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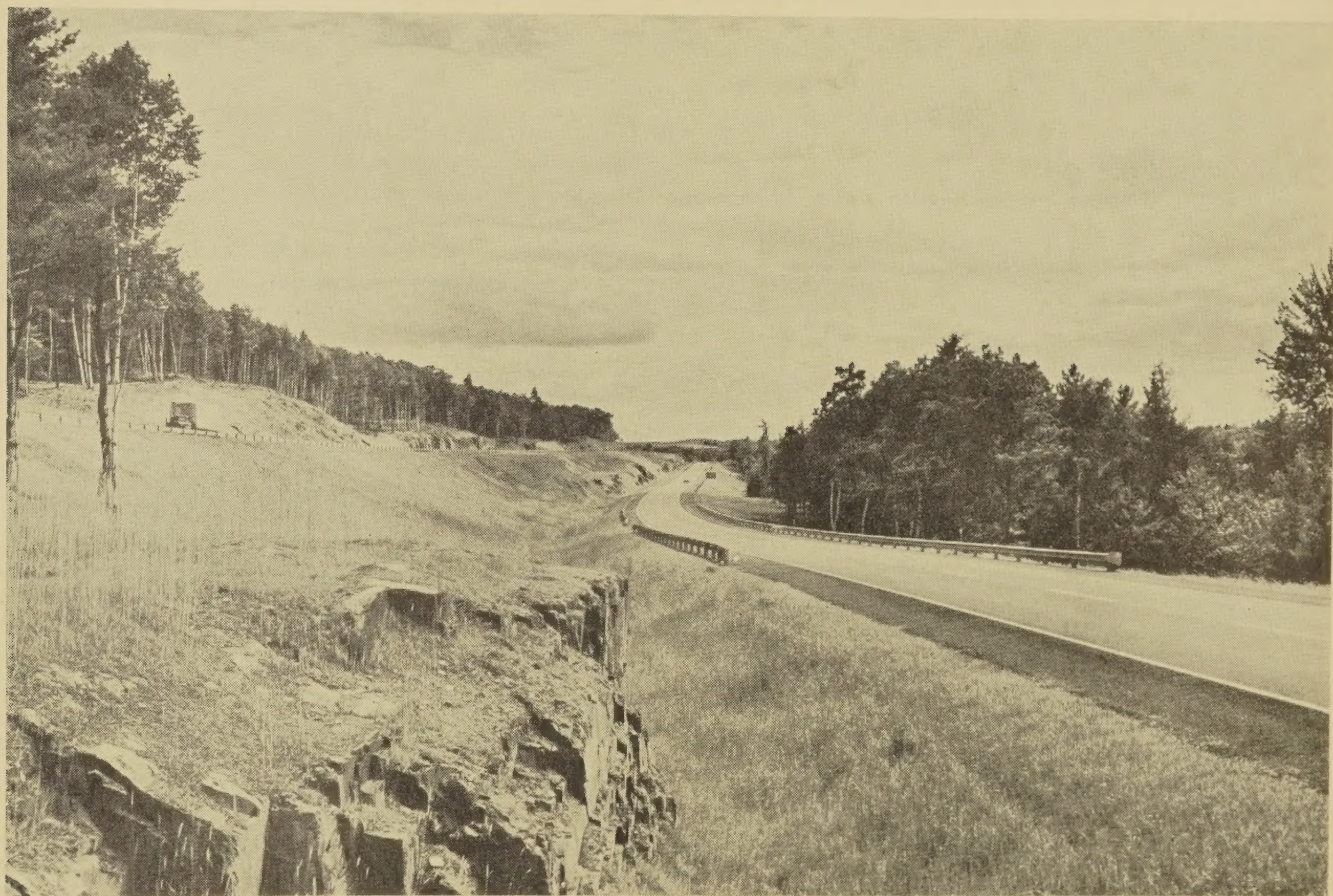

Interstate 95–6, north of Old Belgrade Road, near Waterville, Maine.

View is toward the south on southbound roadway and shows the use of split profile on side hill location.

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IN THIS ISSUE: *Article on why drivers choose an expressway or primary route*

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IN THIS ISSUE

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Attitudes of Drivers Determine Choice Between Alternate Highways

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

Reported [1,2] by RICHARD M. MICHAELS,
Science Advisor, Program Management Staff

The research information presented in this article is based on a study of the factors that influence a driver's choice of alternate routes. Through the study in which the attitudes of drivers toward two highways were measured, an attempt was made to determine the utility of attitude scaling methods for predicting the choice. Establishment of such a subjective measure was sought for use in highway design, traffic planning in general, and predicting the use that will be made of new and improved highways. The author believes that the data collected show that this subjective method of evaluating route choice is a simple and effective means of predicting use of highway facilities.

In addition to the attitudes of the drivers, traffic characteristics of the routes were measured and the tension generated on each was determined. Nine test drivers were used for the tension tests. The routes employed were 47-mile sections of an expressway design toll road and a parallel rural primary highway. Drivers were sampled entering and exiting on both highways. A summated rating attitude scale was administered to a sample of 3,259 drivers. Descriptive information was obtained about the driver, his trip, and travel habits. Analysis of results showed that these drivers held stable attitudes that clearly differentiated between the routes. Direct measurement of driver attitudes seems to be a far better predictor of route choice than any descriptive information about the drivers or their driving habits.

In addition, the results provide a means of rationalizing the attraction of traffic to an expressway on the basis of drivers who seek to minimize tension in driving. The data suggest that total stress incurred in driving is a more important determinant of route choice than either operating costs or traveltime costs. A model of route choice and attraction of traffic is proposed based upon tension generation that can be related to traveltime data. Analysis of this research shows that drivers evaluate the use of alternate highways in a rational, though subjective, fashion. Such evaluation, however, seems to be very independent of the usual monetary plans often used to measure highway benefits and costs.

Introduction

WHENEVER a driver is provided alternate routes, he must make an evaluation [o]f the benefits and costs of using each in order [t]o make a choice. If he knew nothing about [a]vailable alternate highways or did not make [a]n evaluation of them, his choice would be [r]andom. Because drivers do not operate in a [r]andom manner, it seems reasonable to [a]ssume that they learn the characteristics of the highways and out of this learning develop a basis for evaluation of alternate routes. A driver's choice thus becomes dependent on the diverse characteristics of the alternates relative to his trip objectives, and these determine stable choice behavior. This behavior is of considerable significance both in determining the use of highway facilities and the benefits a driver derives from them.

Three major factors have been developed to account for the patterns of choice that a driver makes between alternate highways. The first is the time savings obtained by taking one route instead of the other. The second is the direct and indirect operating cost savings obtained by taking one route instead of the other. The third is the comfort and convenience savings obtained by taking one route instead of the other.

In general, traveltime savings have been the dominant criterion of use of alternate facilities; the best predictor being the traveltime ratio. In both rural (*1*, *2*)[3] and urban studies (*3*, *4*) a driver seems to choose routes that provide significant time savings, even though he may have to drive a longer distance. Discussions in all these studies imply that the driver values time directly and, hence, scales that variable. From an economic standpoint, a considerable effort has been made to determine the dollar equivalent of this time scale. For passenger car drivers these attempts have not been particularly successful (*5*). The relation of operating cost to choice by a passenger car driver seems to be weak (*6*). Either the driver does not evaluate operating cost differences or these differences are insignificant. When related to the total costs of a trip, operating cost differences between alternate routes may be very trivial for the passenger car driver.

In addition to these physical measurements, the purely subjective concept of comfort and convenience has been developed. This has generally been described qualitatively as the ease of driving or freedom of movement. Claffey (*6*) has scaled this factor in terms of the changes in speed imposed on the driver and, hence, counted the impedances to movement. Michaels (*7*) has differentiated among highways on the basis of the tension aroused in a driver from traffic and geometric design features. His results indicate that tension reduction is the greatest single saving accruing to a driver who chooses an expressway over a parallel uncontrolled-access highway, and the driver seems to subjectively evaluate alternates in conformity to the tension induced on each.

Although the research reports on the problem of use of alternates have described what traffic does, little research has been carried out on driver perception of alternate routes available (*3*). Further, no attempts have been made to measure on a quantitative scale the evaluations a driver makes or his relation of these evaluations to choice of routes. Thus, no reliable way now exists to predict usage of facilities except by empirical studies of traffic.

Regarding any benefit in analysis of highway facilities, obviously, drivers evaluate on a predominantly subjective basis. No economic determination seems feasible unless the

[1] Presented at the 44th annual meeting of the Highway [R]esearch Board, Washington, D.C., January 1965.

[2] Prepared in cooperation with the Maine State Highway [C]ommission and the Maine Turnpike Authority. Ralph [.]. Sawyer, formerly Planning and Traffic Engineer of the [M]aine State Highway Commission, and William B. Getchell, [.], formerly Executive Director of the Maine Turnpike [A]uthority, both now dead, contributed invaluable assistance [a]nd counsel for the research on which this article is based. [T]he author also was assisted in obtaining data by Daniel [B]ridges and Harold C. Wood, Jr., both employees of the [B]ureau of Public Roads.

[3] References indicated by italic numbers in parentheses are listed on page 236.

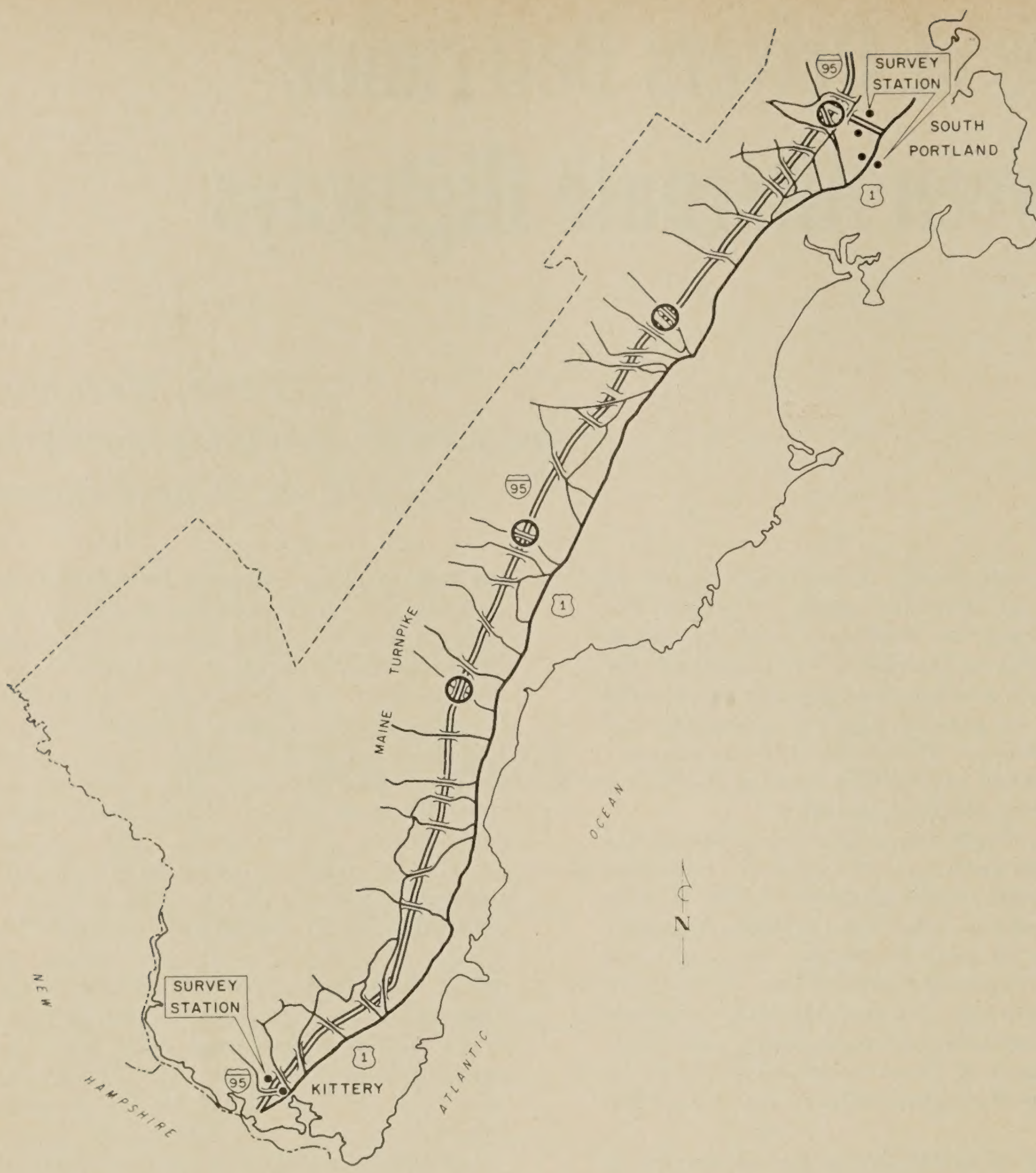

Figure 1.—Map locating study routes.

scale of value drivers use and its relation, if any, to dollars is known.

Considering the problem of selection of alternate routes, a reasonable assumption is that choice will be based upon what the driver has learned about the alternate. Either directly or indirectly, a driver must develop some stable evaluations. That is, he must have some predisposing views toward the routes or his choices would be random. These predisposing views are, by definition, the attitudes an individual holds toward some object or process. If route choice is rational, then a direct measure of a driver's evaluation should be his attitudes toward the alternate. By determining the intensity of these attitudes toward a pair of highways, it should be possible to determine how these attitudes are related to the characteristics of the highways and the choices drivers make.

To achieve these objectives, however, it is first necessary to determine whether a stable set of attitudes exists toward highways of different characteristics. Second, it is necessary to determine whether these attitudes depend on the characteristics of the drivers, which are relatively permanent, or upon the characteristics of a particular trip that would cause highly variable attitudes. In this context, the study discussed here was developed. The aim was to test the hypothesis that drivers on each of two highways had significantly different attitudes toward the two highways and that these attitudes were based on the more enduring characteristics of the routes and the drivers.

Development of the Attitude Scale

The attitude scaling technique employed in this study was the Method of Summated Ratings. It employs a series of direct statements to which the respondent expresses the extent of his agreement. An example of such a statement might be, "A road with many hills and curves is interesting to drive." The test subject then responds in one of five categories ranging from "strongly agree" to "strongly disagree." A score of 0, 1, 2, 3, or 4 is given to his response, according to the category chosen, a score of 2 being neutral. Thus, by using a set of such items, a total attitude score can be obtained for any test subject toward the road under study.

The general procedure for preparing such an attitude battery is described by Edwards (*8*). In the study reported here, it was decided to compare attitudes on a toll road and a rural primary road as these are two of the more common that a driver has to choos between, and yet they have radically differe design characteristics. To develop the fin items for the attitude scale, 61 statemen were initially prepared. They described variety of characteristics of a rural primar road and an expressway, both positive an negative. They were presented to 260 sta members of the Bureau of Public Road Instructions given were:

"Place yourself in a hypothetical situatio of having the choice of two routes for hon to work trips: (1) a controlled-access to road, and (2) a parallel free-access primar roadway. The toll on the turnpike is $ The trip is 30 miles on both routes. Assun that the primary route is similar to U.S. between Baltimore and Washington, between Alexandria and Woodbridge.

"The attached questionnaire is design to elicit attitudes toward these two types highways. You should respond to ea statement in terms of your own person feelings, checking one of the five categori that range from strongly agree to strong disagree."

Some basic objective information w obtained about the respondents, includi age, sex, and the percentage of time th would choose the toll road. Adding the la item permitted an initial check on the validi of the final scale, for it was hypothesized th those responding most positively to expres way items would be those most likely to u that facility. All items were scored in ter of favorability toward the expressway. T returns were then analyzed according to t standard procedure in which the highe scoring quarter of the sample was compar with the lowest scoring quarter; well o half the items significantly differentiated b tween the two highways. The final batte was composed of 18 items, from the origi group of 61, that were the most discriminati between the groups having high and l scores.

A further analysis was made on this pret group. The attitude scores were correlat with the respondents' percentage of choice the toll road. The two distributions w dichotomized and a phi coefficient was co puted. The correlation coefficient was +0. between attitude scores and choice of rout Thus, it was reasonable to conclude that, this hypothetical situation, a stable set attitudes existed toward the two types highways that was significantly related to choice of routes the respondents would ma

In addition to the final attitude battery questionnaire was included to obtain so basic descriptive information about respondent's trips so that the attributes of driver and his trips could be related to attitudes. These items were to provide means for testing the stability of the attitu and fell into three basic categories. The fi was the characteristics of the driver and vehicle, including age and sex of driver, age of car. The second was the charact istics of the trip, including purpose, num of car occupants, the driving time alre completed, and driving time to be complet he third was the descriptive information of he driver's estimate of the frequency with hich he made this kind of trip and the fre- uency with which he used the alternate route. The item on driving time was included ecause no statements relating to traveltime lone were in the attitude battery. In the ample used to develop the scale, time was not discriminating factor between the groups coring high and low. By treating traveltime s an independent variable, subjective esti- iates of driving time could be related to the espondent's attitudes toward the routes. bviously, if traveltime were a dominant riterion of choice, then a correlation should xist between the driver's attitude toward the oute and the duration of the trip that he was ndertaking. By using this approach, an idependent test could be made of a driver's hoice of routes and of traveltime.

Selection of Test Location

In considering a pair of roads of sharply fferent characteristics between which a river might choose, the ideal would be a iir that had a common beginning and a com- on terminus. In addition, the pair should long enough to permit a meaningful choice the driver. A pair of highways that these requirements is the Maine Turnpike tween Kittery and South Portland and the rallel rural primary, U.S. 1, which has been udied extensively over the past decade , *2*). The sections are approximately the me length, about 45 miles. At the Kittery d, the choice of route is a simple one for the iver, for the connection is a Y. At the uth Portland end, U.S. 1 and the Turnpike in again. A map of the two roads is shown figure 1.

The characteristics of both routes are pical of a modern toll road and a rural imary. The Turnpike is a 4-lane divided ghway on which interchanges are spaced to 15-miles apart; they generally have en built to Interstate design standards. S. 1 varies from 2- to 4-lanes and passes rough several small towns and undeveloped untryside. Access is not controlled, and e route has a variety of traffic control devices.

Procedure

A survey team of nine men was used. e sampling schedule was set for daylight urs between 8 a.m. and 5 p.m., and was ected at both ends of each highway. ring the first 4 hours, vehicles were stopped they entered the test sections; during the xt 4 hours, they were stopped as they left test sections. Samplings were obtained m north and south ends of both routes, t drivers were not stopped twice on the ne trip. By counterbalancing the order, approximately equal sampling of drivers ering and exiting at both ends of the two hways was obtained.

To obtain the most stable attitudes toward routes under study, only Maine or New mpshire drivers were stopped. No fixed cedure was established for stopping a particular vehicle. The complexities of traffic and the fact that only two interviewers were at each station precluded any formal sampling procedure. However, by extending the sampling period for more than 30 days, it is believed that most biases were eliminated.

When a driver was stopped, a common set of instructions was given:

"Good morning. We are doing research on why drivers pick particular roads for their trips and would like to enlist your assistance. We have a questionnaire that we would like you to complete, which will take about 5 minutes of your time. If you can spare that time, we would appreciate it."

If the driver agreed, the attitude form was handed to him and the instructions for filling it out were read with him. When the interviewer and the driver were satisfied as to what was wanted, the interviewer withdrew and the driver completed the attitude questionnaire. When finished, he handed the form back to the interviewer who then asked the objective questions and marked the verbal replies on a coding sheet. The two parts of the form had a common number so that both parts of the survey could be combined subsequently.

