independence of the observing groups and Experiment 13 represented night and day observations in the full-scale outdoor situation.

Several models based on possible assumptions using allowable logic and valid vision principles were tested. Two of these showed the best fit for laboratory results as a whole. Certain others, which showed a better fit for one experiment, but poorer ones for others, were discarded. A semilogarithmic model did not fit except in Experiment 14.

The model giving best fit for laboratory results was

$$P = \frac{BR_{SiBi} + BR_{LiSi}}{\sum_{i}^{n}\left(BR_{SB} + BR_{LS}\right)} \times AR_{LS} \times SF \times 100 \qquad (1)$$

where

P = percent "seen first"

B_B = background brightness

B_{Si} and B_{Li} = sign and letter brightness respectively for sign i

A_{Li} and A_{Si} = area of legend and of sign i

A_{Si} and A_{Si-1} = area of sign i and of next smallest sign i - 1

Brightness ratios:

$$BR_{SB} = \frac{B_S}{B_B} \text{ if } B_S > B_B$$

$$= \frac{B_B}{B_S} \text{ if } B_B > B_S$$

$$BR_{LS} = \frac{B_L}{B_S}$$

Legend to sign area ratio:

$$AR_{LS} = \frac{A_{Li}}{A_{Si}} \text{ expressed as percent of largest ratio}$$

Size factor:

$$SF_1 = \frac{A_{Si}}{A_{Si} + A_{Si-1}}$$

$$SF_2 = (1 - SF_1) \frac{A_{Si-1}}{A_{Si-1} + A_{Si-2}}$$

The model giving second best fit for laboratory results used contrast rather than brightness ratio:

Sign-to-background percent contrast

$$C_{SB} = \frac{B_S - B_B}{B_S} \times 100 \quad \text{if } B_S > B_B$$

$$= \frac{B_B - B_S}{B_B} \times 100 \quad \text{if } B_B > B_S$$

Similarly, letter-to-sign percent contrast

$$C_{LS} = \frac{B_L - B_S}{B_L} \times 100 \text{ or } \frac{B_S - B_L}{B_S} \times 100$$

Then, percent "seen first"

$$P = \frac{C_{SiBi} + C_{LiSi}}{\sum_i^n \left(C_{SB} + C_{LS}\right)} \times AR_{LS} \times SF \times 100 \tag{2}$$

The model as applied to outdoor results calculated average distance seen:

$$D = \frac{C_{SB} + C_{LS}}{2} \times ER \tag{3}$$

where ER = expected recognition distance (small dimension of sign in feet × 1200) or clear sight distance, whichever is smaller.

Best Models for Laboratory Data

Experiment 12, since it presented blank green signs against three different backgrounds, was a good test case, especially since the blue-gray background actually included two brightness values. Figure 1 shows the comparison of three calculated values against the observed data for the three different backgrounds. The values corresponding to Eq. 1 are labeled BR/DK percent. A calculation corresponding to Eq. 2 is labeled ΔBRI percent. The third calculation labeled S/B percent was similar to that for Eq. 1 except that the ratio was always sign/background. Except for the yellow-brown background, the calculated values for the two models were about equally good fits. For the yellow-brown and the dark green, the bright/dark was identical with the sign/background percent. It showed a slightly better fit than ΔBRI for the yellow-brown.

Figures 4 and 5 show that the calculated brightness ratio values from Eq. 1 fitted quite well for Experiments 6, 7, and 8. Figure 4 shows the fit obtained when size was constant (upper figures) and when brightness was constant (lower figures). Figure 5

