NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **60**

EFFECTS OF ILLUMINATION ON OPERATING CHARACTERISTICS OF FREEWAYS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **60**

EFFECTS OF ILLUMINATION ON OPERATING CHARACTERISTICS OF FREEWAYS

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION:
- HIGHWAY SAFETY
- ROAD USER CHARACTERISTICS
- TRAFFIC CONTROL AND OPERATIONS

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

NCHRP Project 5-2 FY '63
NAS-NRC Publication 1714
Library of Congress Catalog Card Number: 73-600029

FOREWORD

By Staff

Highway Research Board

This report will be of special interest to illuminating engineers, traffic engineers, and public officials responsible for the lighting needs of the nation's expressways. This well-documented three-year investigation is an effort to measure the effects of expressway lighting on traffic operations, accidents, driver performance, and driver apprehension. The research also includes a visual evaluation of illumination in the expressway environment.

As the nation's highway death toll continues to increase, all individuals interested in the safe operation of highways strive to find solutions to the safety problem. It is known that the number of highway fatalities occurring during periods of darkness is disproportionately large when compared to the daytime condition. Some engineers advocate that continuous expressway lighting will significantly reduce the nighttime accident rate and improve night driving operations. This obviously would involve large sums of money. Unfortunately, factual information pertaining to the nature of the benefits of continuous freeway lighting is meager. "Public Lighting Needs," a special report prepared in February 1966 for the United States Senate by a joint committee of the Institute of Traffic Engineers and the Illuminating Engineering Society, points out the need for lighting research:

> A difference of opinion on the relative value of lighting has hampered attempts at acceptance of national standards, and has limited federal and state participation in the cost of urban street and freeway lighting. These differences result from the limited amount of adequate research.

NCHRP Project 5-2 was initiated in 1963. Its purpose was to measure the effects of roadway illumination on expressway drivers. A 5-mile segment of the Connecticut Turnpike in the Bridgeport area was selected for the study site. Three research agencies simultaneously studied the effects of reducing the expressway level of illumination from 0.6 footcandles to 0.2 footcandles.

Illumination and its relationship to traffic flow was researched by Yale University's Bureau of Highway Traffic and is the subject reported in Part I of this report. Series of observations of traffic flow were undertaken at two intensities of artificial illumination and during daylight. Accident data were analyzed for changes in accident rates that could be related to the change in illumination, and a comparative study involving traffic stream characteristics is presented.

The Systems Research Group of the Ohio State University studied the effects of illumination changes on driving performance. These studies are reported in Part II of this report. Test subjects drove an instrumented vehicle under two illumination levels and their driving performance was compared. Parameters studied include elected speeds, steering activity, and gas pedal movements. A separate study on Ohio test sites is also reported, in which driver response to nighttime glare encounters with oncoming vehicles is investigated.

Presented in Part III of this report is a visual evaluation of illumination in the roadway environment by the Institute for Research in Vision of the Ohio State University. Special photometers were built and mounted on a test vehicle, which acted as a mobile photometer. As the vehicle traversed the expressway, dynamic measurements were made of the vehicle visual surround. A comprehensive visibility analysis was conducted for the expressway environment under the two levels of fixed illumination. The analysis also details the extent to which disability glare reduced visibility and the extent to which the deleterious disability glare reached the eye of a driver from different portions of the visual environment.

Part IV presents the results of a study conducted by the Institute for Research, a private research agency located in State College, Pa. The object was to measure the effects of fixed lighting conditions on driver attitudes. The effort was not intended to measure drivers' likes or dislikes regarding lighting conditions, but rather to measure the relationship between roadway lighting and driver discomfort, utilizing driver apprehension measurements as the yardstick. Driver questionnaire information was obtained from motorists driving through the Connecticut Turnpike test section. The questionnaire information was used to determine driver apprehension based on a numerical score. The analysis included tests of the effects of illumination, weather, moon brightness, traffic volume, driving experience, and driver familiarity on driver apprehension. Driver dissatisfaction was measured in a separate questionnaire isolating primary sources of complaint with nighttime driving.