Speed and volume measurements

In addition to the attitude survey, traffic measures were taken on the two routes. Rather complete volume counts were made daily for both the Turnpike and U.S. 1. On U.S. 1, volume counters were placed at three locations for hourly traffic counts. On the Turnpike, volume was sampled at four locations during several different time periods. In addition, a radar speed meter recorded daily samples of traffic speed on both routes. Thus, a fairly complete record of the traffic characteristics on both test sections was obtained during the period of the study.

Tension measurements

The galvanic skin reflex (GSR) test was employed to obtain tension measurements on both the Turnpike and U.S. 1. During the 1-month study each of the interviewers was used as a test subject and drove both routes twice in both directions. The procedure outlined in previous reports (*7*, *9*) was employed.

Results

During the 4 weeks of surveying on both routes, a total sampling of 3,259 different drivers was obtained. No significant differences were noted between drivers sampled at the two ends of the test routes. Also, no differences were noted between drivers sampled on entering the test sections and those leaving them. Hence these data were pooled. As shown in table 1, approximately the same

Table 1.—Attitudes of drivers toward the Maine Turnpike and U.S. 1

Sex of drivers	Maine Turnpike			U.S. 1		
	Number sampled	*Mean attitude score*	*Standard deviation*	*Number sampled*	*Mean attitude score*	*Standard deviation*
Male	1,138	41.33	9.40	1,039	32.09	9.56
Female	482	38.52	9.54	600	30.26	8.65
Total	1,620	----------	----------	1,639	----------	----------

Table 2.—Distribution of drivers sampled on Maine Turnpike and U.S. 1, by sex

Sex of drivers	Maine Turnpike		U.S. 1		Total	
	Number sampled	*Percent*	*Number sampled*	*Percent*	*Number sampled*	*Percent*
Male	1,138	70.4	1,039	63.4	2,177	66.7
Female	482	29.6	600	36.6	1,082	33.3
Total	1,620	100.0	1,639	100.0	3,259	100.0

Table 3.—Age of vehicles on the Maine Turnpike and U.S. 1, by sex of driver

Vehicles		Vehicle distribution by drivers sampled on—			
Age	Sample	Maine Turnpike		U.S. 1	
		Male	Female	Male	Female
Year	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Less than 1	18.6	22.5	22.1	16.7	13.2
1–3	39.3	45.9	39.6	34.2	35.9
4–6	26.2	20.1	27.1	28.1	32.8
More than 6	15.7	11.4	11.1	21.3	18.0

Table 4.—Analyses of variance of attitudes of male and female drivers toward Maine Turnpike, based on age of drivers and vehicles

Source of variance	Sum of squares	Degree of freedom	Mean squares	F, ratio	Probability (F)
MALE DRIVERS					
Driver age	656.53	3	215.51	2.468	<0.05
Vehicle age	996.48	2	498.24	5.706	<0.01
Age × vehicle	243.35	6	40.56	----------	(1)
Residual	99,454.14	1,139	87.32	----------	----------
Total	101,341.50	1,150	----------	----------	----------
FEMALE DRIVERS					
Driver age	464.30	3	154.80	1.543	(1)
Vehicle age	263.10	2	131.55	1.312	(1)
Age × vehicle	418.42	6	69.74	----------	(1)
Residual	48,342.20	482	100.30	----------	----------
Total	49,488.02	493	----------	----------	----------

[1] Not significant.

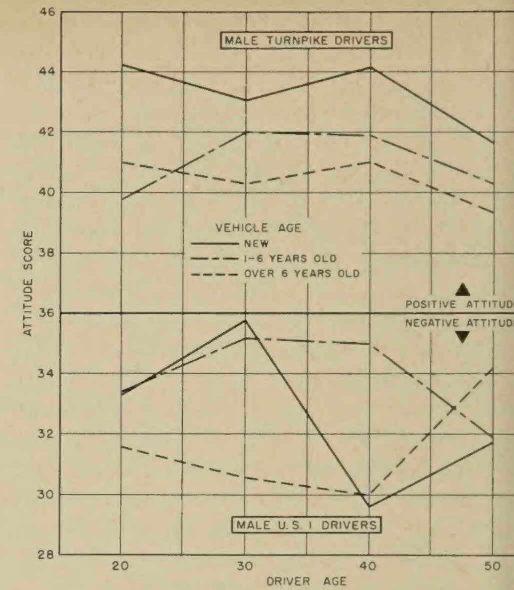

Figure 2.—Male driver attitudes tow[...] turnpike as function of driver and veh[...] age and travel route.

Table 5.—Analyses of variance of attitudes of male and female drivers toward U.S. 1, based on age of drivers and vehicles

Source of variance	Sum of squares	Degree of freedom	Mean squares	F, ratio	Probability (F)
MALE DRIVERS					
Driver age	2,532	3	844.0	9.58	0.01
Vehicle age	629	2	313.5	3.56	0.05
Age × vehicle	1,390	6	231.7	2.62	0.05
Residual	86,299	980	88.1	----------	----------
Total	90,850	991	----------	----------	----------
FEMALE DRIVERS					
Driver age	1,148	3	382.7	5.50	0.01
Vehicle age	755	2	377.5	5.42	0.01
Age × vehicle	722	6	120.3	1.73	(1)
Residual	42,605	604	69.5	----------	----------
Total	45,230	615	----------	----------	----------

[1] Not significant.

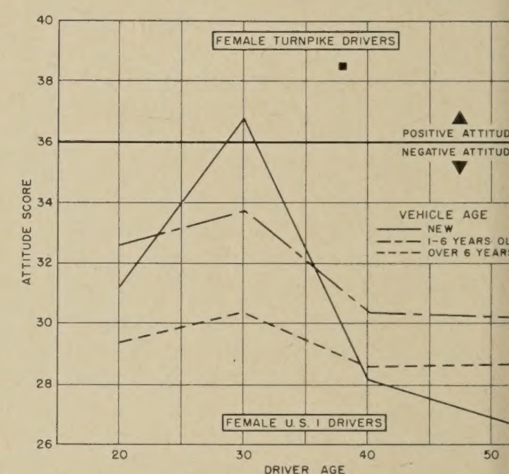

Figure 3.—Female driver attitudes tow[...] turnpike as function of driver and veh[...] age and travel route.

number of observations were taken on both routes. This, of course, does not represent the distribution of traffic but only the method of sampling on the two highways.

Fourteen percent of the drivers stopped declined to participate in the survey. This percentage was the same on both routes. In addition, approximately 6 percent of the drivers stopped had been interviewed before. As might have been expected, the percentage of repeats from the first week to the last week rose on U.S. 1 from 1.9 percent at the end of the first week to 5.7 percent the third week. On the Turnpike, the figures rose from 0.8 percent, at the end of the first week, to 10.3 percent the third week.

Attitude Survey

The Turnpike was used as a reference for assigning a quantitative score to the responses when the attitude questionnaires were scored. Thus, all statements about U.S. 1 that reflected a positive attitude toward it were given a 0 score for the category of "strongly agree" and a score of 4 for the response of "strongly disagree." For those items that were unfavorable statements about U.S. 1, strong agreement was scored as 4 and strong disagreement as 0. Statements about the Turnpike were scored in the obvious reverse manner. Thus, the total score of a respondent was interpreted to reflect his attitude toward the Turnpike. The scores on each of the items and the descriptive information obtained from the interview were placed on punchcards, and all of the basic analyses of the attitude sampling was performed by a computer.

A summary of the attitudes of drivers on each route is shown, by sex, in table 1. The higher the score, the more positive the feelings of the drivers toward the Turnpike. A score of 36 indicated a neutral attitude toward the Turnpike. As shown in table 1, significant differences were stated for choosing between the two highways. Drivers on U.S. 1 had negative attitudes toward the Turnpike, and Turnpike users had positive attitudes toward it. Also, the differences stated by the sexes were significant. The male drivers on the turnpike were significantly more positive toward the Turnpike than the female driver.

On U.S. 1, the male driver, although ha[...] a negative attitude toward the Turnpike, [...] less negative than the female driver. [...] attitudes of male and female drivers on [...] routes were significantly different from [...] tral. Thus, it is reasonable to conclude [...] use of the attitude scale showed a differ[...] ation between the users of the two highw[...]

The sex distribution of the drivers on [...] two routes was analyzed and, as show[...] table 2, two-thirds of the total samplin[...] drivers was male. More significant, howe[...] is the difference between the proportio[...] male or female drivers on the two rou[...] Significantly more female drivers trav[...] U.S. 1 than the Turnpike. Compariso[...] this sex distribution with attitudes tow[...] the Turnpike (table 1) indicates a significa[...] less positive attitude of the females than [...] males toward the Turnpike. Therefor[...] was concluded that a correlation ex[...] between the attitudes held by the two s[...] toward the highways and the actual ch[...] they made.

The third category under the driver [...] vehicle characteristics concerns that of ve[...] age. The percentages of vehicles on [...]

ıte, by their age, and by sex of their drivers shown in table 3. Two inferences may be ıde from this table: First, in this sample, hicles driven by females were older than ose driven by males. Second, and more nificant, the percentage of older vehicles the Turnpike was considerably less than ose on U.S. 1.

Drivers in the sampling on both routes were npared for age differences. In relation to itudes toward the two highways, rather arcut differences existed. An analysis of riance was performed for both driver age d vehicle age, the attitude scores being the pendent variable. The summary tables for les and females using the Turnpike are shown table 4 and for those on U.S. 1, in table 5. th driver age and vehicle age were statistily significant in every analysis except for female drivers on the Turnpike. In ures 1 and 2 the mean attitude scores as a ıction of age are shown for all conditions. hicle age is the parameter in these curves. shown for the male drivers, attitudes vard the Turnpike became less positive as ir age increased. Vehicle age also had a ar effect on the attitudes. Thus, the wer the automobile, the more positive was attitude toward the Turnpike. In general, same results were obtained for the female vers on U.S. 1; that is, there was a definite lering of attitudes by age of vehicle and ver. A peak in attitudes toward the Turnke seemed to occur in the age range of 25 to , after which drivers' attitudes became re negative toward the Turnpike. No nificant differences were noted for the nale driver on the Turnpike. From these alyses it was concluded that attitudes vard the alternate highways were signifiıtly dependent on the stable characteristics the driver and his vehicle. Analyses of ese results further indicate that attitudes vard alternate routes were very stable, olving partially out of the enduring characistics of the driver and his vehicle.

Attitudes and Trip Characteristics

The second class of relations to a driver's itude concerned the characteristics of the ecific trip during which the driver was npled. The objective of this analysis was determine whether the attitudes toward two highways as markedly modified by purpose of the trip, the number of occunts in the vehicle, and the traveltime sociated with the trip. Analysis showed at no significant relations existed between her the trip purpose or the number of cupants in the vehicle and the driver's itude toward the Turnpike. Similarly, the ation between subjective estimates of trip ration was unrelated to driver's attitude vard the Turnpike. Thus, the results of s analysis on the characteristics of the ecific trip indicate that a driver's attitude s independent of the specific trip. The oice, then, between alternates was made on basis of stable and preexisting attitudes vard the different types of highways.

The results relevant to traveltime should not be interpreted to mean that there were no differences in the distribution of trip durations on the two highways. Table 6 contains the frequency distributions for the sample. These time vaules are subjective estimates of the time already spent driving as well as being estimates of the time required to complete the trip. Therefore, the longer the trip, the more likely it was to be made on the Turnpike. Thus, approximately 32 percent of all drivers sampled on the Turnpike had been traveling for less than one-half hour and 54 percent had more than 1 hour left to drive. But on U.S. 1, 70 percent of the drivers had been driving for less than one-half hour and only 25 percent needed more than another one-half hour of driving to complete their trip. A slightly different presentation in figure 4 shows the percentage distribution of remaining triptime for drivers who had just started their trips. Only 15 percent of those on U.S. 1 expected to be driving for more than one-half hour, whereas 71 percent of the drivers starting their trips on the Turnpike expected to drive for more than one-half hour. Thus, the drivers on longer trips were the ones that tended to gravitate toward the Turnpike

A clearer understanding of the effects of triptime and attitudes can be obtained by examining reports of only those travelers on both routes who had approximately common origins and destinations. If only those Turnpike drivers are selected who had been traveling for less than one-half hour and who had between one-fourth hour and 1 hour left to travel, they could be compared with U.S. 1 drivers who also had been traveling for less than one-half hour but who had between one-half hour and 2 hours more to drive. Obviously, drivers who chose U.S. 1 sacrificed time. The attitudes of male drivers of different ages who chose the Turnpike were compared; the scores are shown in table 7. There were no significant differences among the ages of Turnpike drivers; whereas on U.S. 1, choice of the Turnpike decreased significantly when the drivers were older. However, the U.S. 1 driver always had a significantly negative attitude toward the Turnpike. Thus, it is concluded that for trips having common origin and destination, the driver's choice between the two routes was related mostly to his attitude toward the alternate. For drivers on U.S. 1, this showed that they chose the rural primary route instead of the expressway although this choice increased traveltime 30 percent.

The sample was also analyzed in relation to the frequency with which drivers made trips between South Portland and Kittery. Trip frequency was defined in three categories: Less than 1 trip a year, 1 to 12 trips a year, or more than 1 trip a month. The distribution was computed for both the Turnpike and U.S. 1 and for the two sexes. The percentage of the total sampling on each route for the two sexes and the trip frequencies are shown in table 8. In the Turnpike sampling, the majority of the drivers made the trip more than once a month. On U.S. 1, however, the

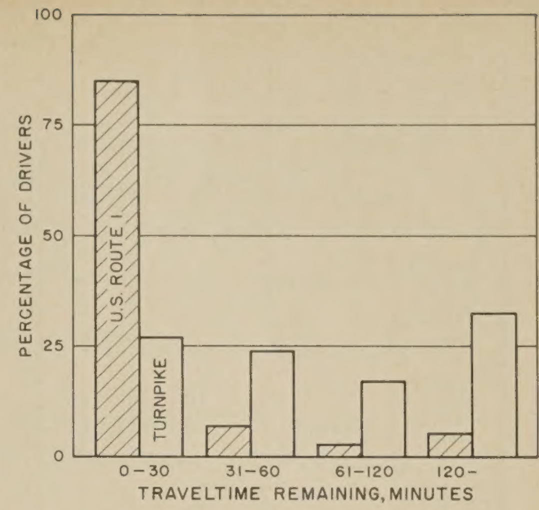

Figure 4.—Remaining trip time after driving less than 30 minutes, percentage distribution.

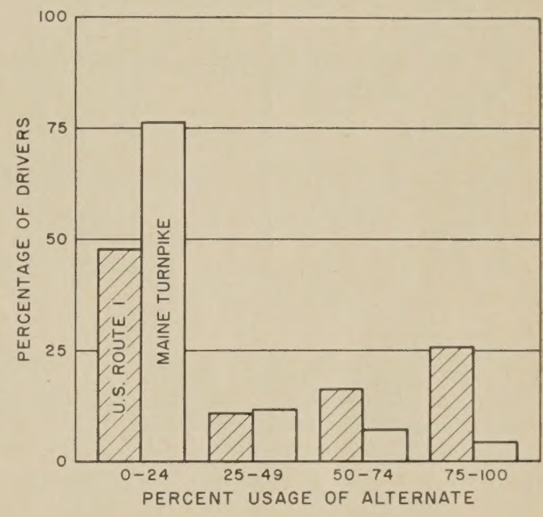

Figure 5.—Frequency of usage of alternate routes by drivers sampled, both routes.

majority of the drivers made the trip between once a year and once a month. A chi-square test was used to test the differences between the number of trips made on the Turnpike and those on U.S. 1, and the differences between the distributions were significant. When trip frequency increased to more than one trip a month, the proportion of these trips made on U.S. 1 decreased and the proportion on the Turnpike increased. This may indicate that the Turnpike exerted an attraction for drivers as the frequency with which they traveled between Kittery and South Portland increased.

The attitudes of drivers toward the two routes were also analyzed as a function of frequency with which trips were made between South Portland and Kittery. The mean attitude scores are shown in table 9. Because of the significant differences among ages of drivers, the data also are separated by that variable. Two inferences may be made: First, the influence of age is the same as discussed previously. Second, as a function of trip frequency, a consistent and significant increase occurred in the average attitude score of both male and female drivers toward the Turnpike. In addition, the drivers on U.S. 1, although having negative attitudes toward the Turnpike, tended to have a change in attitude,

Table 6.—Distribution of driving times for drivers traveling on Maine Turnpike and U.S. 1

Driving time completed, minutes	Maine Turnpike						U.S. 1					
	Driving time left, minutes						Driving time left, minutes					
	Less than 15	15-30	31-60	61-120	More than 120	Total	Less than 15	15-30	31-60	61-120	More than 120	Total
Less than 15:												
Male	55	12	45	35	68	215	190	146	29	16	29	410
Female	4	2	22	11	23	62	136	96	17	4	7	260
15-30:												
Male	16	40	32	32	66	186	91	146	31	14	19	301
Female	8	23	15	24	25	95	94	92	20	13	6	195
31-60:												
Male	35	43	27	34	42	181	41	51	12	11	14	129
Female	13	21	12	8	13	67	12	34	9	5	6	66
61-120:												
Male	31	44	33	59	85	252	25	27	17	16	20	105
Female	10	28	20	35	35	128	7	20	7	8	3	53
More than 120:												
Male	36	64	38	72	173	383	14	16	10	26	48	114
Female	12	23	22	32	64	153	8	16	4	1	16	45
Cumulated total:												
Male	173	203	175	232	434	1, 217	361	386	99	83	130	1, 059
Female	47	97	91	110	160	505	227	266	57	31	38	619

Table 7.—Mean attitude scores for male drivers whose trips had approximately common origins and destinations

Driver age	Mean attitude scores for male drivers on—	
	Maine Turnpike	U.S. 1
Less than 24	--------	35. 37
24–34	42. 47	34. 22
35–44	43. 32	33. 72
More than 44	41. 73	29. 90

approaching neutrality, toward the Turnpike as trip frequency increased. Thus, as trip frequency increased, a general shift to more positive attitudes toward the Turnpike occurred. This result offers further evidence that a driver's attitude toward the two highways shifted, on the basis of his driving experiences on both of the routes, toward favoring the expressway.

A final general analysis was made concerning the extent of utilization of the alternate routes by drivers. Each driver sampled was asked what percentage of time he used the other route for his trips. The percentage of the drivers sampled, who used the alternate route a specific percentage of the time, is shown in figure 5. Because of no differences in data for male and female drivers, all the data were combined. The drivers sampled on the Turnpike rarely used U.S. 1—only 12 percent of the sampling of Turnpike drivers used U.S. 1 for more than half their trips. But drivers sampled on U.S. 1 frequently used the Turnpike—42 percent used it for more than 50 percent of their trips. This usage also indicates an attraction of drivers toward the Turnpike.

Attitude Scale

The attitude scale employed in this study was composed of two classes of items. One classification of the statements was by their reference to either the Turnpike or U.S. 1, and the other was according to whether they were favorable or unfavorable. Hence, the the items in the attitude scale can be classified in a 2 by 2 matrix. In addition, the total attitude score was arbitrarily scored in relation to the Turnpike—a negative statement about U.S. 1 was interpreted as being favorable toward the Turnpike; conversely, a positive statement toward U.S. 1 was interpreted as being negative toward the Turnpike. An item analysis of the attitude scale was made to determine the effects of these different kinds of statements. A sampling of data on the respondents was selected at random on the basis of the percentage of the time they used the alternate route. Each item was classified as to whether it referred to the Turnpike or U.S. 1 and as to whether it was a favorable or unfavorable statement. In these classes, the score value was determined by the extent of agreement with the item itself by the respondent. Thus, a score value of more than 2 indicates agreement with the item, regardless of whether it is favorable or unfavorable. Conversely, a score value of less than 2 indicates disagreement with the statement. In tables 11 and 12, the data are shown for the male drivers.