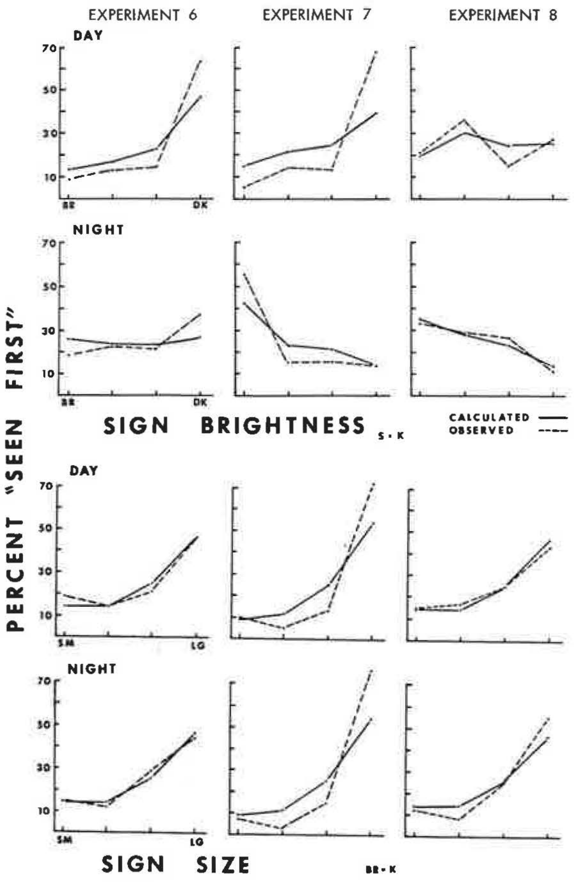


Figure 4. Calculated and observed values for size and brightness experiments (upper figures, size constant; lower figures, brightness constant).

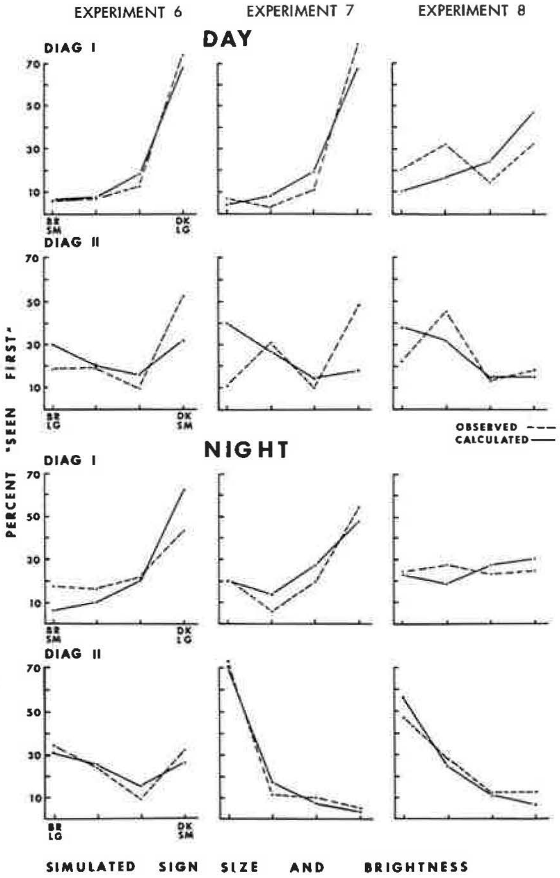


Figure 5. Calculated and observed values for diagonal 1 and diagonal 2 size and brightness experiments.

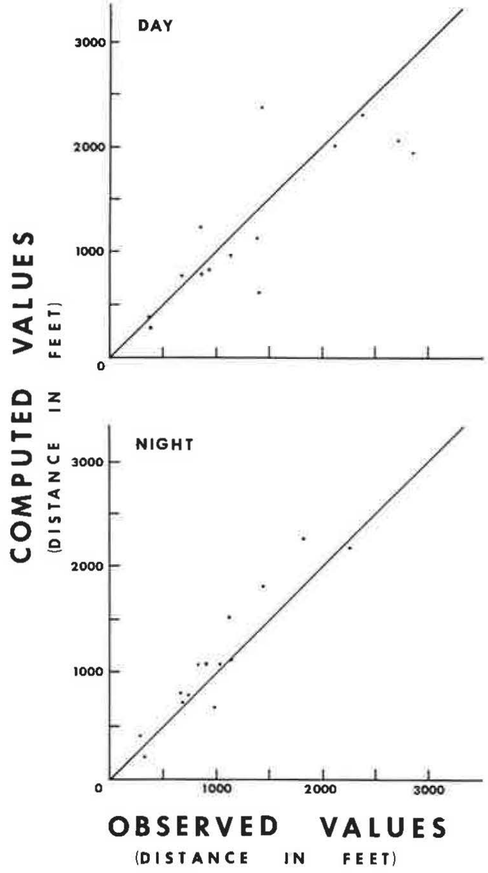


Figure 6. Experiment 13, outdoor observations—calculated and observed distances.