Part V comprises the list of references and the several appendices for Parts I through IV, including motor vehicle accident data and traffic flow data for Part I, supplemental data from the Connecticut tests of Part II, glare analyses from Part III, and explanatory material pertaining to details of Part IV.

The findings reported in this research are somewhat unexpected. The reduced lighting condition did not seem to adversely affect nighttime accident rates, traffic flow, driver performance, or driver apprehension. Furthermore, the lower illumination level of 0.2 footcandles seems to have adequately simulated the daytime lighting condition, as did the higher illumination level of 0.6 footcandles. In terms of the variables measured it is believed that future research might be most profitable in the region of this lower value of illumination.

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ACKNOWLEDGMENTS

Part I of this report presents research done under NCHRP Project 5-2(1) by the Yale University Bureau of Highway Traffic, for which Fred W. Hurd, Director, acted as principal investigator. Matthew J. Huber and Joseph L. Tracy of the Bureau staff were responsible for direction of the research activities and preparation of the report. Other staff members involved with the project included the following:

Kent T. Healy and Thomas J. Seburn—Project advisory group and design of the research.

David Blevins, Harvey Boutwell, and Robert Bleyl—computer programs for data analysis.

David Witheford (first year of project)—details required to establish, coordinate and start the project.

John Howard—all photographic work and equipment modifications.

Ara Baltayan—maintenance and repair of camera and data reduction equipment.

Others to whom special acknowledgment is due are:

Robert M. Williston and Paul Silversmith, Connecticut State Highway Department—members of the Bureau's project advisory group.

Electrical Section, Connecticut State Highway Department—lighting changes for data collection phases of the study.

Professor Hilary Seal; Yale University—guidance in statistical analysis of the accident data.

Israel Zevin, Bureau of Planning and Design, Connecticut State Highway Department—traffic volume data necessary to perform the accident analysis.

A portion of the computations was made possible by funds from the National Science Foundation grant to Yale University for support of computer use.

Parts II and III present research done under NCHRP Project 5-2(2) by the Engineering Experiment Station of The Ohio State University, for which Drs. Thomas H. Rockwell and H. Richard Blackwell acted as co-principal investigators.

Part II was performed and reported by the Systems Research Group, Department of Industrial Engineering, with Dr. Rockwell and Glenn F. Lindsay as researchers and authors. Acknowledgment is also made to the Connecticut State Highway Department for its assistance during the Connecticut Turnpike tests; to J. E. Wagner, Ohio Department of Highways, for the assistance rendered in locating suitable glare study test sites; to Roy Samuelson of the Systems Research Group for his efforts in conducting the glare studies and working with the Connecticut data; and to L. Tracewell for the development and maintenance of the instrumentation required.

Part III was performed and reported by the Institute for Vision in Research, with Andries J. Birkhoff and Dr. Blackwell as researchers and authors. Acknowledgment is also made to the Connecticut State Highway Department; to Glenn Lindsay and John N. Snider of the Systems Research Group; and to Dr. Johannes F. Schwar of the Transportation Engineering Center, The Ohio State University.

Part IV presents research done under NCHRP Project 5-2(3) by the Institute for Research, State College, Pa., for which Dr. Paul M. Hurst acted as principal investigator. Kenneth Perchonok of the Institute staff was responsible for direction of much of the research activity and preparation of sections of the report. Special acknowledgment is due Harry Polstein, Superintendent of the Stratford Toll Station on the Connecticut Turnpike, for the help provided by his group in data collection.

PART I

OPERATING CHARACTERISTICS OF FREEWAYS

MATTHEW J. HUBER AND JOSEPH L. TRACY
BUREAU OF HIGHWAY TRAFFIC
YALE UNIVERSITY

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PART I

OPERATING CHARACTERISTICS OF FREEWAYS

SUMMARY

The studies reported in Part I were conducted by the Yale Bureau of Highway Traffic in cooperation with the Connecticut State Highway Department under NCHRP Project 5-2(1). This study is a report of observations on the traffic stream made under two intensities of artificial illumination, 0.2 fc and 0.6 fc (average values as measured and reported to the Project by the Connecticut State Highway Department) and under daylight conditions, together with an analysis of the accident rate under day and night conditions over a 5-year period.