As shown in table 10, regardless of t route upon which they were sampled, a regardless of the percentage of their trips the Turnpike, drivers responded positively favorable statements about the Turnpike. response to unfavorable statements, driv sampled on the Turnpike, regardless of th frequency of use, disagreed with the state- ments and, hence, provided a positive respon toward the Turnpike. Drivers on U.S. however, strongly agreed with the negat Turnpike statements if they were infreque users of the Turnpike and strongly disagre if they were frequent users. Thus, there w a significant shift in response to the negat statements by U.S. 1 drivers as a funct of the frequency with which they used Turnpike.

Conversely, as shown in table 11, driv sampled on the Turnpike were essentia neutral in their responses to favorable sta- ments about U.S. 1, regardless of whet they were frequent or infrequent users of Turnpike. Drivers sampled on U.S. 1, sponded to the favorable items positiv but less so if they used the Turnpike most the time. On unfavorable statements ab U.S. 1, agreement was consistent amo drivers sampled on the Turnpike when qu tions were independent of the frequency wh which the Turnpike was used. The U.S driver, however, had a definite shift fr disagreement with unfavorable statements he were an infrequent user of the Turnpi to a positive response if he were a frequ user.

The significant aspect (tables 10 and 11) is the fact that drivers sampled on the Turnpike made consistent responses to statements about both routes, whether they were frequent or infrequent users of the Turnpike. The drivers on U.S. 1, however, shifted significantly in response to both types of statements, according to whether they were frequent or infrequent users of the Turnpike, but the major shift was in response to the unfavorable type of statement. These responses were to items that seemed to be the most discriminating type in the scale. Accordingly, drivers sampled on the Turnpike showed significant stability in their responses, regardless of the frequency of their usage of the Turnpike. The drivers sampled on the Turnpike consistently agreed with positive statements about the Turnpike and disagreed with unfavorable statements. He also significantly agreed with statements about the unfavorable characteristics of U.S. 1. Drivers sampled on U.S. 1, however, showed an adaptability to change in their responses, which was a function of experience with the Turnpike. Conclusion from the foregoing analysis is that the negative characteristics experienced by drivers on U.S. 1 in relation to the Turnpike caused drivers to shift to the Turnpike and minimized the probability of Turnpike drivers shifting back to U.S. 1.

Speed Volume and Traveltime Results

On the Turnpike, speed and volume were determined on a sampling basis. Speed and volume measurements were made at 10-mile intervals, both northbound and southbound. A radar speed meter was mounted in the rear of a stationwagon that was parked on the shoulder. The speed meter was aimed at the approaching traffic at an angle of about 10°. This angle was larger than is recommended for the most accurate speed measurements, so some error is in these measurements. Normally, a sample of 100 vehicles was counted, and the time required for them to pass the counting station was also determined. Thus, it was possible not only to determine the speed distribution but also to estimate the hourly volume passing that point. The same procedure was followed on U.S. 1.

The cumulative speed distributions for the Turnpike are shown in figure 6—similar data on U.S. 1 are also included. Data were kept separate for the two directions in morning and afternoon sampling periods. The mean speed of these samples (Turnpike) was approximately 1.9 miles per hour, and the standard deviation was 9.1 miles per hour. The speed distribution is slightly negatively skewed. These speeds should be considered cautiously for, as has been shown by Shumate and Crowther (*10*), there is nonhomogeneity among spot speed samples. For U.S. 1, the cumulative speed distributions also are shown in figure 6. The mean of this sample was 43.7 miles per hour and the standard deviation was 10.3 miles per hour. This speed distribution is also negatively skewed but not so much as that for the Turnpike. The variability of speeds, from

Table 8.—Relative frequency of trips of drivers sampled on Maine Turnpike and U.S. 1

Frequency of trips	Male drivers on—		Female drivers on—	
	Maine Turnpike	U.S. 1	Maine Turnpike	U.S. 1
Year	*Percent*	*Percent*	*Percent*	*Percent*
Less than 1	4.7	7.3	12.4	13.6
1–11	44.1	53.4	42.6	47.3
More than 12	51.1	39.4	45.1	39.0

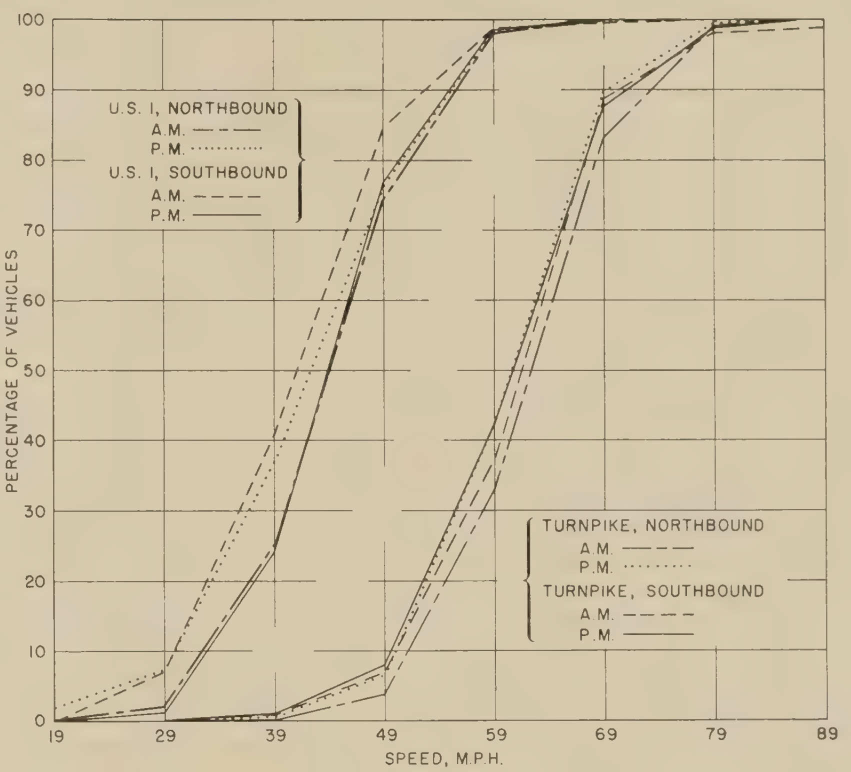

Figure 6.—Vehicle speeds on both routes, cumulative distribution.

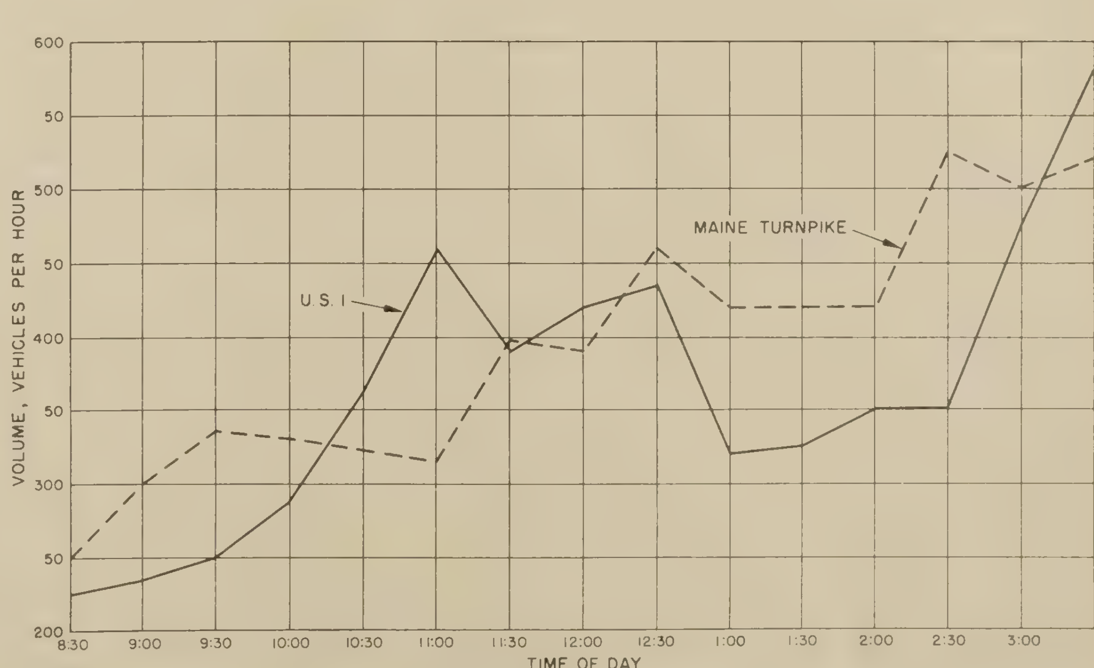

Figure 7.—Calculated average hourly volumes on both routes.

Table 9.—Mean attitudes toward the two highways as a function of the frequency of trips between South Portland and Kittery

Trip frequency, per year	Attitudes by age and sex of driver							
	Less than 24		24–34		35–44		More than 45	
	Male	Female	Male	Female	Male	Female	Male	Female
Maine Turnpike:								
Less than 1	------	------	40.07	39.00	41.18	------	36.93	------
1-11	38.92	38.02	40.25	36.87	41.31	38.00	39.13	39.25
More than 12	43.21	33.78	43.23	40.33	42.93	41.10	41.77	38.24
U.S. 1:								
Less than 1	32.65	28.48	34.54	30.32	32.08	26.33	29.98	27.19
1-11	32.96	31.15	33.05	32.29	31.34	29.63	30.00	28.47
More than 12	31.32	31.54	34.97	32.79	33.68	29.12	30.72	30.36

Table 10.—Average item score of favorable statements for Maine Turnpike, by male drivers who use the Turnpike, either rarely or frequently

Percent drivers use Maine Turnpike	Favorable statements		Unfavorable statements	
	Maine Turnpike drivers	U.S. 1 drivers	Maine Turnpike drivers	U.S. 1 drivers
Less than 24	2.45	2.14	1.71	2.58
More than 75	2.54	2.44	1.70	1.70

Table 11.—Average item score of favorable statements for U.S. 1, by male drivers who use the Maine Turnpike, either rarely of frequently

Percent drivers use Maine Turnpike	Favorable statements		Unfavorable statements	
	Maine Turnpike drivers	U.S. 1 drivers	Maine Turnpike drivers	U.S. 1 drivers
Less than 25	2.09	2.60	2.46	1.61
More than 75	2.00	2.20	2.42	2.13

sample to sample and location to location. was much more on U.S. 1 than on the Turnpike. Therefore, the reliability of these summary statistics is questionable.

Volume of traffic was calculated for both the Turnpike and U.S. 1 on the basis of the same samples of the speed distribution. The average calculated hourly volume between the hours of 8 a.m. and 4 p.m. are shown for both routes in figure 7. The volume on U.S. 1 was not uniform over its entire 47-mile length; it was consistently larger at the more populous northern end. In addition, on U.S. 1, three counting stations were set up: One at each end of the study section and a third—a permanent counting station—about the middle of the test section. The calculated hourly volumes shown in figure 7 are approximately the same as those obtained at the counting stations. The volumes on the two routes were comparable and generally were parallel in their variations throughout the day.

Traveltime data were obtained from the trips made by the nine test drivers used for the GSR study. In these runs, the drivers were instructed to float with the traffic. This was done four times on each highway. Thus, 36 observations of traveltime were made on each route. Summary statistics are shown in table 10. The standard deviations indicate that on both routes the coefficient of variation in traveltime was 7 percent. This implies a variation for travel speed of approximately 17 percent on U.S. 1 and 14 percent on the Turnpike. Actually, the mean traveltime on U.S. 1 closely approximated the traveltime predicted from the mean speed of traffic on U.S. 1. On the Turnpike, however, the average speed of the test drivers was nearly 7½ miles per hour faster than that of traffic sampled on the Turnpike. This would indicate that the mean traveltime on the Turnpike for normal traffic may be up to 4½ minutes more than that shown in table 12. Finally, the maximum difference in time saved by selecting the Turnpike was calculated on the basis of the confidence intervals shown in table 12. In traveling between South Portland and Kittery a driver could obtain a maximum traveltime savings of 35 percent ±4 percent by driving on the Turnpike.

Tension Measurements

The data for the nine test subjects were analyzed by determining the peak magnitude of GSR for observed interferences that caused

Table 12.—Traveltime between South Portland and Kittery on the Maine Turnpike and U.S. 1

	Maine Turnpike	U.S. 1
	Minutes	*Minutes*
Mean traveltime	41.1	63.9
Standard deviation	3.61	4.31
95 percent confidence interval	±1.25	±1.51

the driver to change his speed or positior on the roadway. These interferences were (1) Other vehicles traveling in the same di rection, (2) vehicles merging into path o driver, (3) vehicles turning out of path o driver, (4) traffic control devices, (5) pedestrian on or near path of driver, (6) grades, (7 curves, (8) shoulder objects, and (9) opposin vehicles. The fourth—traffic control de vices—appeared on the Turnpike runs as wel as those on U.S. 1 because highway mainte nance operations were continually performe on the Turnpike during the period in whicl GSR data were taken. Normally, advisor speed signs were placed on the highway t protect the maintenance crew, and these wer included in the definition of traffic control

The magnitude of GSR per minute, whicl is the defined measure of driver tension, wa statistically analyzed by the analysis o variance. A summary of this analysis i shown in table 13. Significant difference were recorded between the routes and sub jects but not direction. These results ar similar to those reported previously (7) The comparison of tension between the tw routes is shown for each subject in figure 8 The average tension differed considerabl between subjects, but U.S. 1 generated sig nificantly more tension for each driver tha the Turnpike. The range of reduction c tension among this group of subjects o the Turnpike was from 22 to 61 percent The overall average saving of tension b taking the Turnpike was 46 percent.

Each route was divided into four, 10½-mil sections. The tension data were analyzed t determine whether differences in tension we generated between the sections of the tes routes. As had been expected, no significa variations from segment to segment we recorded on the Turnpike. Nor were signif cant differences recorded between the sectior on U.S. 1. This was an unexpected findin because the highway and traffic from sectio to section of U.S. 1 had different characte istics and land use adjacent to the highwa varied considerably. One reason for the lac of difference was that the predomina interference in generating GSR arose directl from other vehicles in the driver's patl rather than differences in sections of the higl way. Furthermore, when driving throug the more complex environments, all drive reduced their speed and thus reduce the probability of unexpected interference These compensatory changes may well hav eliminated any differences in GSR from th different sections.

Table 13.—Analysis of variance of GSR data

Source of variance	Sum of squares	Degree of freedom	Mean squares	F, ratio	Probability (F)
Routes	308.65	1	308.65	305.59	<0.01
Subjects	421.11	8	52.64	52.12	<0.01
Direction	0.89	1	0.89	0.89	(1)
Routes and subjects	62.60	8	7.83	7.75	<0.01
Routes and directions	28.59	1	28.59	28.31	<0.01
Subjects and directions	34.87	8	4.36	4.32	<0.01
Residual	44.38	44	1.01	----------	----------
Total	901.14	71	----------	----------	----------

[1] Not significant.

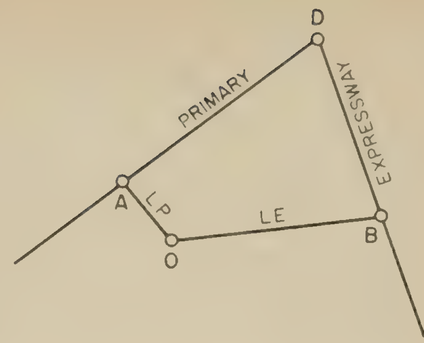

Figure 9.—Geometry of diversion situation.

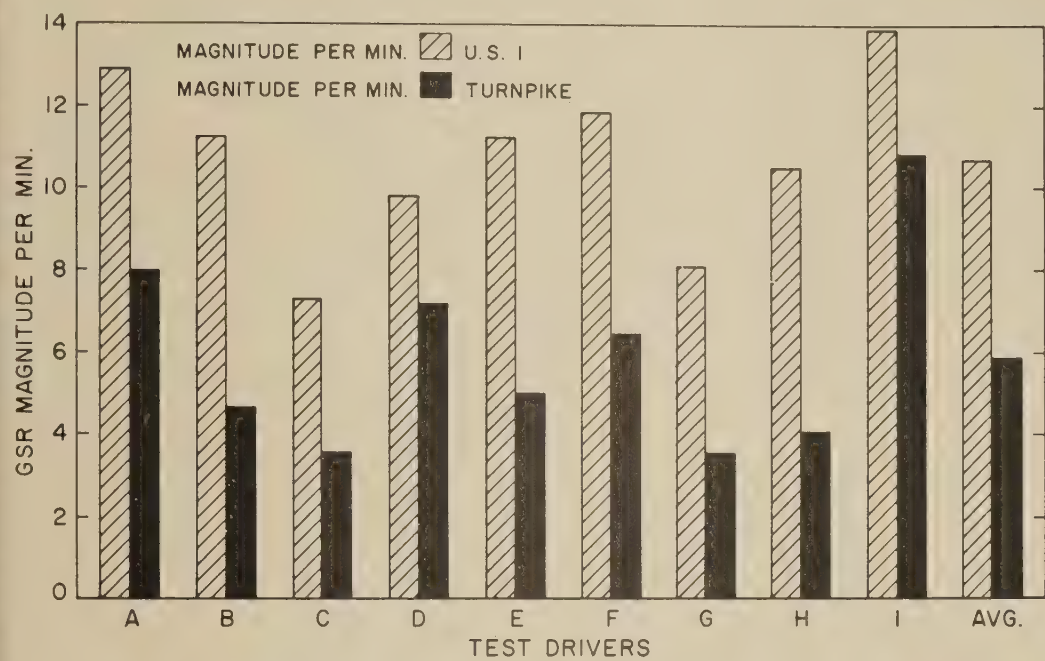

Figure 8.—Mean tension generation on both routes.

Interpretation of Results

One of the main objectives of this study was to determine whether drivers had stable attitudes that correlated their choices between alternate highways. The results clearly established that they do. The attitudes of the users of the one highway differed significantly from the attitudes of the users of the other. Furthermore, the users of the Turnpike had significantly positive attitudes toward that controlled-access highway, and users of the rural primary had significantly negative attitudes toward the Turnpike. On the basis of the results, only a small proportion of drivers who hold a positive attitude toward the Turnpike actually will drive on the primary. Furthermore, in the alternate choice situation studied, an attitude scale appears to be strongly related to choice, much more so than any descriptive information about the characteristics of the drivers or their trips.

The results of the study clearly showed that drivers do evaluate their experiences on different highways. This evaluation is developed from a variety of elements in the highways they travel. Whether consciously or unconsciously, drivers weigh the different features of highways and combine subjective experiences into an overall evaluation. This is reflected in attitudes and predisposes drivers toward the choice of one highway instead of another. As a matter of fact, it is these attitudes that overwhelm all the specific short-term aspects of a particular trip and dictate the choice of route.