shows the corresponding fits for diagonal 1 (bright small to dark large) and for diagonal 2 (bright large to dark small). Reasonably good correspondence was obtained.

Model Applied to Field Results

When the field observations were compared with calculated results based on Eq. 3 (additive contrast percent times estimated recognition distance) and on the clear sight distance available, rather good correspondence was found. Figure 6 shows the calculated vs the average observed distances for night and day observations. The next-to-longest observed distance was taken as an indication of the actual amount of clear sight distance if less than the calculated expected recognition distance. Expected recognition distance was 1200 feet per foot of sign height for day conditions. This means assumption of twice the legibility distance for a letter of that height.

If the calculated values corresponded exactly to the observed values, the points would all fall on the straight line. Although they do not, they fall close enough to it to indicate rather good correspondence.

DISCUSSION

Possible Differences Between Laboratory and Full-Scale Conditions

For the outdoor observations, use of the brightness contrast percent, Eq. 3, gave distance values corresponding quite well to the observed values when clear sight distance was taken into account. The calculated brightness contrast values from Eq. 2 did not fit the laboratory data quite as well for Experiments 6, 7, and 8. They produced a somewhat lower percentage for the most frequently seen sign combination.

It is possible that the laboratory observations exaggerated somewhat the advantage of the sign "seen best." In order to obtain more observations, the observers saw the test sign series twice. In spite of the scrambling of different sign combinations, some might respond consistently to the same sign a second time. If they developed a habit of response and then responded the same way in the second series, theoretical calculations indicated this might raise their score by about 10 percent, and thus increase the score for the preferred sign. Therefore, the more conservative percent contrast is probably the better relationship of the two to use for practical application.

Implications of the Two Models

Both mathematical models must be viewed as tentative approximations pending further research. However, on the basis of Eq. 1, brightness ratios of sign-to-background and legend-to-sign are major factors in sign visibility and they are additive but modified by the proportion of the area in legend and in sign. Therefore, if sign-to-background brightness ratio becomes zero, visibility would depend on the legend-to-sign brightness ratio reduced by the relative area factor (about 0.56 in Experiment 6). With our experimental signs this would divide legend-to-sign brightness roughly by two. Where two signs are being compared, the relative size of the two signs also would play a part as indicated by the sign area ratio.

On the other hand, Eq. 2 indicates additive percent contrast of sign-to-background ratio and legend-to-sign weighted equally. These are modified by the same ratio of legend-to-sign area where two signs are compared, and by ratio of sign size (area). Here again, if sign-to-background contrast becomes zero, the remaining legend-to-sign contrast percent is reduced by one-half, and also reduced by the proportion of legend-to-sign area in different size signs.

To achieve the best visibility and at the same time not interfere with legibility, both models indicate that sign-to-background and legend-to-sign brightness ratio or contrast must be balanced. Further research is needed to determine the optimum combination of these.

The contrast percent is probably the more practical and valid of the two relationships for application to full-scale situations.

Importance of Environmental Background

It has been shown that contrast of a darker sign against a bright background is as important as contrast of a bright sign against a dark background. In many cases it would be desirable to achieve the first for day and the second for night in the same sign installation.

A study by Hanson and Woltman (6) showed the wide range of backgrounds against which highway signs are seen. Dark trees, bright sky, and highway bridges furnished 23, 19, and 16 percent of the backgrounds for traffic signs. In winter, of course, backgrounds are largely snow in many areas.