The nighttime measurements were made on the Connecticut Turnpike during the months of November-December 1964 and January 1965. Daytime measurements were recorded in May-June 1965. Four sites were selected for field observations—(a) tangent, (b) curve, (c) on-ramp, and (d) off-ramp—in order to evaluate a range of different operation conditions under the different intensities of illumination. In addition to the four test sites there were tangent and curve control sites selected beyond the geographical limits of the lighting change. These two control sites provided a measure of any daily or seasonal fluctuations in the traffic stream behavior that might be independent of lighting changes. No sites similar to the on-ramp or off-ramp were available for control sites. A combined total of more than 58,000 vehicles were analyzed at all sites at night and 12,000 vehicles were analyzed during the daylight.

Data on the traffic stream were collected by time-lapse photography, with cameras mounted on light standards adjacent to the roadway. Because most observations were made at night, the headlights of oncoming vehicles were selected as the most readily identifiable point. Transverse and longitudinal positions of each vehicle were observed for each frame of the film and flow data were calculated from the vehicle position.

The principal results of the observations were as follows:

1. The distribution of passenger vehicles and commercial vehicles by lanes was unrelated to the lighting conditions—similar volume levels resulting in similar lane usage—under either level of illumination at all observation sites. Flow rates in the daytime observations were greater than at night, but percentage of lane use did not change, except for a decrease in the percentage of trucks.

2. In general, when a change in placement did occur vehicles tended to travel closer to the right-hand edge of a lane when nighttime illumination increased. A change in mean placement (about 0.5 ft) was observed at the tangent test site for all lanes, for both passenger and commercial vehicles, with similar but lesser shifts about 0.3 ft) in mean placement observed at the tangent control site. At the other three sites (curve, on-ramp, and off-ramp) there was no uniform change in mean placement, changes greater than 0.2 ft occurring in only one

or two lanes at any site. Daytime placements were within 0.2 ft of one or the other sets of nighttime placements, and did not favor either level of illumination.

3. There was no pattern of change in variation in placement when related to a change in illumination level. Daytime variances in placement were not related to one particular level of nighttime level of illumination.

4. Statistically significant changes in mean velocity were obtained in all but one (of the eight possible) lanes for passenger vehicles at the curve and off-ramp when the illumination intensity was changed. Changes in velocity at the tangent and on-ramp sites were not as great as at the other two sites, but all mean velocity changes were less than 2 mph, even when statistically significant. Those changes that did take place indicate a tendency for mean speed to decrease with an increase in lighting intensity. Similar changes were found for mean velocities of commercial vehicles, but were not satistically significant, because of smaller sample sizes. Daytime velocities were less than nighttime velocities at some locations and greater at others, but the differences rarely exceed 2.0 mph. Daytime velocities showed no tendency to be more identifiable with one nighttime level to the exclusion of the other.

5. The influence of lighting change on variation of speeds is mixed. Increases and decreases in standard deviation were noted when the intensity of illumination was increased. Changes in variation of speeds were also observed at the control sites where no change in lighting took place. There does not appear to be a relationship between variation in speed and changes in lighting. Daytime variances were less than nighttime variances but not related particularly to variances observed at one level or the other.

6. Analysis of headways within lanes and between lanes indicated no relationship between intensity of illumination and deviation of observed headways from the theoretical headways determined by a negative exponential distribution. Daytime headways were observed to underestimate low headways (0 to 0.5 sec) in amounts similar to nighttime observations.

7. The influence of headways was further analyzed by separating out vehicles which had headways both in front and behind of more than 6.0 sec. Two other categories include those vehicles with one headway (either before or after) greater than 6.0 sec. The final category included vehicles with neither leading or trailing headway greater than 6.0 sec. The velocities of vehicles with headways both fore and aft greater than 6.0 sec are significantly different from velocities of vehicles in other headway categories. Headway categories and placements are unrelated. The relationship between headways and velocities is independent of illumination, day or night.