A third aspect of the study concerned the problem of attraction of traffic to an expressway. In several of the analyses it was very evident that attitudes shifted toward favoring the Turnpike. The most clear-cut example is the one in which the individual items on the scale were analyzed according to the route sampled. The significant finding was that the more drivers use the two highways, the more the primary suffers by comparison. The learning experience apparently increases drivers' awareness of the negative characteristics of the primary, so they become more dissatisfied with it. The direct experiences obtained in driving the primary-type of highway seem to force drivers onto a turnpike. Thus, the overall problem of the attraction of traffic to an expressway may be considered to arise from the direct experiences drivers have in driving it and any alternate. Because the expressway is perceived by drivers to have fewer negative effects than an alternate primary, a slow shift to the expressway occurs that seems to be motivated by a desire to escape the characteristics of the highway of older design.

Three major factors inherent in this type of situation may motivate a shift in favor of an expressway. First is the reduction in travel-time obtained by choosing the expressway. However, the results of the study showed no significant shifts in attitudes as a function of driving time. Drivers have the same attitude about both routes whether they are traveling for one-fourth hour or more than 2 hours even though, as a proportion of the total trip, savings in time gained from taking the expressway are decreased for long trips.

Second, in the original validation study, an item relative to the time savings to be obtained on an expressway was nondiscriminating; that is, regardless of whether people have positive or negative attitudes toward a turnpike they all agreed that time could be saved on it. Thus, although all drivers knew there was a time saving, it had no influence on their attitudes. As drivers know this to start with, time savings cannot be the basic cause of the shift in attitudes favoring an expressway. Some more subtle aspect of driving must be the source and it seems to be most sensitive to the negative characteristics of the primary.

Third, the direct cost of travel to the user is a factor. However, this does not seem reasonable, as the shift is in the wrong direction. That is, if cost of travel were a significant determinant of choice, a shift of attitudes away from a turnpike would occur, especially as trip frequency increased. However, the results clearly showed that, as the frequency of trips increased, there was an increasingly positive attitude toward the Turnpike and an even more likelihood that a driver would choose it. Also, two items were added to the scale that directly affect economic evaluation by the driver. These two items were actually the same except that one dealt with direct out-of-pocket cost, whereas the other dealt with cost per vehicle-mile.

The two statements read, "I would always travel the Turnpike between South Portland and Kittery if the cost were no more than" and alternatives were provided; for example, one increased the cost from 25 cents to \$4, doubling over each of the five categories and another increased the cost from one-half cent a mile to 8 cents a mile. As might have been expected, the cost per mile item was nondiscriminating. Very few drivers had any

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idea of per mile cost. The result was that estimates on both routes were randomly distributed; a small proportion of drivers omitted a reply to the item. More surprising, actual out-of-pocket cost was also nondiscriminating. The reliability on the Turnpike was a little higher, possibly because the drivers had just received a toll ticket. Further, drivers sampled on both highways consistently reported to the interviewers that the cost of the Turnpike was irrelevant to their choice. This finding may simply mean that most drivers in this sampling were very indifferent to the expense of traveling the Turnpike at current cost levels.

Neither time savings nor direct costs seem to be dominant in determining the attraction of traffic to the turnpike. What seems to be required is something that drivers must learn by direct experience: Something related primarily to the negative characteristics of the rural primary type of highway. This leads inevitably to the consideration of the stresses arising in driving on the two routes. From the results of the GSR phase of the study discussed here, the tension aroused in the test drivers on the Turnpike was approximately one-half that generated on the primary. This tension was caused by interferences that had purely negative effects. It seems reasonable that shifts in traffic to an expressway facility is actually a forcing of drivers away from the primary route so that they can avoid its stress inducing characteristics. Stated more generally: Drivers make choices between routes to minimize the total stress to which they are subjected in driving. Thus, for the passenger car driver, the basis for scaling the benefits to be obtained from using an expressway are neither economic nor timesaving, but they are stress saving.

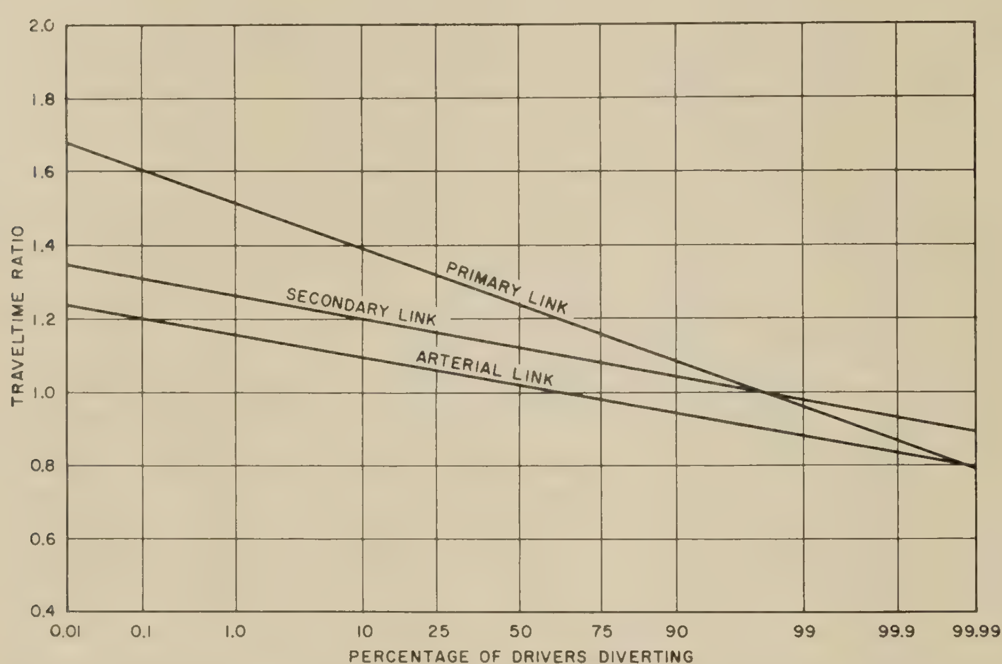

Figure 10.—Theoretical diversion distributions, different connections from primary to expressway.

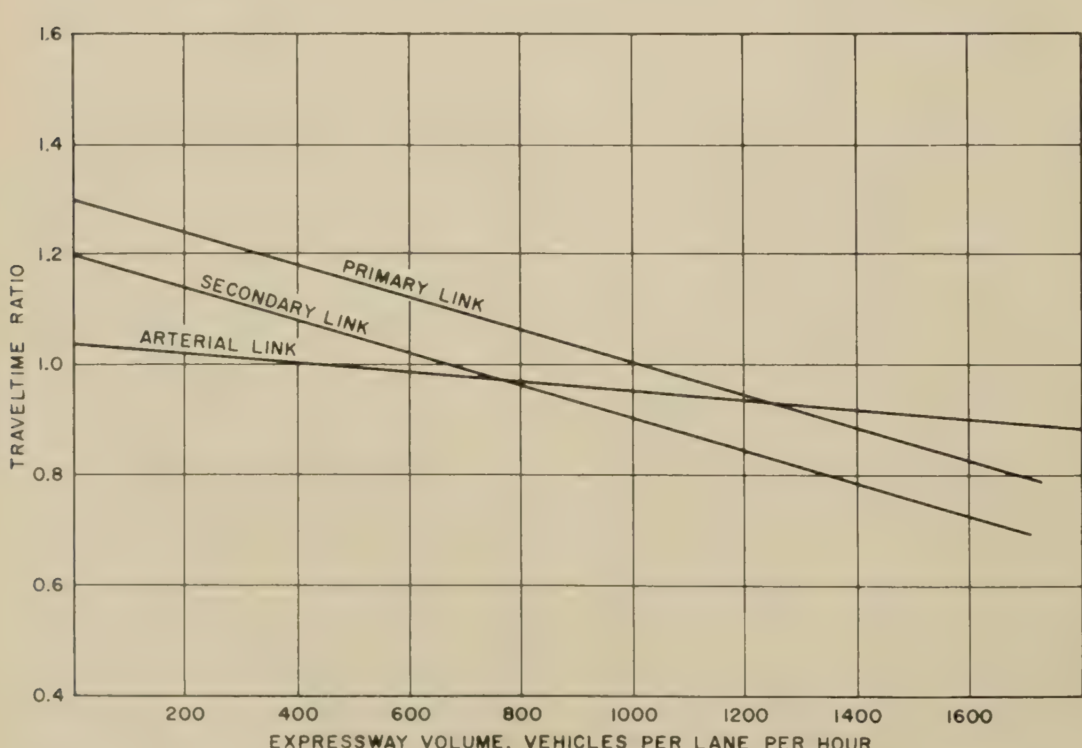

Figure 11.—Expected traveltime ratio, 50 percent diversion, as function of expressway volume.

The objective of minimizing the stress level in driving may explain two characteristics of the distribution of trips in the study results. First, the more frequent a trip, the more likely the drivers were to take the Turnpike. Second, the longer the duration of the trip, the more likely it was to be made on the Turnpike. Obviously, the total stress experienced on either route was a function of the particular properties of the route and the duration of the trip. That is, the total tension incurred is the integration of the unit stress over the duration of the trip. These tension inducing interferences occur randomly in time, the mean value being more on the primary highway than on the Turnpike. Because the variance in rate of occurrence of tension inducing interferences is high, the differences between the stress experienced on two highways in any short time interval will be unpredictable. Frequent repetitions or an increased sampling interval—that is, longer trips—will be required for the driver to reliably detect the difference between the alternates. By making frequent repetitions or longer trips, drivers will more likely detect the differences in tension on the alternate routes and thereby modify their choice behavior. The traveltime distribution and trip frequency data collected for this study conform to this hypothesis.

In simplest terms, the tension generated on any trip is some function of total traveltime and the frequency and intensity of stressing interferences. Using a relative measure of tension, a dimensionless constant is obtained. The relative stress obtained on any trip on a highway may be defined:

$$S=\frac{T_n}{T_R}\,(t) \quad (1)$$

Where,

T_n=magnitude of GSR per minute on highway n.

T_R=magnitude of GSR per minute on reference highway.

t=trip duration.

Thus, if tension generated on a freeway is used as a reference, a numerical value of relative stress can be calculated when the type of highway on which travel is done and trip duration are known. In this and previous studies (*6, 7*) it was shown that tension generated relative to the controlled-access highway was approximately 1.8 for a primary highway and 3.3 for an urban arterial. For a rural secondary highway having a low volume of traffic, the ratio probably is intermediate between these two, or about 2.5. Similarly the relative stress for any set of routes may also be computed by summing the stress for the components and the minimum stress route determined.

Relative to the problem of diversion to an expressway, this model suggests that: Drivers will divert to an expressway if the total stress experienced in reaching the expressway and on the expressway to the destination does not exceed that of the trip from origin to the alternate highway and on the alternate to the destination.

A general situation is shown in figure 9. Assume that an expressway, E, and a primary P, have a common terminus. Also, assume that the origin of a trip is located in the space bounded by the two routes so that there is a direct connection to either by link L. According to the hypothesis proposed herein, a driver will divert to the expressway to reach his destination if the total tension generated on the link, L_E, and the expressway, E, is equal to or less than the tension generated on the link, L_P, and the primary, P. When the origin lies on the primary and link L is a perpendicular connection to the expressway, E (fig. 9), then an inequality is obtained, as shown in equation (2), which defines the minimum separation between the primary and expressway for which 50-percent diversion will occur:

$$K_L \sin \theta + K_E \cos \theta \leq K_P \qquad (2)$$

The constants are the relative stress developed on each of the links. The solution of equation (2) is simply derived. Solving in terms of the cos θ, a quadratic equation is obtained, the real root of which is shown in equation (3):

$$\cos \theta = \frac{\left(\frac{T_P}{T_E \cdot V_P \cdot V_E}\right) + \left(\frac{T_L}{T_E \cdot V_L}\right) \mathrm{A}}{\left(\frac{T_L}{T_E \cdot V_L}\right)^2 + \left(\frac{1}{V_E}\right)^2} \qquad (3)$$

Where,

$$\mathrm{A} = \sqrt{\left(\frac{T_L}{T_E \cdot V_L}\right)^2 + \left(\frac{1}{V_E}\right)^2 - \left(\frac{T_P}{T_E \cdot V_P}\right)^2}$$

$\frac{T_P}{T_E}$ = ratio of stress developed on a primary highway to that developed on an expressway.

$\frac{T_L}{T_E}$ = ratio of stress developed on the link between primary and expressway.

V = mean speed in m.p.h. on appropriate highway.

It is further possible to define the travel distance ratio and the traveltime ratio. The equations are:

$$\frac{d_L + d_E}{d_P} = \sin \theta + \cos \theta \qquad (4)$$

Where,

d_L = distance on link.
d_E = distance on expressway.
d_P = distance on primary.

and,

$$\frac{t_L + t_E}{t_P} = \frac{V_P}{V_L} \sin \theta + \frac{V_P}{V_E} \cos \theta \qquad (5)$$

Where,

t = traveltime on each link.
V = mean travel speed on each link in m.p.h.

By using the values for relative stress for three different types of highways and the travel speeds, equations (3), (4), and (5), may be solved, and the results will be as shown in table 14. The mean traveltime ratio decreases consistently as the stress inducing characteristics of the link increases.

Two other aspects may be considered by using this model. One is the variance in tension. In this analysis the relative stress is treated as a constant, although it is, of course, a mean value. On the basis of the data collected in this study, the variance of this ratio was 0.42. Using this ratio, it is possible to calculate the percentage of drivers diverting to an expressway, using equations (3) and (5). Normit plots are shown in figure 10 for the three examples. The other aspect concerns the volumes of vehicles the highways are carrying. As has been stated previously (*7*), the mean tension on an expressway increases linearly to about 1,400 vehicles per lane per hour. Beyond that volume tension increases very rapidly. On urban arterials (*9*) volume seems to have relatively little overall effect on tension generation. For primary highways, however, no data are available on the effect of increasing volume. If it is assumed that the effect of volume on the primary highway is similar to that on arterials, it is obvious that diversion to an expressway will vary solely with volume on that type of highway. The effect of increasing expressway volume on the traveltime ratio for 50-percent diversion is shown for the three types of links in figure 11. These curves were derived from equations (3) and (5). In all three examples, the traveltime ratio for 50-percent diversion decreases until, as volumes exceed 1,000 vehicles per lane per hour on the expressway, an actual time savings must occur before half the traffic diverts.

Note that the diversion curves developed from this special example do not conform to those developed from origin and destination studies in this corridor (*1*). The model predicts much more attraction than actually occurred; this was caused partly by the assumptions about the connection between primary and expressway routes. The choice points are not very direct for drivers within the Maine Turnpike and U.S. 1 corridor. Furthermore, a significant proportion of trips in that corridor are very short. For this kind of traffic, essentially trapped on U.S. 1, diversion to the Turnpike would gain the driver no detectable reduction in stress and, hence, little diversion would be expected.

However, for corridor trips of more than 10 miles and north-south oriented, considerably more diversion should occur than is shown in the general diversion curves (fig. 11). In this respect, Carpenter (*2*) examined through trips between Wells and Saco and reported that 30 percent of them diverted to the Turnpike, even though the traveltime ratio was approximately 1.22. However, on the basis of the link characteristics, the tension ratio for the alternate routes may be calculated and is approximately 1.09. This yields expected diversion of approximately 35 percent of these trips.

A reasonable conclusion is that whenever the alternates available are equally stress inducing, drivers will always choose the route that takes the least time. Therefore, it is not surprising that most drivers, when questioned as to why they chose the route, commonly used traveltime as a response. Not only is total stress directly related to traveltime but also, many of the alternates available offer no significant stress reduction. Furthermore, such trips are often so short that stress differences are hardly detectable. It is evident from results of the study reported, however, that drivers will actually tolerate a time loss, as well as a distance loss, if the total stress to which they may be subjected is perceptibly reduced. On the basis of this model, measures that reduce stress should cause both increases in trip length and trip frequency. As driving is a stressful and energy consuming task, each driver has a tolerance or limit beyond which the subjective cost of driving becomes excessive. The satisfactions to be gained by a trip are less than the energy required to achieve it. If trips are predominantly goal oriented, the stress imposed on a driver becomes the equivalent of a cost, the value of which is determined in part by the desirability of the goal. Conversely, reduction of this subjective cost by the addition of improved highways not only makes any given trip easier, but also makes lower priority goals more attainable. Thus, new travel is generated.

It would seem that the value of these subjective costs of driving could be determined experimentally, either: (1) by subjective scaling of simulated trips, which is a variation of game theory techniques, or (2) by subjective evaluation of actual trips made under well-defined conditions. However, a significant problem would remain: The measurement of the value a driver places on the need to make the trip. It is the ease with which the highway transportation satisfies this need that is the measure of the subjective benefits of the highway transport system. It would seem, then, that methods exist for quantifying the subjective costs of travel but not for subjective benefits. One thing, however, becoming increasingly clear is that, although passenger car drivers make rational evaluations of transportation, their benefit-cost ratio appears to have little in common with the economic criteria normally used in highway transport.

Table 14.—Theoretical solution of expected diversion from a primary highway to an expressway

Link type	Separation between primary and expressway	Trip distance	Travel-time
	Radians	*Ratio*	*Ratio*
Primary	0.99	1.39	1.24
Secondary	.34	1.28	1.12
Arterial	.13	1.12	1.02

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NEW PUBLICATIONS

New Highway Map of the United States

The Bureau of Public Roads has recently published a new highway systems map of the United States showing the National System of Interstate and Defense Highways, the Federal-Aid Primary Highway System, and the U.S. Numbered Highway System. The eight-color map is printed on a single sheet, measuring 42- by 65-inches. The scale of the map is 1:3,168,000; that is, 1 inch equals 50 miles, and it is drawn on the Albers equal-area projection. The actual map compilation was made by the U.S. Geological Survey, with the cooperation of the Bureau of Public Roads and the State highway departments.

The new map may be ordered under the short title, *Federal-Aid Highways*, from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, at $1.50 per copy.

In addition to the three highway systems, the map also shows national forests, parks, and Indian reservations; all information represented is as of March 1, 1965. It should be noted that the map shows highway routes without regard to condition or completion, and many of the Interstate System routes are not yet built. Although the map will serve many useful purposes, it is not a touring or road-condition map.

For the 41,000-mile National System of Interstate and Defense Highways, commonly called the Interstate System, the locations of all routes are shown on the map, but only about one-half of the mileage is open to traffic at present. The System is scheduled for completion by 1972. The Federal-Aid Primary System totals about 227,000 miles (exclusive of the Interstate System); the majority of its routes are parts of the State highway systems. The U.S. Numbered System, 170,000 miles in extent, was devised by the American Association of State Highway Officials as a means for guiding travelers; it does not designate Federal-aid highways. However, most U.S. numbered routes are on the road systems eligible for Federal aid.

Illumination Variables in Visual Tasks of Drivers

By[1] H. RICHARD BLACKWELL, Director, The Institute for Research in Vision, The Ohio State University; RICHARD N. SCHWAB,[2] Electrical Engineer, Office of Research and Development, U.S. BUREAU OF PUBLIC ROADS; and B.S. PRITCHARD,[3] formerly Research Associate at the Institute.

The research reported in this article originally was conceived as a very limited study of the illumination levels needed for adequate performance of certain types of visual tasks that might be required of drivers. The authors originally planned to apply a general method, previously developed for visual tasks related to interior environments, to problems related to determining the illumination requirements for visual performance of driving tasks at night. However, the general method was not entirely satisfactory and new techniques for studying these problems had to be developed. The new techniques are explained.