PROCEDURE FOR TRAFFIC ENGINEERING APPLICATIONS

The following is a suggested procedure for predicting sign visibility on the basis of project results.

Measure or Estimate Background, Sign and Legend Brightness

Photometric measurements can be made with the Pritchard Spectra photometer which includes a correction for average human visual sensitivity. If this is not possible or if this degree of accuracy with attendant time and cost of making such measurements is not desired, an approximation can be obtained for daylight conditions by taking colored photographs under good daylight, using Kodachrome II or an equivalent slower type of color film that gives most accurate color. For this purpose, use at least three exposures bracketing the one indicated as normal by the light meter. Then choose the projected picture that gives the most correct-appearing colors.

Use of 35-mm color slides gives better reproduction than color prints. Slides should be projected in a completely dark room with a good quality projector and white reflective screen. This will avoid poor color from stray light and from uneven or low illumination introduced by poor projectors. Photometric measurements of sign, letters, and background can be made from the projected pictures.

Calculate Percent Brightness Contrast

For day conditions use photometric data from outdoor or laboratory measurements to calculate contrast. For night sign visibility use values for different reflective and other sign materials from such studies as Straub and Allen (7, Fig. 12) and Powers (8, Fig. 8). Other studies are understood to be under way that will give actual or calculated luminance for sign materials under headlights at a given distance.

Estimate Recognizable Distance

Use the small dimension of the sign. For most conditions, assume the sign will be recognizable or visible twice as far as legibility distance of the same size letter. Therefore, use 100 feet per inch (or 1200 feet per foot) of the small dimension of the sign. This assumption will not be valid below a certain minimum brightness. On the basis of other studies (7, Fig. 21, and 9) it is suggested that, for signs less than 0.05 ft-L in maximum brightness, 400 feet per foot be used. Apply factor to estimated recognizable distance or to clear sight distance to sign, whichever is smaller.

Apply Factor To Estimate Relative Visibility

Use Eq. 2, including area and size factors where applicable, as follows:

Case 1, daylight, one sign—Relative area factor is inoperative here. Therefore, use average of contrast percents.

Case 2, daylight, two signs—Use sum of contrast factors to determine factor for each sign. If signs are of different size, apply sign area and legend area ratios. Apply factor to estimated recognizable distance as described earlier for each sign.

Case 3—For night visibility prediction use the same procedures, obtaining contrast values as suggested previously.

Results

The resulting figure gives an estimate of the distance in feet a given sign is most likely to be seen by the average driver. Comparing distance estimates for competing signs will give an estimate of relative visibility of each one relative to the others.

CONCLUSIONS

1. Average visibility and attention value of highway signs can be estimated from characteristics of legend, sign and environmental background. Visibility and the sign characteristics fundamental to its production are relative in character.
2. Relative brightness and contrast of sign-to-background and of legend-to-sign are of primary importance for visibility and attention value.
3. In visibility effects from colors, relative brightness is of most importance, but hue contrast enhances the brightness effects in some cases. However, color is important and effective in transmitting coded meanings.
4. For best visibility, a sign should be darker against a bright day background but brighter against a dark day or night background. Legend-to-sign contrast may enhance or oppose effects of sign-to-background contrast. They should be balanced to obtain best visibility (and attention value) and at the same time high legibility.
5. A formula for estimating visibility effects is suggested on an approximate basis and within limits.

RECOMMENDATIONS

1. The question of whether and how much the reduction of letter-to-sign brightness contrast impairs legibility should be investigated. Such contrast reduction may occur in using higher sign brightness to carry the important color message to the motorist.
2. A method of obtaining better color and legend effectiveness is needed for cases where a sign is darker than a bright sky background and the legend is in shadow. In such a case, the visibility and legibility of the legend is low because of relatively low legend-to-sign brightness.
3. Another study has reported that contrast of signs to environmental background varies greatly. Backgrounds should be considered in designing traffic signs.
4. Much more research is needed to confirm and refine the tentative approximate relationships reported here.

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