8. An examination of clustering of vehicles, by vehicle type, showed that the patterns were different at the various test sites. At the two ramp sites (on-ramp and off-ramp) commercial vehicles were observed in clusters of two or more successive commercial vehicles more often than expected from the number of commercial vehicles in the stream. There was no evidence of clustering relating to changes in illumination or to daytime.

9. Observations of the percentage of merging vehicles, the gaps accepted by the merging vehicles, and the point of merge into the through lane at the on-ramp site showed no significant difference when related to the change in illumination or to daytime observation.

Accident data for 47 miles of the Connecticut Turnpike, including the 4.1 miles of lighting change, were analyzed for changes in accident rate that could be related to the change in the illumination intensity. The lower intensity of illumination was in effect for a 10-month interval in the test area. Data for 36 months before and 14 months after the period of reduced lighting were also available.

The accident rates, day and night, were analyzed both in the segment of lighting change and the adjacent segments to the east and west. Seasons of the year were also considered in the model.

The analysis of the accident information revealed no evidence that the nighttime accident rate was related to the intensity of illumination in the test area. It is noted that because of the relatively "good" accident experience on the Turnpike there were only 36 nighttime accidents during the period of 0.2 fc in the test segment, limiting the significance of the changes in accident rates.

The following observations are made concerning the results:

(a) The change in illumination intensity from 0.2 fc to 0.6 fc was not readily discernible to the human eye. A change from no overhead lighting to 2.0 or 3.0 fc may produce a different result.

(b) The volumes ranged from a low of 989 vph to 2,516 vph in the direction studied. Both of these observations were on 4-lane segments of the Turnpike and do not approach the capacity of the facility.

(c) Although the observed volumes were less than the capacity of the Turnpike, at the average speed and headway on the roadway there was a vehicle observed about every 112 to 300 ft. At these spacings the headlights of the vehicles can be assumed to provide lighting to adjacent vehicles, adding to the light provided by the overhead luminaires.

(d) The observations were made as nearly as possible to the rush hour and in the late fall months. It is therefore reasonable to asume that the drivers observed during these conditions have a substantial degree of familiarity with the Turnpike and may be less influenced by lighting changes than a different population of drivers.

The results of this study are compared with those reported by Taragin and Rudy, made on the Connecticut Turnpike in 1958 and 1959. The present study, made at more locations, over all lanes of the roadway, and at higher volumes, does not show any substantial differences from the conclusions of Taragin and Rudy.

CHAPTER ONE

INTRODUCTION AND RESEARCH PLAN

This part of this report covers research completed under NCHRP Project 5-2(1). The objectives of the research conducted by the Yale Bureau of Highway Traffic were the study and analysis of stream-flow characteristics and accidents under two intensities of artificial illumination and daylight conditions. The project design involved comparative studies with freeway lighting intensities of 0.2 fc and 0.6 fc. Data collection was conducted on a 4.1-mile section of the Connecticut Turnpike in the Bridgeport area (Fig. 1). The Turnpike is continuously lighted for more than 50 miles from the New York State line at a maintained intensity of 0.6 fc. Stream-flow data were obtained at specific test and control locations within the test area. Accident data for the periods before, during, and after the