Data developed from this study show that drivers experience many different degrees of difficulty in performing visual tasks that might be encountered in night driving—the degree of difficulty experienced being dependent to a large extent on the factors that influence the background luminance and the contrast of the task. A very comprehensive study of illumination and visibility variable would be required before any general understanding of the problems related to seeing while driving could be achieved, according to the authors. They note that the study reported in this article is not such a comprehensive work but that the results obtained should be useful for defining variables of interest for further research on highway lighting requirements. Some of the pitfalls that should be avoided in this further research are discussed.

On the basis of the data presented and the assumptions made, the authors estimate that 1.30 footcandles of illumination would be required for a driver to see a small black dog 200 feet away in the driving lane, and that 1.85 footcandles of illumination would be required for the driver to see a manikin of a young girl dressed in a long gray coat in the same location as the dog. An analysis of the data compiled suggests that contrast is more important than luminance in defining visual tasks.

Introduction

THE RESEARCH reported here is based primarily on the *visual task evaluator* (VTE) technique described by Blackwell (*1*)[4] in an earlier publication. In the work discussed in this article the technique has been extended from the earlier work on illumination levels required to perform certain types of visual tasks, occurring in interior environments, to those types of tasks that a driver might encounter in a street or roadway environment. The technique leads to an index of visibility based on the extent to which a practical visual task exceeds the borderline point between barely seeing the task and not seeing it at all. This borderline point is called the threshold of visibility, and the visual task may be that of seeing any object in the visual field that may be of interest to the observer when it is viewed against its normal background environment. An example might be seeing a pedestrian standing by the side of the road.

The degree to which the practical task exceeds the threshold point is measured by using the VTE to reduce the contrast that the object has with its background until the object is no longer distinguishable when viewed through the VTE. The amount that the contrast between any object and its background must be reduced to reach threshold may be used as an index of the extent to which that object exceeds the visibility threshold.

In the original use of the VTE technique, Blackwell used this measure of contrast reduction to define a value $\tilde{C}$ for each task studied. $\tilde{C}$ is defined as the physical contrast of a 4-minute, luminous, disk target having a visibility level equivalent to that of the task of interest—equivalence being specified as an equal amount of contrast reduction required to bring each task to its visibility threshold. The 4-minute disk target can be used, therefore, as a comparison standard, and the contrast ($\tilde{C}$) of this target can be used to determine the illumination level required for a selected level of task performance based on laboratory performance data (*2*). In the study reported here, the VTE defines illumination levels in terms of a performance criterion adopted as a standard by the Illuminating Engineering Society (*3, 4*). Several special procedures were required in applying this method to the roadway environment; they are described herein and their validity established.

In addition, the VTE technique specified the relative visibility of a task under different roadway conditions, thereby allowing the examination of the effect of different aspects of illumination upon visibility. The particular aspects of the roadway illumination examined include the type of light source, the type of pavement, the spacing between light sources, the location of the task on the roadway, and the distance between the observer and the task. The relative visibility also has been related to background luminance and task contrast—the two physical parameters that determine task visibility within the roadway situation.

This study data showed a wide range in the degree of difficulty of different visual tasks that might be encountered on roadways at night. Indeed, different tasks require levels of illumination that range from moonlight to full daylight. The difficulty of a task depends, to a most significant extent, upon the factors influencing background luminance and task contrast, and these include all the factors that affect the amount of illumination striking a vertical object and its horizontal background. This implies that a very comprehensive study of illumination and visibility variables in roadway visual tasks is required before any

[1] This article is based on research conducted under Ohio HPS-HPR 1(32), *A Study of Highway Lighting*, by the Transportation Engineering Center, Engineering Experiment Station, The Ohio State University under sponsorship of the Ohio Department of Highways, and in cooperation with the U.S. Bureau of Public Roads. The project also was supported by the Illuminating Engineering Research Institute. A complete technical presentation of this research is available in reference (*5*).

[2] Mr. Schwab was formerly Research Assistant at The Institute for Research in Vision.

[3] Now dead.

[4] References indicated by italic numbers in parentheses are listed on page 248.

great understanding of the problem of seeing while driving can be achieved. The research reported in this article does not represent such a comprehensive study. It should be useful however, in defining the variables of interest for a more comprehensive study.

The primary data were collected at one test site in Hendersonville, N.C., where lighting variables could be controlled and changed readily. Other test sites also were used and the results obtained were very similar. For this article, only data from the Hendersonville test site were used to derive average values of the illumination required for roadway tasks because these were the most complete data (*5*). The lighting at the test site was assumed to be reasonably representative of general practice.

Summary

Field tests were conducted on the visibility of a series of realistic objects located on a test roadway having lighting that could be changed. Visibility was assessed through the VTE technique. It was necessary to develop special techniques when applying the VTE to the study of roadway visual tasks. One technique involved the evaluation of the visual effect of disability glare. A special attachment for a photoelectric photometer was developed to do this, and the results were analyzed on the basis of laboratory visibility data. Another technique involved the use of a small part of the visual field when evaluating the state of visual adaptation. Physical measurements of the contrast in several roadway tasks were used to demonstrate that visual adaptation should be measured over a small part of the field next to the most visible detail of the object, rather than over a much larger area as previously had been used with the VTE procedure.

Visibility assessments were used first to evaluate the influence of such variables as objects, illuminants, viewing distance, location of object on the roadway, location of object to luminaires, luminaire spacing, and pavement material. Roadway tasks were concluded to vary grossly in difficulty and all the variables studied had important effects upon target visibility. The relative significance of the different roadway variables developed from the test data obtained should be estimated with caution, until a more complete, theoretical understanding of the causative factors involved has been obtained.

The data have also been used to determine the illumination needed to bring roadway visual tasks to a level of performance currently used in defining standards by the Illuminating Engineering Society. Average values required for visibility of objects at a distance of 200 feet were 1.30 footcandles to see a toy black dog and 1.85 footcandles to see a little girl manikin. Frequency graphs were prepared to illustrate the number of locations on the roadway providing this criterion level of task visibility for different levels of roadway illumination. In 99 percent of the locations on a lighted roadway, about 4 footcandles were required to see the dog and about 5 footcandles were required to see the manikin. Data were also prepared to illustrate the relative levels of illumination required to increase visibility to the criterion level at distances of more than 200 feet. When the distance was increased to 400 feet, an increase in illumination of about 2.5 times was required to see the dog and about 15 times to see the manikin. Care must be exercised in interpreting these illumination requirements. First, illumination levels depend critically upon the geometry involved. Hence, the illumination levels derived from the test data can refer only to roadway lighting installations of the same geometry. Second, many of the conditions encountered at the test site may not apply to real roadways. For example the pavement surfaces at the test site were unusually clean and unmarked. Third, the visibility criterion adopted by the IES for indoor tasks may not be applicable to roadway tasks. Analysis of the data, however, illustrates the value of studying the roadway visual problem by using the VTE technique. These tests produced useful information on the relative influence of different roadway variables and required illumination for selected objects at a selected level of visibility.

Equipment and Calibration

The basic instrument used for the tests discussed herein was the original laboratory model of the VTE, which is shown mounted on the table at the right in figure 1; a Pritchard photometer is mounted on the tripod at the left. The extra lens beside the photometer control box is the *disability glare lens*, which is described subsequently. A schematic optical diagram for the VTE is figure 2. An observer looking through the VTE sees an image of the real world beyond the objective lens centered in the photometric comparator cube. Surrounding this central circular image of the external world is a doughnut-shaped *annulus* of uniform luminance produced by a lamp within the instrument. This annulus luminance is adjusted to equal the external world by a neutral absorbing wedge, labelled *annulus wedge*. This same lamp also illuminates a variable contrast wedge that is used to reduce the contrast of the image of the external world by a superimposed uniform light veil over the entire image seen through the instrument. The effect is similar to having a fog between the observer and the object viewed. The variable contrast wedge is constructed so that, at any given point on it, the total of the light transmitted through it from the external world and the light reflected from the internal light source are approximately a constant. For calibration purposes, a mirror, $M1$, is inserted to block the beam from the external

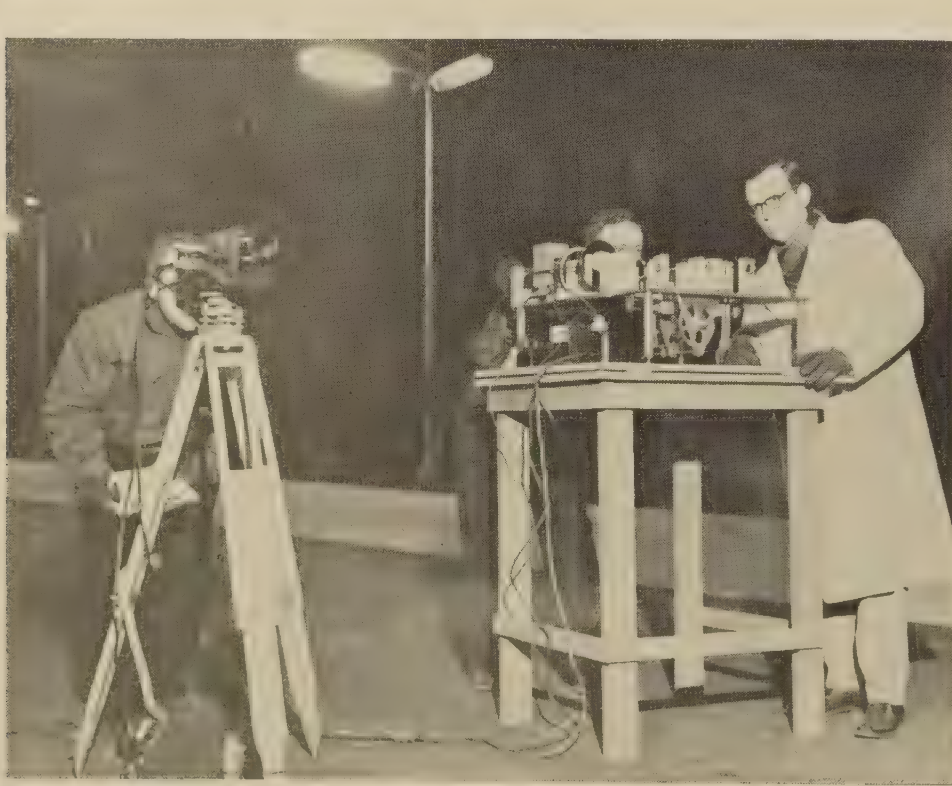

Figure 1.—Equipment for outdoor visibility test. Pritchard photometer, left; visual task evaluator, right.

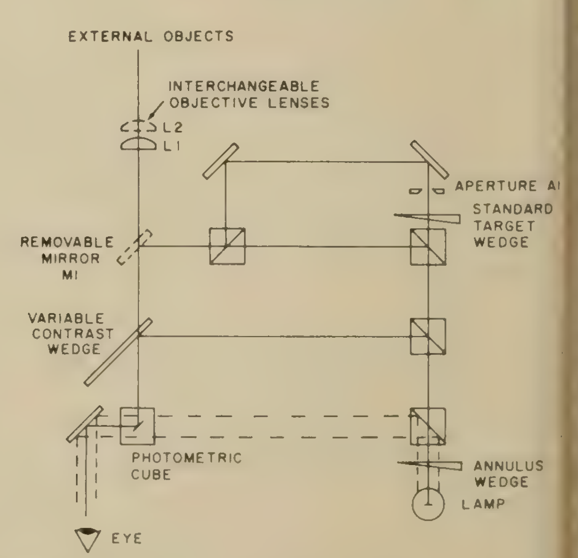

Figure 2.—Diagram of original visual task evaluator.

world and reflect a standard 4-minute disk target, the size of which is controlled by aperture $A1$; the contrast is controlled by the standard target wedge.

The calibration method used for the study reported here is summarized: In a photometric laboratory the transmission of the annulus wedge, T_A, was measured for all possible wedge settings. The luminance of an external object, when viewed through the VTE, was adjusted so that its luminance exactly matched that of the annulus when the annulus wedge was set for maximum transmittance. The luminance of the external object was then measured. This luminance, B_o, varied with lamp output and, therefore, had to be measured periodically. The next calibration determined the extent to which each setting of the variable contrast wedge reduced the contrast of the external scene. The extent of this reduction was termed *contrast rendition*, *CR*, and was measured by setting up an external object of equal luminance to the annular field when the variable contrast wedge was set for maximum transmittance. The transmittance, T, and the reflectance, R, were then measured photoelectrically by successively blocking the reflected and transmitted beam at different settings of the variable contrast wedge. The contrast rendition was defined as:

$$CR = \frac{T}{T+R} \qquad (1)$$

The final calibration measured threshold contrast for the standard target at several settings of the annulus wedge; this determined the background luminance against which the standard target was seen. With the removable mirror, $M1$, in place, the contrast of the standard target was varied by adjusting the standard target wedge until the 4-minute disk target was at the threshold of visibility. This process was repeated several times at each of several settings of background luminance by either reducing the contrast so that a visible target became invisible or by increasing the contrast of an invisible target until it became visible. Values of threshold contrast, C_m, thus obtained were plotted for different background luminances, and the smooth curve shown in figure 3 was drawn through them.

The values of C_m used represent the average of three sets of calibration data obtained by Pritchard between the fall of 1958 and the spring of 1960 and the original calibration data obtained during the 1957–58 VTE work on interior tasks. It was originally believed that data should be analyzed in terms of calibration data obtained at the same time each practical task was measured (*6*). Because it was subsequently learned that, for a practiced operator, use of an average calibration curve was preferable, average calibration data were used in the study discussed here. Also, for a second, untrained observer, this average calibration curve seemed to apply very well. In fact, when two observers attempted to make readings on the same practical tasks, the average calibration data (fig. 3) applied more reasonably to information obtained by the second observer than the calibration curves obtained directly by him. Therefore, the Pritchard calibration data were used in analyzing all VTE measurements, regardless of the observer.

Field Procedures

The original procedure for use of the VTE consisted of the following steps. First, the operator viewed the practical visual task through the VTE and centered the image of the task in the field of view. The variable contrast wedge was then set for maximum transmittance, the objective lens, $L2$, was inserted, and lens $L1$ was removed. Lens $L2$ produced a completely out-of-focus image of the external world, subtending exactly 2 degrees of visual angle. The resultant blurring of the external world image integrates the luminances within the field of view and produces the appearance of uniform brightness over the central circular area of the photometric cube. The brightness of the surrounding annulus, controlled by the annulus wedge, was then easily adjusted to match the average brightness of the central area. The average luminance, $\overline{B}$, of the task was defined from the calibration described earlier as:

$$\overline{B} = B_O \times T_A \qquad (2)$$

The annulus wedge was left in the position of the photometric match. Objective lens $L1$ was substituted for $L2$ to form an in-focus image of the external world. The variable contrast wedge was adjusted until the visual task of interest was reduced to threshold visibility and the contrast rendition, *CR*, read for that setting of the variable contrast wedge. The equivalent contrast, $\tilde{C}$, was then defined as,

$$\tilde{C} = \frac{C_m}{CR} \qquad (3)$$

where, C_m is the value read from figure 3 at a background luminance equal to $\overline{B}$. $\tilde{C}$ measures the intrinsic visual difficulty of the task because of physical variables such as object size, shape, luminance contrast, and chromatic contrast. $\tilde{C}$ does not reflect the difficulty of the task related to the background luminance present because its use in establishing the illumination requirements of different visual tasks requires $\tilde{C}$ to be independent of the illumination level present at the time the visual task is assessed.

After a value $\tilde{C}$ for a task has been obtained, the background luminance, B_r, that is required for performance of the task at a selected level of adequacy can be determined. As mentioned in the introduction, the performance criterion used in this article was based on certain assumptions of what constitutes adequate performance. These assumptions were: (1) That the task—detecting the presence of the standard object—be performed 99 percent accurately by trained laboratory observers; and (2) that information about the task be derived at the rate of five assimilations per second. To compensate for the difference between use of laboratory observers and so-called *commonsense seeing* and other variables, such as lack of complete information as to where and when the object was to appear, a field factor of 15 was introduced to adjust the laboratory performance data upwards. Justification for using these assumptions has been discussed by Blackwell (*1*, *4*).

Based on the preceding assumptions, laboratory performance data can be obtained to relate contrast threshold to background luminance, B_r, required to reach a certain performance level. Such a curve is shown as the solid line in figure 4. The ordinate corresponds to the logarithm of $\tilde{C}$ and the abscissa to the logarithm of B_r; therefore, after $\tilde{C}$ was measured, B_r was obtained by reading the curve in figure 4

The required illumination, E_r, was computed from the value of B_r. In the roadway study, the relationships were solved:

$$E_r = B_r \times \frac{\overline{E}_h}{\overline{B}} \qquad (4)$$

Where,

$\overline{E}_h$ = the average horizontal illumination provided by the roadway lighting system.

$\overline{B}$ = the average luminance of the task as defined in equation (2).

The logic of equation (4) is explained in the rest of this paragraph. The roadway lighting system producing average illumination, $\overline{E}_r$, provides luminance $\overline{B}$ for a particular task at some point along the roadway. If the visual task assessment showed that a luminance, B_r, was required to perform the task at the selected level of adequacy, the ratio $B_r \div \overline{B}$ represents the extent to which the lighting system produced an adequate luminance. *Assuming no change in illumination geometry*, the required average illumination, E_r, would equal the actual average illumination, times the ratio $B_r \div \overline{B}$. It cannot be overemphasized that no change in illumination geometry must be assumed. Obviously, in a three-dimensional situation such as in roadway lighting and viewing, unless the illumination geometry is maintained precisely, a change in illumination level could alter task contrast and, hence, task visibility. The assumption used in writing equation (4) is that, in effect, the system of roadway illumination is on a dimming control. The illumination could, therefore, be set at E_r to provide a selected level of visual performance for any task of interest by adjustment of the illumination up or down to the required level.

Disability Glare

In order to apply the VTE technique to a roadway environment, a special method was employed to allow for the deleterious effects of disability glare on task visibility. The field of view of the VTE was limited to the central 2-degree area around the object.

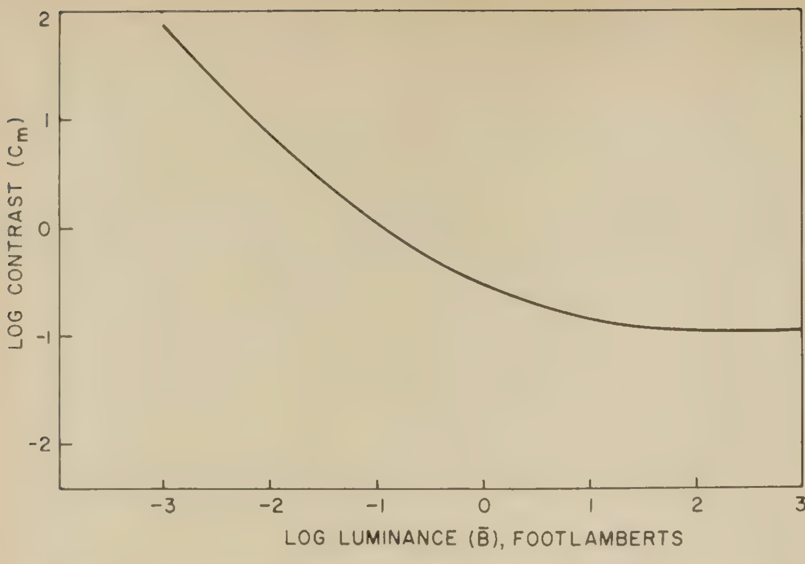

Figure 3.—Variation in threshold contrast as a function of background luminance.