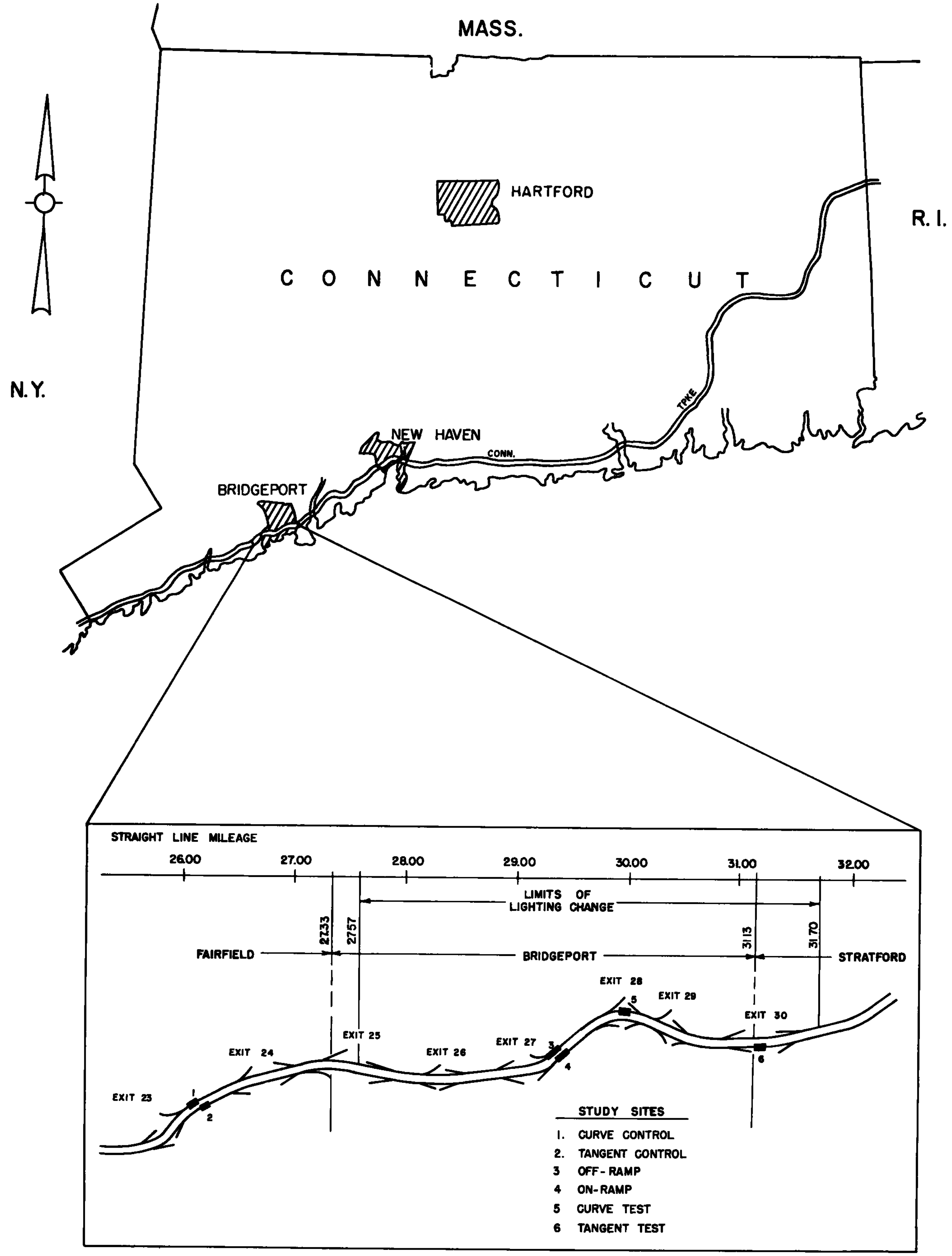


Figure 1. Study area on Connecticut Turnpike (I-95).

lighting change, a total elapsed time of 60 months, were analyzed. The accident analysis was based on data for a 47-mile section including the test segment.

The studies reported here, together with related studies by the Ohio State University research groups (Systems Research Group and the Institute for Research in Vision) and the Institute for Research (State College, Pa.) were made possible through the cooperation of the Connecticut Highway Department.

The research under Project 5-2(1) was undertaken jointly by agreement between Yale University and the State of Connecticut, who mutually agreed that the study be undertaken specifically by the Yale Bureau of Highway Traffic and the Traffic Engineering Division of the State Highway Department. Responsibility for the study rested with an Advisory Committee composed of personnel from both agencies. This joint effort resulted in the design of the project, methods of study, and analysis. The Highway Department was primarily responsible for the design, installation, and supervision of the lighting changeover and the provision of available accident data. The Bureau of Highway Traffic was responsible for instrumentation; collection, processing, and analysis of data; and overall project supervision.