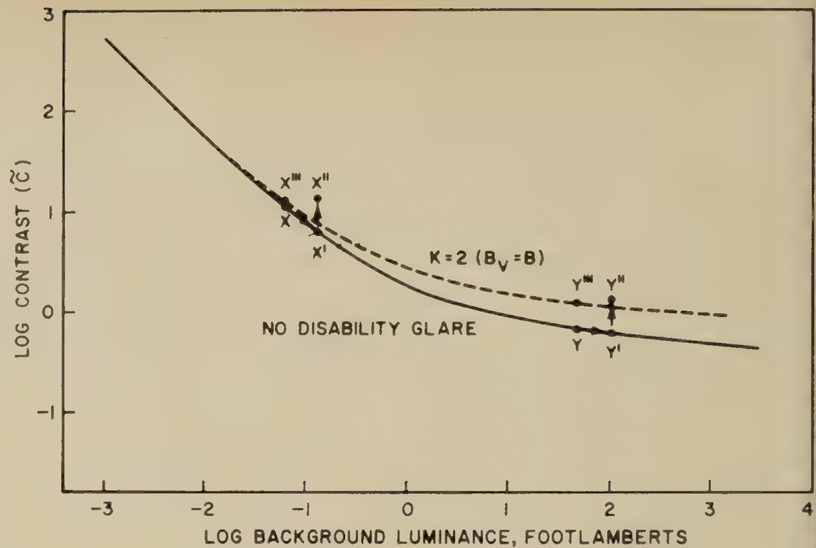

Figure 4.—Background luminance as a function of target contrast for standard level of visual performance: No disability glare, solid curve; disability glare, dashed curve.

Because the main sources of disability glare were the luminaires located outside this area, these effects were not included in the initial visibility assessment. It might have been possible to enlarge the area viewed through the VTE by changing lenses; however, because of the physiological differences of individual observer's reactions to glare, it seemed preferable to use a calculation method.

The method used depended on the effects of disability glare described in an earlier publication by Blackwell (*2*). Disability glare can be assessed in terms of a uniform luminance veil, B_v, that is superimposed over the entire field of view and is equivalent in its effect on visibility to all the discrete sources of luminance in the field. The effects of disability glare are shown in terms of the standard performance curve in figure 4. The value of veiling luminance. B_v, that is equal to the disability glare effect increases the direct luminance, B, to B_e, the effective luminance, where:

$$B_e = B + B_v \qquad (5)$$

The increase in luminance produced by disability glare is shown for two initial values of B, designated X and Y. The task contrasts required for the standard level of performance are indicated by the location of the points X and Y on the solid curve. At the corresponding value of B_e, the contrast required for the eye to see at a selected level of visual performance is decreased by an amount equal to the differences between points X' and Y' and the original points X and Y.

Disability glare has a second effect, that of reducing the task contrast present; this effect may be described as:

$$C' = C \times \frac{B}{B + B_v} \qquad (6)$$

Where,

C' = the apparent task contrast in the presence of the disability glare, B_v.

C = the initial contrast of the task.

Because disability glare decreases task contrast, the physical value of task contrast must be increased to provide the contrast needed for adequate performance. This effect is shown in figure 4 by a comparison of the location of the points X'' and Y'' with those of points X' and Y'. The horizontal displacements of X' from X and Y' from Y are precisely the same on a double logarithmic plot as the vertical displacements of X'' from X' and Y'' from Y', equations (5) and (6). The values of X'' and Y'' are the contrasts required at the luminance values B rather than the values B_e, so they must be plotted at the locations X''' and Y'''. The constructions used in locating the points X''' and Y''' may be used for all points falling on the standard performance curve. The dashed curve (fig. 4) represents the resultant effect of disability glare on the standard performance curve when B_v is equal to B. A disability glare constant, K, was used to define the amount of glare present as:

$$K = \frac{B_v + B}{B} \qquad (7)$$

In figure 4, B_v was assumed to be equal to B, so K is equal to 2.

The method for determining the value of B_r in the presence of disability glare requires use of the dashed curve in figure 4, rather than the solid curve. Obviously, for a specified ordinate value of $\tilde{C}$, the luminance required to attain a specific level of performance is higher when disability glare is present than when it is absent. For convenience, the background luminance required when disability glare is present is referred to by the notation B_r'. Similarly, E_r' is used to refer to the required illumination in the presence of disability glare. For a fixed value of K, the larger the value B_r and E_r were originally, the more B_r' will exceed B_r and E_r' will exceed E_r.

To compute the values of E_r', a measure of the value of B_v in each roadway situation was required. Individual values of the illumination produced at the eye by each glare source could have been measured for each situation and a value for B_v computed; however, the work for this type of approach seemed prohibitive. A photometric device for direct measurement of B_v was required.

Some years ago, Fry (*7*) described a device consisting of a wide-angle lens that forms an image of the entire world out to 90 degrees on either side of straight ahead and an absorbing photographic mask that selectively transmits illumination coming from different points in the field in different proportions to satisfy an empirical formulation for disability glare. Such a device could be utilized as the objective lens of a photometer so that the summation could be performed photometrically. The device, although simple in principle, was exceedingly difficult to construct. The image produced by the wide-angle lens was distorted

Figure 5.—Night view of three targets at test site.

and the photographic mask, therefore, had to have the same spatial distortion built into it. Furthermore, the transmission of light through the mask was required to change over a range of from 10,000 to 1. It was not possible to achieve this range in one piece of photographic material. Therefore, two separate masks were required, each having a central opaque spot that excluded all light from the central 2-degree area and symmetrically graduated density that radiated out from the central spot. An improved design for a disability glare lens has been described by Fry, Pritchard, and Blackwell (*8*).

In actual use, the Pritchard photometer was pointed at a visual task of interest and a value of average task luminance was obtained. The ordinary objective lens was then removed, and the disability glare lens was substituted for it, without moving the photometer. A photometric reading was made using each of the two masks. The effective luminances obtained were added to equal B_v. The value of K was computed from equation (7). After computing the value of K, allowance was made for the 7-percent component of disability glare when the eye was exposed to a field of uniform luminance, as shown by Moon and Spencer (*9*). The visual performance data represented by the solid curve in figure 4 contain this magnitude of disability glare. Thus a value of K' was computed from the relation:

$$K'=\frac{B_v+B}{B}-0.07$$

$$=K-0.07 \qquad (8)$$

The value of K' was used to construct contours such as the dashed curve (fig. 4), because the solid curve represents a baseline with the 7-percent disability glare already present. These procedures suffice for the computation of values of E_r and E_r' in practical roadway situations.

Relative Visibility Calculations

To arrive at an understanding of how different illumination variables affect visibility, it was necessary to obtain a measure of the relative visibility of a specific task under different conditions. Such a measure is the relative visibility factor (RVF), which is defined as:

$$RVF=\frac{\tilde{C}}{\bar{C}} \qquad (9)$$

Where,

$\tilde{C}$=the equivalent contrast of the standard target.

$\bar{C}$=the value of target contrast for the standard level of visual performance at the luminance $\bar{B}$ (solid curve in fig. 4).

The value of RVF is an indication of the difficulty of the visual task in terms of object size and shape, luminance and chromatic contrast, and average task luminance. RVF thus differs from $\tilde{C}$ only in the significance of the absolute values of the two quantities and in the fact that it reflects the effect of

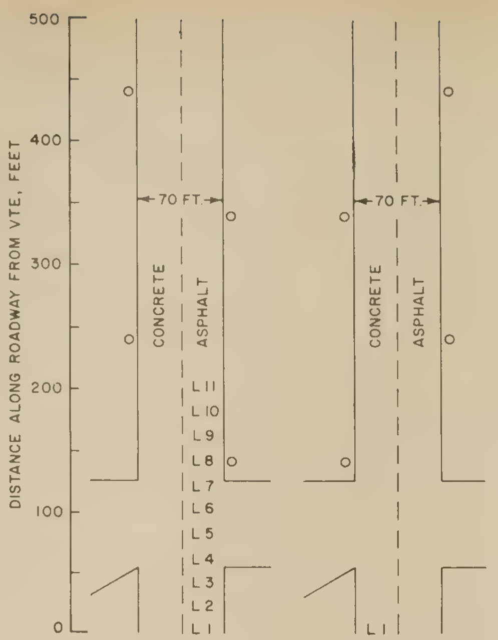

Figure 6.—Plan of layout at test site.

the level of background luminance, whereas $\tilde{C}$ does not. A value of RVF equal to unity signifies that the roadway illumination provides exactly the level of visual performance represented by the standard performance curve. RVF values larger than unity show that the task is more visible than required to meet this performance criterion, whereas RVF values less than unity show that the task is not as visible as is required.

As for the required illumination values, allowance for disability glare can be accomplished by adjusting the standard performance curve. The relative visibility factor in the presence of glare (RVF') is defined as:

$$RVF'=\frac{\tilde{C}}{\bar{C}'} \qquad (10)$$

Where,

$\bar{C}'$=the value of $\bar{C}$ adjusted for disability glare.

Visual Tasks

It was believed desirable to utilize realistic roadway tasks that might be fairly representative of collision type situations rather than simplified tasks such as black disks that frequently have been used in similar studies. For primary use, a toy black dog and a manikin of a 12-year-old girl were selected. The manikin was outfitted in a loose-fitting, full-length gray coat having 20-percent reflectance. In addition, one series of measurements was made on seven other objects: (1) Black disk, 1 foot in diameter; (2) manikin wearing a coat having 60-percent reflectance; (3) toy, pink poodle dog; (4) black automobile without lights or retro-reflectors; (5) yellow highway cone marker; (6) bicycle lying flat on the roadway; and (7) red brick. The manikin, in the coat having 20-percent reflectance, and the two dogs are shown in figure 5, at the test site.

Roadway Installations

The plan layout of the test facility is shown in figure 6. The right half of the roadway was paved with asphalt and the left with concrete. The surrounding ground sloped off toward the right and toward the far end of the road. The area was wooded, particularly toward the right side. A white frame house was in the woods at the far end of the street. Luminaire poles were spaced at 100-foot intervals on each side of the roadway, as illustrated. Five poles were used for the first two series of tests; for the third series, a sixth pole was added at the end of the roadway, 230 feet beyond the last luminaire on the left side. Each pole had a 4-lamp fluorescent luminaire mounted transverse to the curb, a 400-watt mercury lamp, and an incandescent luminaire that could accommodate either 6,000- or 15,000-lumen lamps. Only one type of luminaire was used on a specified series of measurements.

The VTE was set up in the middle of the driving lane on the appropriate side of the pavement to be used in the particular series of measurements, as shown in the elevation layout in figure 7. The first operating luminaire, shown as a small circle (fig. 6), was always on the same side of the roadway as the measurement booth. The luminaires were spaced 200 feet apart on each side of the roadway, in staggered locations. In one test, only half the luminaires were used, and the spacing between them on one side of the road was 400 feet. Because the basic arrangement of luminaires was staggered, the spacing for this one test was designated as 200 feet.

Experimental Data

Three series of tests were made at Hendersonville, N.C. For convenience, these tests have been designated as test series I, II, or III. Each series is described separately because several important changes in the experimental technique were made as the work proceeded. The results have been analyzed for all three series of measurements and are included in the analysis of data.

Test series I

In the first series of measurements made at Hendersonville in the spring of 1959, the visual task, type of light source, type of pavement, spacing between luminaires, and lane in which the task was located were varied in a systematic way. After the data had been analyzed, certain questions arose as to the validity of the method previously described for using the VTE. It seemed from the data that the tasks became more visible as the viewing distance was increased. This effect was opposite to that expected on the basis of the object's decreasing angular size. The annulus brightness had been matched to the average brightness of an out-of-focus image, thereby equating the average luminance of the field of view to the luminance of the internal light source. It was suggested that the method used might have distorted the experimental data and produced these unexpected results. This would have been true if the eye had been adapted to the brightness

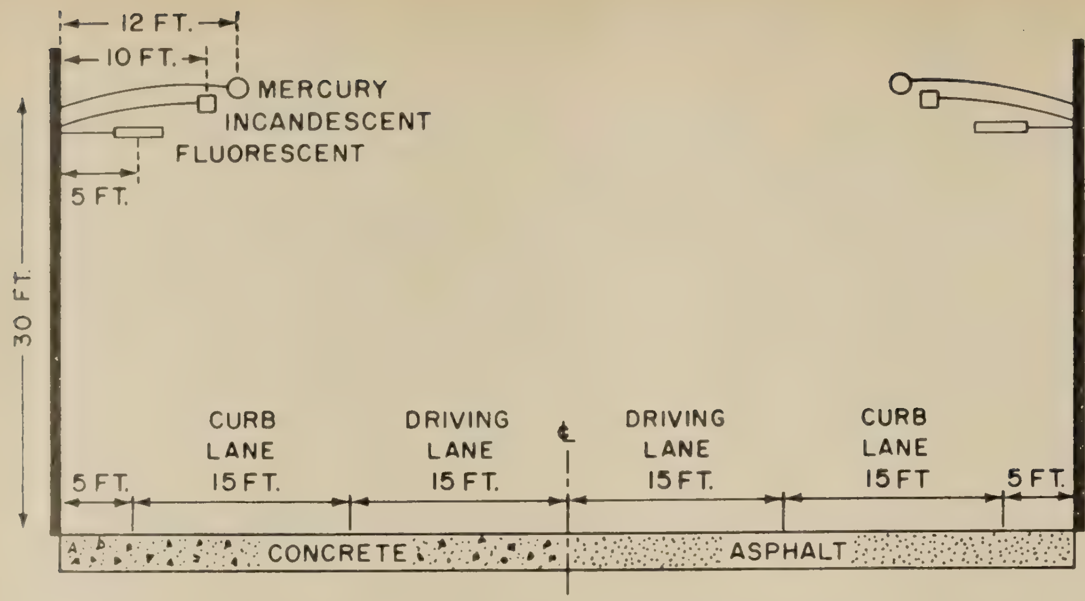

Figure 7.—Elevation layout of Hendersonville test site.

at a point in the visual field near the object rather than to an average field brightness. The second series of measurements were designed to investigate whether the procedure for measuring field brightness had introduced an error into the results.

Test series II

Two approaches were used in the investigation of the VTE procedure. First, a new procedure was developed that would be free of the suspected error. On the basis of earlier work (*2*), measurements were made of the physical luminances expected to influence visibility under the different conditions. Then predictions were made as to the relative visibility of the several objects viewed at different distances, and the two VTE procedures were used to make measurements of these objects. These measurements were analyzed in relation to the predicted visibility values. Most of the variables studied in test series I also were employed in use of the new procedure. An observation distance of 180 feet was employed.

The new VTE procedure, designated the *final* procedure, included several steps: Before setting the annulus wedge carefully, the variable contrast wedge was adjusted to ascertain the part of the object that disappeared last and, hence, was initially most visible. The VTE then was directed so that the background adjacent to the most visible part of the object was at the edge of the circular inner field of the photometric comparator in juxtaposition to the annular field. Objective lens $L1$ was left in place so that the image of the external world was in focus. Then, the annulus wedge was set to match the brightness of the selected area of the background, and the variable contrast wedge was set for maximum transmittance. From this point on, the procedure followed was exactly the same as in test series I. Because the *blurring lens* was not used in the *final* procedure and because of the resultant nonuniformity of the background luminance, it was somewhat difficult to obtain a photometric match between the small part of the background and the surrounding annular field. Otherwise, the procedure for test series II caused no difficulties.

Physical measurements were made of the luminance of the most visible part of the object and its adjacent background, as determined by the *final* VTE procedure. The Pritchard photometer was used; its aperture restricted the field to a diameter of 10 minutes of circular arc. Photographs were taken of the target under each different condition, so the visual area of the relevant element of the target could be computed with precision. Comparison of the values of $\tilde{C}$ obtained from the two VTE procedures showed equivalent results for all targets at distances of less than 220 feet. At longer distances, the value of $\tilde{C}$ obtained from the original procedure was substantially larger than the values obtained from the *final* procedure.

The relations of RVF, RVF', and $\tilde{C}$ were judged from the data shown in figure 8; the ordinate scale on the left of the figure shows the values of RVF and RVF' and the ordinate scale on the right shows the values of $\tilde{C}$. The role of disability glare at different locations in the roadway installation can be ascertained

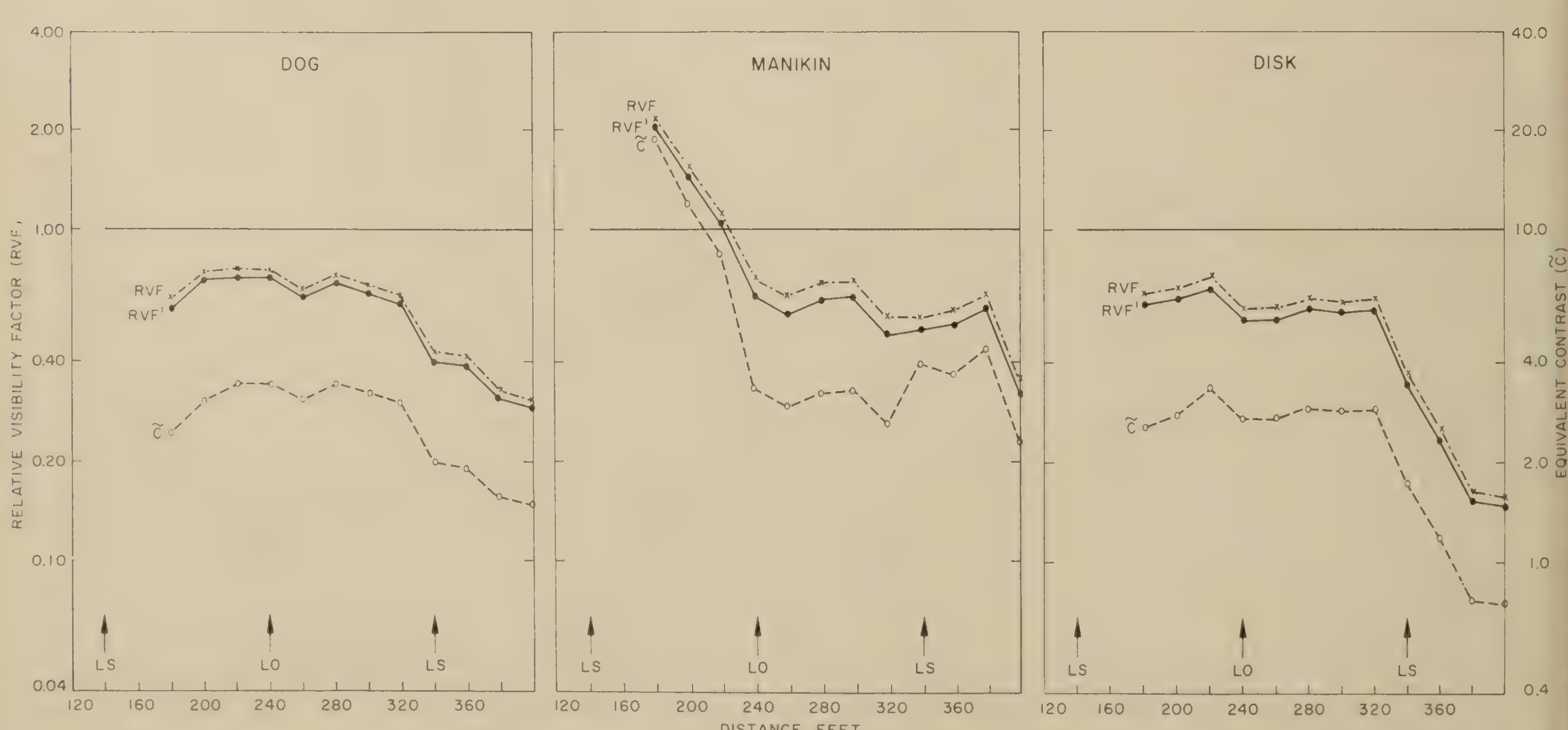

Figure 8.—RVF, RVF', and $\tilde{C}$ as functions of visibility distance in relation to location of luminaires. Horizontal line represents level of visibility required for standard performance level.

by comparing the values of RVF and RVF'. As stated previously, the role of variations in pavement luminance may be evaluated by comparing values of $\tilde{C}$ and RVF. In figure 8, the luminaire locations are indicated by: LO, luminaire on the opposite side of the roadway, and LS, luminaire on the same side of the roadway as the task. Values of RVF, RVF' and $\tilde{C}$ change according to distance in much the same way (they are parallel), thus establishing that these variations in background luminance as a function of distance were not important causative factors in determining object visibility at different distances. In almost no test did the values of RVF' exceed unity. Therefore, the lighting system was not producing a level of visibility sufficient to satisfy the performance criterion.

Test series III

The third series of test measurements were made because of a desire to obtain additional data under the VTE procedure used in test series II. In particular, it seemed desirable to study the relationships between visibility indices and distance for illumination geometrics other than those obtained in the earlier measurements, in which the VTE was always located at position $L1$, as shown in figure 6. During test series III, the VTE was located at each of the 11 positions, $L1$ to $L11$. At each position, the dog and manikin were moved so that the distance between the object and the observer ranged from 180 to 400 feet. All these measurements were made on asphalt pavement, under 15,000-lumen incandescent luminaires at 100-foot spacings, and the objects were located in the driving lane.

Analysis of Data

The focal point of interest for the test series II was to test the extent to which the original and *final* VTE procedures yielded visibility indices in agreement with expectations based upon physical measurements. The luminances of the most visible detail of each object and its background for each of several distances were measured. These data were used to compute a measure of the target visibility expected to exist. The procedure involved the following described steps: The luminance contrast was computed from the relation proposed earlier by Blackwell (*10*):

$$C=\frac{B_t-B_b}{B_b} \tag{11}$$

Where,

B_t=object luminance.
B_b=background luminance.

Then the contrast was adjusted by a factor to allow for the fact that the area of the object differed under different conditions. The factor F was defined as:

$$F=\frac{\bar{C}_s}{\bar{C}_a} \tag{12}$$

Where,

$\bar{C}_s$=threshold contrast for a 4-minute luminous disk.
$\bar{C}_a$=threshold contrast for a target having the angular size of the element of greatest visibility.

Values of $\bar{C}_s$ and $\bar{C}_a$ were read for the particular background luminance, B_b, from the visual threshold curves of Blackwell (*2*) for 1-second exposure duration. These threshold data are for circular objects. In making these calculations, noncircular elements were considered to have the same threshold contrast as circular objects of equal area. A value of contrast obtained in equation (11) was then adjusted by using equation (12) to allow for differences in target size as:

$$C'=CF \tag{13}$$

Generally, good agreement was obtained between the physically measured value of B_b obtained with the Pritchard photometer and the value of $\bar{B}$ obtained from the annulus wedge settings on the VTE. However, there were tests in which the two values disagreed considerably. This was particularly true of the data obtained under the *original* VTE procedure. It seemed more reasonable to conclude that the value of $\bar{B}$ was in error because of the comparative difficulty and uncertainty in visual photometric measurements. Errors in $\bar{B}$ would be expected to alter values of $\tilde{C}$ as related to C'. When $\bar{B}$ was too large, $\tilde{C}$ would be reduced because the veiling luminance would be larger than it should be. Conversely, when $\bar{B}$ was too small, $\tilde{C}$ would be spuriously large. A correction factor F' was developed where:

$$F'=\frac{\bar{C}_{\bar{B}}}{\bar{C}_{B_b}} \tag{14}$$

Where,

$\bar{C}_{B_b}$=threshold contrast for an object having the area of most visibility at B_b.
$\bar{C}_{\bar{B}}$ =threshold contrast for the same element at $\bar{B}$.

These threshold values were also read from the same threshold curves used for equation (12). Then the corrected computed equivalent contrast of a traget element was determined:

$$C''=C'\ F' \tag{15}$$

The correction factor F' reduced C' whenever $\tilde{C}$ was spuriously small, or increased C' whenever $\tilde{C}$ was too large. Thus, in effect the correction was being made in the wrong quantity. This should be remembered when considering values of $\tilde{C}$ as related to C''.

Values of $\tilde{C}$ obtained under the original and *final* VTE procedures were than evaluated. These values were compared with corresponding values of C''. Data for various objects under different luminaires and pavement combinations are presented in Part A of figure 9 for the original and Part B for the *final* procedure. Double logarithmic plots are used. All of these data represent a fixed distance of 180 feet. Thus, there is no parameter along which to order values of C'' and, hence, figure 9 contains only a simple regression line. The solid line in each part of the figure has a 45-degree slope representing that $\tilde{C}$ is proportional to C''. Because the line does not pass through the (0, 0) origin, $\tilde{C}$ is proportional to a constant times C''. This is, of course, acceptable because there was no satisfactory way to relate the threshold data and the measurements made with a VTE. The data seems to cluster more closely about the regression line in Part B than in Part A, particularly the data for the manikin. This was interpreted to mean that the values of $\tilde{C}$ obtained under the *final* VTE procedure agree more closely with the computed indices of visibility than do corresponding data obtained under the original procedure.

A better procedure for evaluating the values of $\tilde{C}$ obtained at various distances in terms of corresponding values of C'' can be achieved by plotting the values of both $\tilde{C}$ and C'' as a function of distance. The data obtained for the dog from test series II and III are shown in figure 10 and for the manikin in figure 11. The data for the black disk from test series II are plotted in figure 12. There was no evidence that results from either VTE procedure agreed better with values of C'' in the tests of the dog and of the black disk. However, data obtained for the manikin under the *final* VTE procedure agreed with the predicted visibility indices better than data obtained under the original VTE procedure.

The data shown by solid lines in figures 10, 11, and 12 were of considerable intrinsic interest because they represented the expected variation in visibility as a function of distance. The variations in C'' with distance are explained in the following terms: For the dog and black disk, visibility decreased slowly as a function of distance because of decreased angular size. In addition, visibility increased somewhat whenever the object was nearer than a luminaire on the same side. At this location, the objects received little illumination and, therefore, were very dark and had comparatively high negative contrast. The test in which the manikin was used produced a large sinusoidal variation in visibility as a function of distance and a superimposed general decrease in visibility as a function of distance because of the decrease in size. The locations having peak visibility corresponded to locations in which the manikin was slightly beyond a luminaire on the same side. In this location the manikin had a high degree of illumination, was very bright, and had high positive contrast to the background.

Required Illumination for Roadway Visual Tasks

On the basis of the preceding analysis, the values of $\tilde{C}$ obtained under the *final* VTE procedure seemed at least somewhat more valid than those obtained under the original procedure. Also, the two VTE procedures effected equivalent results for the shorter distances between observer and task. In

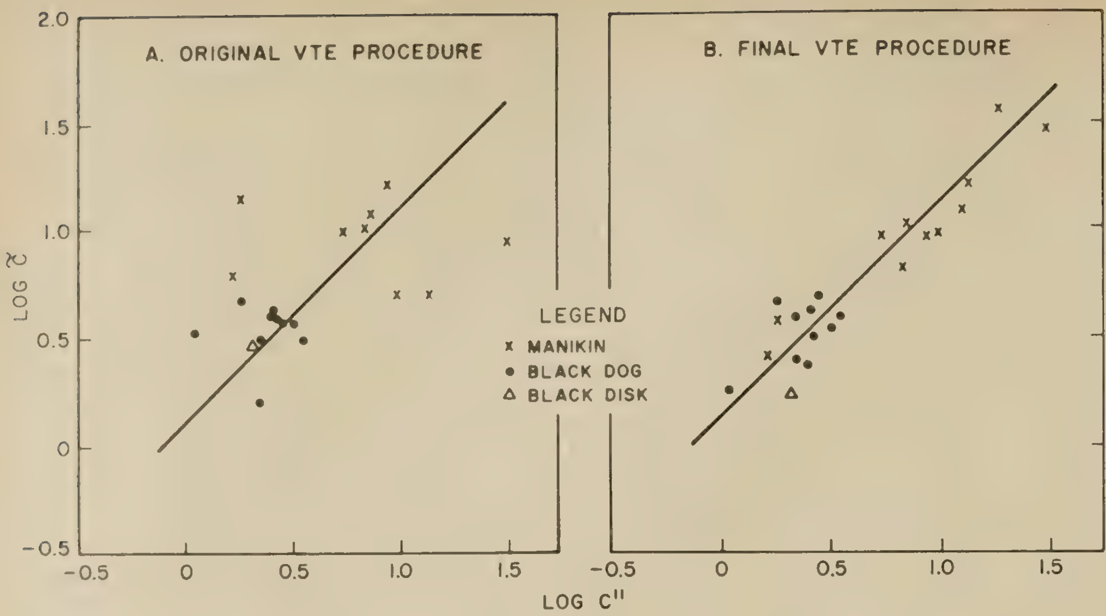

Figure 9.—Variation log C̃ as a function of corrected, computed equivalent contrast, log C''.

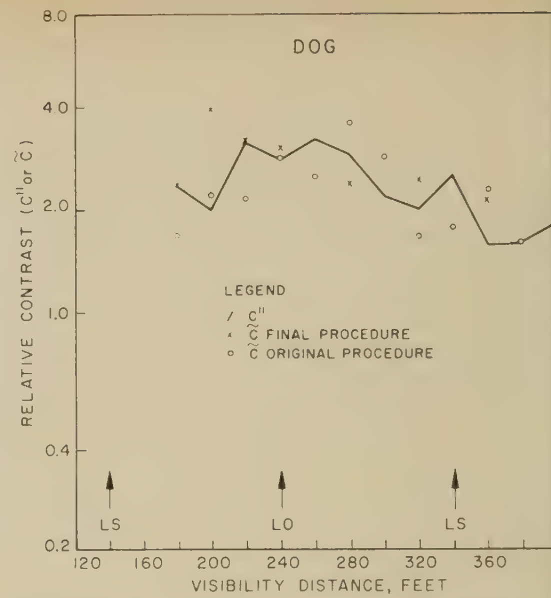

Figure 10.—Relative C'' and C̃ as functions of visibility distance, for a dog.

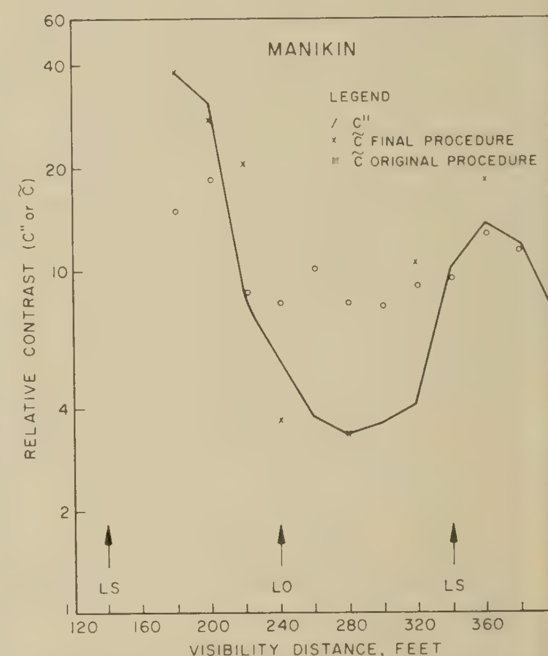

Figure 11.—Relative C'' and C̃ as functions of visibility distance, for a manikin.

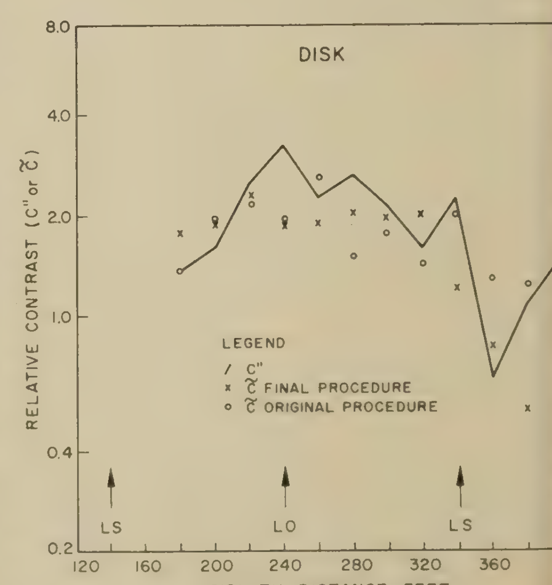

Figure 12.—Relative C'' and C̃ as functions of visibility distance, for a disk.

the test made with the manikin, the two VTE procedures produced approximately equivalent data for distances less than 220 feet. In the tests made with the dog and disk, the cutoff point was about 320 feet. By keeping these two findings in mind, it was then possible to sort through all the data obtained in the three series of measurements and attempt to determine what illumination (E_r and E_r') would have been required to bring the performance of these tasks to the assumed criterion level.

Test series I and II

Because it was concluded that the experiments of test series I, in which the original VTE procedure was used, distorted the visibility indices, at least for the longer distances, it was decided to restrict the use of test series I data to distances of less than 220 feet. The comparison between the original and *final* VTE procedures indicated that these two yielded equivalent results under these conditions; therefore, data at two distances—180 and 200 feet—were used.

For all experiments of test series II, the *final* VTE procedure was used, so all distances were suitable in computing values of E_r and E_r'. The different roadway conditions used during test series I were studied in test series II for a distance of 180 feet only. In addition, the dog, manikin, and black disk were studied at various distances for one illuminant-pavement combination.

Several analyses involving the data from test series I and II can be presented before discussing data from test series III because in test series III only the dog and manikin were studied under one illuminant-pavement combination. Therefore, test series I and II data contain the only information on other tasks, illuminants, and pavement. Values of E_r and E_r' for these tasks are summarized in table 1, and values for the dog and manikin obtained in the same tests are presented for comparison. The results show that different visual tasks occurring on the roadway require illumination that ranges from 0.3 to nearly 1,000 footcandles. The presence of some high values was not surprising because the more difficult roadway tasks seem at least as difficult as some of the tasks that were studied indoors and produced equally high values. From among the tasks studied, the two chosen for major emphasis—the dog and manikin—were analyzed as being a fair representation of the task of mean difficulty. All the tasks were chosen as being typical of collision obstacles.

The amount of disability glare for different roadway conditions was analyzed, and values of K' are shown in table 2. Disability glare differed significantly with the type of illuminant, being least for incandescent, a little worse for mercury, and considerably worse for fluorescent illumination. Disability glare was considerably worse on asphalt than on concrete pavements. This difference was expected because the luminaires, relative to the visual environment, seemed to be brighter when seen against the pavement material having the lower reflectance. Disability glare was also worse in the tests on the manikin than on the dog; this could have been predicted because the line of sight was elevated more for viewing the manikin than the dog.

Data on the effect of luminaire spacing is presented in table 3. To see the dog, more footcandles were required when luminaires were spaced 200 feet rather than 100 feet apart, but markedly lower illumination was required to see the manikin where the luminaires were farther apart. The differences in the effect on the illumination required to see the dog were probably not significant, but the differences required to see the manikin were. These results are explained in these terms:

A luminaire was located 40 feet in front of the object in each test. The difference in luminaire spacing, therefore, caused a difference in the distance to the first luminaire *behind* the object. The manikin was seen as an object brighter than its background because the luminance contrast was larger when the luminaires were spaced farther apart. The manikin's luminance was unaffected by spacing but its background was darker when the luminaires were farther apart. The dog was seen as an object darker than its background because the wider spacing of luminaires reduced luminance contrast by reducing background luminance. This analysis of luminaire spacing has no generality beyond the situation tested and depends decisively upon the fact that in each test a luminaire was located 40 feet in front of the object. Had the VTE and object positions been altered, a very different result might have been obtained. This analysis demonstrated the danger of generalizing from data based on tests in only one location beneath the luminaires. Data on the task at several locations within a single cycle of the luminaires was very necessary, and the need for such data was part of the reason for conducting test series III.

Required illumination for the two major objects located in the driving and curb lanes were computed, and the results are given in table 4. In the curb lane, the object was located 5 feet to the left of the right pavement edge and was viewed from the same location in the driving lane. Had parking been allowed, this would have been the parking lane. In this test, however, no cars were parked and the lane could have been used to drive in. The values of illumination for curb and driving lanes refer particularly to the lighting needed in the respective lanes. Thus, in interpreting requirements for illumination in the curb lane, it was necessary to consider how much was produced by the lighting system in the curb lane and how much was needed.

Values of the illumination required for each object, considering disability glare, E_r', were approximately 3 times higher for the curb lane than the driving lane. Values of the required illumination, not considering glare, E_r, were approximately 2.2 times higher in the curb lane than in the driving lane. Analysis of these data, therefore, showed that a portion of the difference in requirements for illumination under the two conditions was the result of a difference in disability glare But other factors must have been at work.

The values of B_r and B_r' were higher in the curb lane when the dog was the object than in the driving lane, thus indicating that the task was more difficult in the curb lane. No consistent differences in B_r and B_r' were produced by the data about the manikin. Therefore, the visual tasks studied were at least as difficult, if not more so, in the curb lane. Also, the luminaires were less effective in producing luminance in the curb lane than in the driving lane. Together, these three factors probably account for the apparent requirement for more illumination in the curb lane for the same performance level as in the driving lane. Because more illumination was required in the curb lane, the resultant lighting problem becomes doubly difficult as in most conventional lighting systems the curb lane will have less illumination than the driving lane.

Table 1.—Illumination required to see objects 180 to 200 feet away in driving lane [1]

Object	Illumination required: No disability glare (E_r)	Illumination required: Disability glare (E_r')	Disability glare constant (K')
	Footcandles	*Footcandles*	
Auto	0.312	0.341	1.39
Manikin, light coat	.349	.358	1.13
Manikin, gray coat	.387	.414	1.35
Cone marker	.415	.436	1.21
Dog, light	1.30	1.52	1.20
Dog, black	1.64	1.80	1.18
Bicycle	7.23	10.8	1.23
Brick	782	>926	1.13

[1] Data shown are the mean values of results obtained from tests I and II, on asphalt pavement, 100-foot spacing of luminaires.

Table 2.—Disability glare constant (K') when observed objects are in driving lane [1]

Pavement and objects	Illuminant: Incandescent, 6,000 lumen	Incandescent, 15,000 lumen	Mercury	Fluorescent
Asphalt:	K'	K'	K'	K'
Dog	1.18	1.18	1.12	1.78
Manikin	1.23	1.35	1.38	2.00
Concrete:				
Dog	1.02	1.05	1.15	1.38
Manikin	1.12	1.12	1.35	1.48
Mean [2]	1.16		1.25	1.66

[1] Data from test series I, 100-foot spacing of luminaires.
[2] Means for the disability glare constant for type of pavement and objects are: Pavement—asphalt, 1.40; concrete, 1.21; object—dog, 1.23; manikin, 1.38.

Table 3.—Illumination required to see object when luminaires are at two different spacings [1]

Test series	Visibility distance	100 feet between luminaires: No disability glare (E_r)	100 feet between luminaires: Disability glare (E_r')	200 feet between luminaires: No disability glare (E_r)	200 feet between luminaires: Disability glare (E_r')
Dog					
	Feet	*Footcandles*	*Footcandles*	*Footcandles*	*Footcandles*
I	180	0.649	0.664	1.30	1.42
I	200	.649	.664	1.37	1.50
II	180	1.27	1.33	.991	1.06
II	200	.986	1.03	.589	.646
Mean		0.889	0.922	1.06	1.16
Manikin					
I	180	0.443	0.463	0.135	0.144
I	200	.461	.471	.283	.311
II	180	1.17	1.32	.235	.240
II	200	.601	.672	.379	.417
Mean		0.669	0.732	0.258	0.278

[1] Source of light, 15,000-lumen incandescent illuminants on concrete pavement.

The illumination required by use of the different illuminants studied is given in table 5. Analysis of the E_r values shows that the illuminants may differ in complex ways even without the disability glare being a factor. Fluorescent illuminants seemed to be superior to incandescent, and mercury illuminants were inferior to incandescent illuminants for objects such as the manikin. Because both mercury and fluorescent illuminants produce more disability glare than incandescent, a study of the values of E_r' shows that for both the mercury and fluorescent illuminants more illumination was required than for the incandescent. The data were somewhat erratic and the differences should be applied with considerable caution, especially as only one type of fixture for each illuminant was compared in this study.

The results of an analysis of the illumination required on asphalt and concrete pavement surfaces are given in table 6. A study of the values of both E_r and E_r' shows that less

Table 4.—Illumination required to see objects in curb lane and driving lane: Source of light, 15,000-lumen incandescent illuminants

Pavement type and test series	Visibility distance	Illumination required				Disability glare constant (K')	
		No disability glare (E_r)		Disability glare (E_r')			
		Driving lane	Curb lane	Driving lane	Curb lane	Driving lane	Curb lane
Dog							
Asphalt:	*Feet*	*Footcandles*	*Footcandles*	*Footcandles*	*Footcandles*		
I	180	1.21	2.00	1.32	2.58		
I	200	1.05	1.81	1.10	2.28	1.18	1.35
II	180	2.65	11.1	2.98	17.6		
Concrete:							
I	180	.649	.721	.664	.810		
I	200	.649	.810	.664	.930	1.05	1.13
II	180	1.27	.939	1.33	.985		
Mean	--------	1.25	2.89	1.34	4.20	1.12	1.24
Manikin							
Asphalt:							
I	180	0.360	1.32	0.395	1.75		
I	200	.349	2.83	.374	4.29	1.35	1.59
II	180	.451	.455	.472	.498		
Concrete:							
II	180	1.17	.381	1.32	.399	1.12	1.20
Mean	--------	0.582	1.25	0.640	1.74	1.24	1.40

Table 5.—Illumination required to see objects in driving lane under different illuminants

Pavement type and test series	Visibility distance	Illumination required							
		No disability glare (E_r)				Disability glare (E_r')			
		Incandescent		Mercury	Fluorescent	Incandescent		Mercury	Fluorescent
		6,000 lumens	15,000 lumens			6,000 lumens	15,000 lumens		
Dog									
Asphalt:	*Feet*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*
I	180	1.84	1.21	1.53	0.876	2.16	1.32	1.83	1.40
I	200	.984	1.05	.763	.739	1.10	1.10	.875	1.02
II	180	.982	2.65	2.30	.754	1.10	2.98	2.96	1.17
Concrete:									
I	180	.762	.649	.616	.917	.780	.664	.692	1.21
I	200	.558	.649	.483	1.08	.558	.664	.517	1.46
II	180	.476	1.27	.580	.685	.481	1.33	.636	.873
Mean	------	1.09		1.05	0.842	1.18		1.25	1.19
Manikin									
Asphalt:									
I	180	0.213	0.360	0.403	0.318	0.218	0.395	0.432	0.429
I	200	.443	.349	1.26	.636	.474	.374	1.48	.920
II	180	.460	.451	.603	.435	.482	.472	.654	.601
Concrete:									
I	180	.311	.443	.708	.295	.318	.463	.852	.339
I	200	.268	.461	.444	.562	.274	.471	.498	.677
II	180	.540	1.17	1.18	.423	.598	1.32	1.31	.509
Mean	------	0.456		0.766	0.445	0.488		0.871	0.579

Table 6.—Mean values of illumination required to see objects on different types of pavement—based on data in table 5

Object	Illumination required			
	No disability glare (E_r)		Disability glare (E_r')	
	Asphalt	Concrete	Asphalt	Concrete
	Footcandles	*Footcandles*	*Footcandles*	*Footcandles*
Dog	1.31	0.727	1.58	0.822
Manikin	.494	.567	.577	.636

illumination was required on concrete than on asphalt pavement when the dog was the object, but when the manikin was the object more illumination was required on the concrete pavement. This finding is explained by the relative reflectances of the objects and the pavement surfaces. The dog was dark and matched the asphalt considerably better than the concrete in reflectance. Therefore, the dog was more difficult to see on asphalt and considerably more illumination was required. Because the manikin was comparatively light and matched concrete somewhat better than asphalt, the manikin was somewhat more difficult to see on concrete and somewhat more illumination was required. This analysis explains clearly that the illumination required on the two different pavements depends intrinsically upon the object on the roadway, and that no general statement comparing the two types of pavement can be made accurately.

Test series III

Values of E_r and E_r' for the measurements of test series III are given in tables 7 and 8. These values represent all the data from the third series of tests; the *final* VTE procedure was used exclusively. Illumination required is presented for each object and each distance; these data represent averages for the 11 different locations of the VTE as related to the luminaires. The values given, however, are restricted to the tests of incandescent luminaires and asphalt pavement. The same conclusion—that the manikin was somewhat less difficult to see on the asphalt pavement than the dog—can be drawn from the test series III data for distances of less than 300 feet. At longer distances, however, the manikin was no longer seen against the pavement in most tests. The small, white, frame house in the woods at the far end of the roadway may have been a critical factor.

Expressing data on roadway requirements for lighting in terms of pavement luminances rather than in illumination units, as has been done in the study reported here, is of considerable contemporary interest. Although the eye is concerned with luminances and not illumination requirements, the data herein are not presented in terms of luminances because:

First, although it is possible to design a lighting installation in terms of the illumination, it is difficult, if not impossible, to design it to provide specified luminances because of the lack of complete knowledge of the reflectance characteristics of pavement surfaces. Second, use of luminances could influence illuminating engineers so that they might forget that illumination has two functions in roadway lighting: (1) To produce pavement luminance; and (2) to produce object contrast. An analysis of the data compiled for this article suggests that contrast is more important than luminance.

The values of E_r and E_r' given in tables 7 and 8, the authors believe, are the best evaluations of the illumination needed to see the dog and manikin under incandescent luminaires and on asphalt pavement. These data can be used to provide a basis for establishing suitable illumination levels for roadway lighting. Consider first the test at a 200-foot distance—the data from test series I and II can be used with confidence for this distance or shorter distances. The data from test series III applied only to objects seen on the asphalt pavement under incandescent illumination. The data from test series I and II were used to define ratios relating illumination requirements for the other illuminant-pavement combinations to the incandescent illuminant-asphalt pavement condition. These ratios were then used to adjust the data from test series III to apply to other illuminants and/or pavements. The factors are summarized in table 9 for useful combinations of illuminant and pavement. The factors for the dog and manikin are maintained separately for E_r and E_r' values, respectively. For test series III, the average values of E_r and E_r' for the incandescent-asphalt combination were taken from tables 7 and 8.

Using the factors, estimated values of E_r and E_r' were computed for each combination of illuminant and reflectance and are given in table 9. The values given in this table represent the estimates of the illumination required for targets located in the driving lane, and each combination of illuminant and reflectance is given equal weight. The E_r' values of 1.30 footcandles required to see the dog and 1.85 footcandles required to see the manikin represent the summary result of the entire study of roadway visual tasks. Of course, as was pointed out, all that can be suggested is to specify the illumination required for adequate visual performance for a *particular* illumination geometry and location of object and observer. Thus, the illumination units have no generality and cannot be used except in terms of similar conditions of illumination and viewing. Where geometry is different, as at other sites tested (*5*), the illumination required also was different, and average illumination could *not* be used as a reliable indicator of visibility.

An adequate understanding of the extent to which objects may be seen anywhere on the roadway when they appear without warning cannot be obtained only from the average values of illumination. To obtain some estimate of this aspect of the roadway lighting problem, values of E_r and E_r', for each of the 11 locations of the VTE used in test series III were computed for each combination of illuminant and pavement surface. The factors presented in table 9 were used to compute these data from the values of E_r and E_r' given for individual locations in tables 7 and 8. These calculations produced 66 values of E_r and E_r' for each target. They were used to generate the cumulative frequency graphs in figure 13. The ordinate in this figure represents the percentage of locations along the roadway in which the target in question was predicted to be adequately visible at 200 feet. Values of average illumination provided by the hypothetical lighting system of the same geometry are shown on the abscissa. Values of E_r' are of primary interest; however, the values of E_r are given only to show how much less illumination could be used if disability glare could be entirely eliminated from roadway lighting.

Table 7.—Illumination required for observer at different locations to see objects at various distances, no disability glare, test series III

Observer location	Illumination required: Visibility distance, feet— 180	200	220	240	280	320	360	400
Dog								
	Footcandles	*Footcandles*	*Footcandles*	*Footcandles*	*Footcandles*	*Footcandles*	*Footcandles*	*Footcandles*
1	1.33	0.552	0.965	1.16	2.30	1.86	1.66	2.71
2	1.03	1.32	1.04	1.27	3.16	1.92	2.34	2.85
3	1.60	1.02	2.51	1.92	1.82	1.78	2.20	3.01
4	1.05	1.45	1.42	1.96	2.24	1.51	2.13	1.88
5	1.27	.890	1.38	1.18	1.25	1.15	1.34	1.44
6	.815	.774	1.60	.980	1.14	2.08	1.77	1.90
7	1.09	1.34	1.06	.975	1.48	1.65	2.50	3.37
8	.772	1.10	1.30	2.00	2.75	2.38	4.07	4.55
9	1.58	1.62	3.02	3.90	3.25	3.03	4.11	1.14
10	1.59	1.42	3.14	2.35	2.76	2.70	2.88	4.29
11	1.76	2.22	2.18	2.00	3.16	3.89	5.19	5.21
Mean	1.26	1.25	1.78	1.79	2.30	2.18	2.74	2.94
Manikin								
1	0.312	0.600	0.791	1.23	1.56	1.51	0.773	3.08
2	.834	1.05	1.23	1.41	1.20	1.42	.956	3.58
3	.842	.840	1.23	3.12	2.60	5.66	2.32	2.27
4	.806	1.06	2.32	1.28	1.08	.724	2.68	2.58
5	.696	1.61	1.12	1.51	.495	1.58	3.20	12.2
6	1.06	1.40	1.83	.914	1.12	3.00	3.00	2.66
7	.825	1.22	1.26	.449	1.45	2.89	14.8	24.8
8	1.96	1.05	.775	1.17	2.56	8.03	7.08	3.88
9	1.02	.721	1.20	1.17	2.30	8.90	34.6	2.44
10	.845	1.57	2.16	2.20	2.20	24.6	10.2	34.6
11	.510	.893	2.26	2.10	2.11	1.92	1.33	2.20
Mean	0.882	1.09	1.47	1.50	1.70	5.48	7.35	8.57

It may be of interest to evaluate the extent to which these average required illuminations depend on the distance at which objects must be seen. The average values of E_r and E_r' from tables 7 and 8 may be expressed as a ratio of the average value for the 200-foot distance. Such ratios are plotted in figures 14 and 15. It is clear that the illumination required differs only a little between 180 and

Table 8.—Illumination required for observer at different locations to see objects at various distances, disability glare (K'), test series III

Observer location	K'	Illumination required: Visibility distance, feet— 180	200	220	240	280	320	360	400
Dog									
		Foot-candles	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*	*Foot-candles*
1	1.20	1.56	0.591	1.11	1.40	2.84	2.24	1.99	3.56
2	1.29	1.30	1.75	1.34	1.60	4.27	2.42	3.02	3.76
3	1.41	2.21	1.32	3.79	2.90	2.51	2.40	3.56	5.11
4	1.66	1.42	2.30	2.25	3.41	4.17	2.24	3.78	3.50
5	1.59	1.97	1.23	2.09	1.82	1.77	1.73	2.06	2.18
6	1.62	1.15	1.09	2.80	1.26	1.68	3.70	3.00	3.22
7	1.62	1.54	2.03	1.37	2.32	2.46	2.74	4.76	4.15
8	1.32	.930	1.26	1.56	2.63	3.88	3.36	6.60	4.98
9	1.32	2.03	2.04	4.79	7.61	5.15	4.80	4.39	2.93
10	1.29	1.96	1.75	4.59	3.40	4.09	3.91	3.09	4.60
11	1.32	2.22	2.99	3.09	2.82	4.68	4.79	6.25	7.89
Mean	------	1.66	1.67	2.62	2.83	3.41	3.12	3.86	4.17
Manikin									
1	1.20	0.312	0.600	0.800	1.44	1.88	1.54	0.781	3.96
2	1.29	.841	1.26	1.52	1.78	1.52	1.45	.969	4.95
3	1.41	.853	.840	1.26	4.73	3.84	5.66	3.52	3.35
4	1.66	.845	1.12	4.64	1.51	1.19	.758	6.13	5.60
5	1.59	.730	2.44	1.57	2.39	.506	1.80	6.38	52.3
6	1.62	1.57	2.22	3.18	1.02	1.20	3.28	4.15	4.21
7	1.62	.883	1.77	1.38	.449	2.24	5.38	64.4	86.0
8	1.32	2.58	1.08	.791	1.22	3.62	13.3	13.5	5.25
9	1.32	1.04	.729	1.25	1.22	3.11	13.4	104.	3.08
10	1.29	.885	1.73	2.92	2.83	2.83	57.4	16.2	45.6
11	1.32	.510	.904	3.20	2.77	2.16	2.01	1.36	2.30
Mean	------	1.000	1.33	2.05	1.94	2.19	9.64	20.2	19.7

Table 9.—Illumination required to see each of two objects 200 feet away on different types of pavement under different illuminants

Pavement and illuminant	No disability glare (E_r)		Disability glare (E_r')	
	Multiplication factor [1]	Illumination required	Multiplication factor [1]	Illumination required
Dog				
Asphalt:		*Footcandles*		*Footcandles*
Incandescent	1.00	1.25	1.00	1.67
Mercury	.964	1.20	1.06	1.77
Fluorescent	.772	.965	1.01	1.69
Concrete:				
Incandescent	.556	.696	.519	.867
Mercury	.536	.670	.548	.915
Fluorescent	.429	.535	.523	.873
Mean	NA	0.886	NA	1.30
Manikin				
Asphalt:				
Incandescent	1.00	1.09	1.00	1.33
Mercury	1.68	1.83	1.78	2.37
Fluorescent	.977	1.07	1.18	1.57
Concrete:				
Incandescent	1.15	1.25	1.10	1.46
Mercury	1.93	2.11	1.96	2.61
Fluorescent	1.12	1.22	1.30	1.73
Mean	NA	1.43	NA	1.85

[1] Ratio of illumination required for condition to that required for an incandescent source on asphalt pavement, determine from test series I and II.

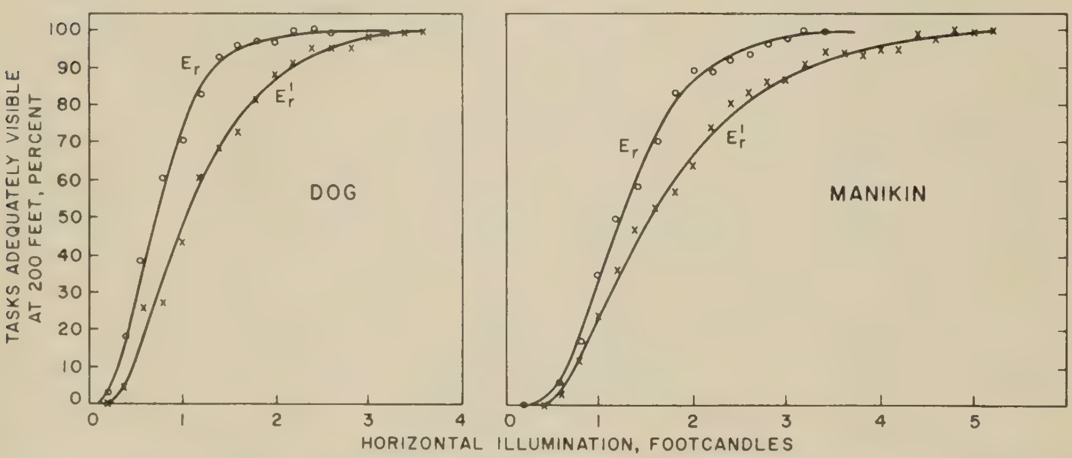

Figure 13.—Percentage of tasks adequately visible at 200 feet for different levels of horizontal illumination.

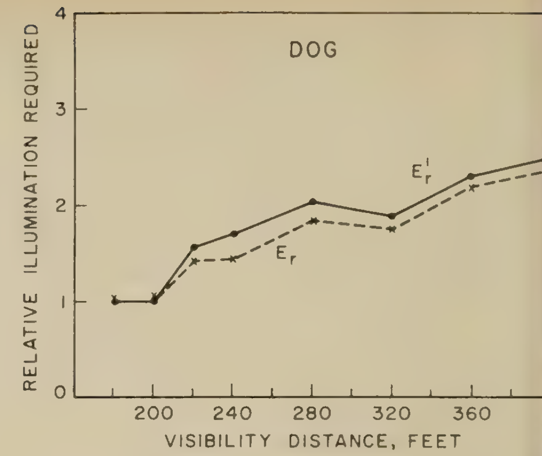

Figure 14.—Relative illumination levels required to see a dog at distances other than 200 feet.

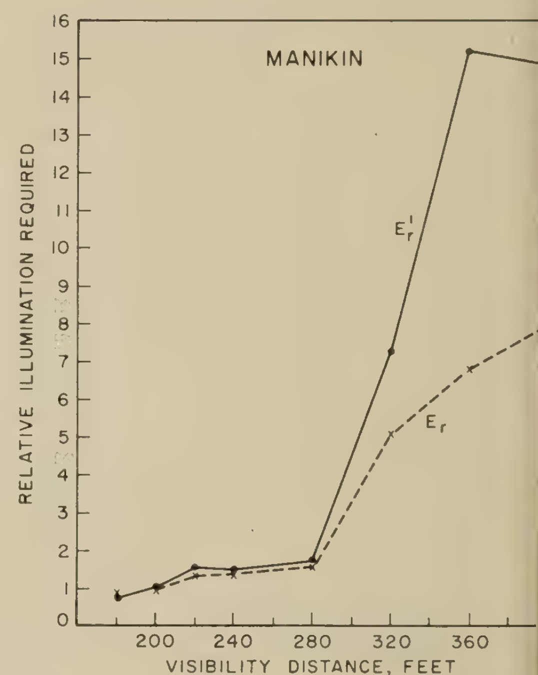

Figure 15.—Relative illumination levels required to see a manikin at distances other than 200 feet.

200 feet, but that considerably more illumination is required at distances of 300 to 400 feet than at 200 feet. To see the manikin, the increase in illumination was considerably more than the increase needed to see the dog.

In evaluating the illumination requirement data from the Hendersonville test site, generally lower illumination values were necessary to meet the same performance criterion than illumination requirements for actual highway sites in Ohio (*5*). Thus, the final required illumination values for adequate visibility reported herein are probably conservative.

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