RESEARCH PLAN

Site Selection

Among the locations available for this study having standard highway lighting, the Connecticut Turnpike in the Bridgeport area best satisfied the requirements of this project because it offers high volumes and a variety of roadway geometrics.

A review of volume data indicated that the highest average daily volumes on the Turnpike occur in this area. The Connecticut Turnpike is a four- to eight-lane divided facility having full control of access. This fulfilled the requirement that the study be made on a freeway.

Furthermore, it was considered to be of interest to compare the results of this study with those of Taragin and Rudy (*1*), who made a study just east of this section of the Turnpike in 1958.

Figure 2 is an aerial view of the Turnpike through downtown Bridgeport. Available traffic volume information indicated that the on-ramp and off-ramp circled in the photograph would be suitable to measure traffic entering and leaving the Turnpike. A curve and a tangent location were also selected within the 4.1-mile limits of the study section. The four test sites are referred to as tangent, curve, on-ramp, and off-ramp throughout the remainder of this report.

Control sites were also established beyond the limits of the study section. At these sites, chosen to match the geometric design and flow rates of the test sites, there was no change in lighting intensity. Observations of traffic flow at the control sites were made simultaneously with observations at the test site, so changes that were the effect of lighting influences could be sorted from effects that were peculiar to the hour and date of the data collection. A further requirement was that the test and control sites be within 5 to 10 miles of each other in order to manage data collection. Within these limits, control sections were found for tangent and curve locations. It was not possible to establish on-ramp and off-ramp control sites because of the absence of suitable locations within reasonable distance of the test sites. Further, there was not sufficient equipment to observe two ramp locations simultaneously.

Figures 3, 4, 5, and 6 are plan views of the test and control sites. Geometric design features are given in Table 1. Both tangent sites are three lanes wide in the direction studied, and the other geometric design features are much alike at the two sites. The two curve sites are more dissimilar (three lanes vs four lanes) and have two different median widths (4 ft and 30 ft). The two sites are used because the volumes are similar and they are the two maximum degree curves within the study limits. At the on-ramp location there are three lanes for through traffic joined by two lanes from the on-ramp itself. These two lanes merge into one and are used as a fourth lane of the Turnpike for a distance 1,900 ft. Vehicles entering the Turnpike at this location have the 1,900-ft distance in which to accomplish the merge with through traffic.

A similar arrangement occurs at the off-ramp. There are four lanes on the Turnpike approaching the exit. The right-hand lane becomes a two-lane exit ramp in the intersection and three through lanes are continued beyond the exit.

Lighting Characteristics of the Study Area

The project requirement within the 4.1-mile study section of the Turnpike was to lower the intensity of illumination to approximately 0.2 fc. Actual lighting intensities as measured and reported by the Connecticut State Highway Department showed values of 0.62 and 0.22 average footcandles during the "before" and "after" data collection periods, respectively (hereafter referred to as 0.6 and 0.2 fc). As a comparative measure, illumination on the earth's surface by the sun may be as high as 10,000 fc; and on cloudy days the illumination drops to less than 1,000 fc (*2*).

The illumination in the test area was reduced to 0.2 fc for a 9-month period (January to October 1964) prior to data collection at that intensity. This period was considered sufficient for the lamps to "burn-in" and reach a normal operating level. When the original level of illumination was restored the same lamps that were removed eleven months earlier were replaced and no "burn-in" time was required. Prior to each phase of the study the luminaires and lamps were thoroughly cleaned.

Illumination in the study section and for a considerable distance either side of the area is achieved through the use of 400-w mercury-vapor lamps in IES Type III luminaires. The lamps used were designed for a minimum initial rating of 20,500 lumens with a mean ratio of 18,700 lumens based on a 16,000-hr life. Nominal operating voltage and current is 135 and 3.2, respectively. Luminaire mounting height is 30 ft at all study sites. At the curve and tangent sites, both test and control, as well as the through tangent segments of the ramp sites, the luminaire

Figure 2. Connecticut Turnpike in downtown Bridgeport. On-ramp and off-ramp test locations circled (center right).

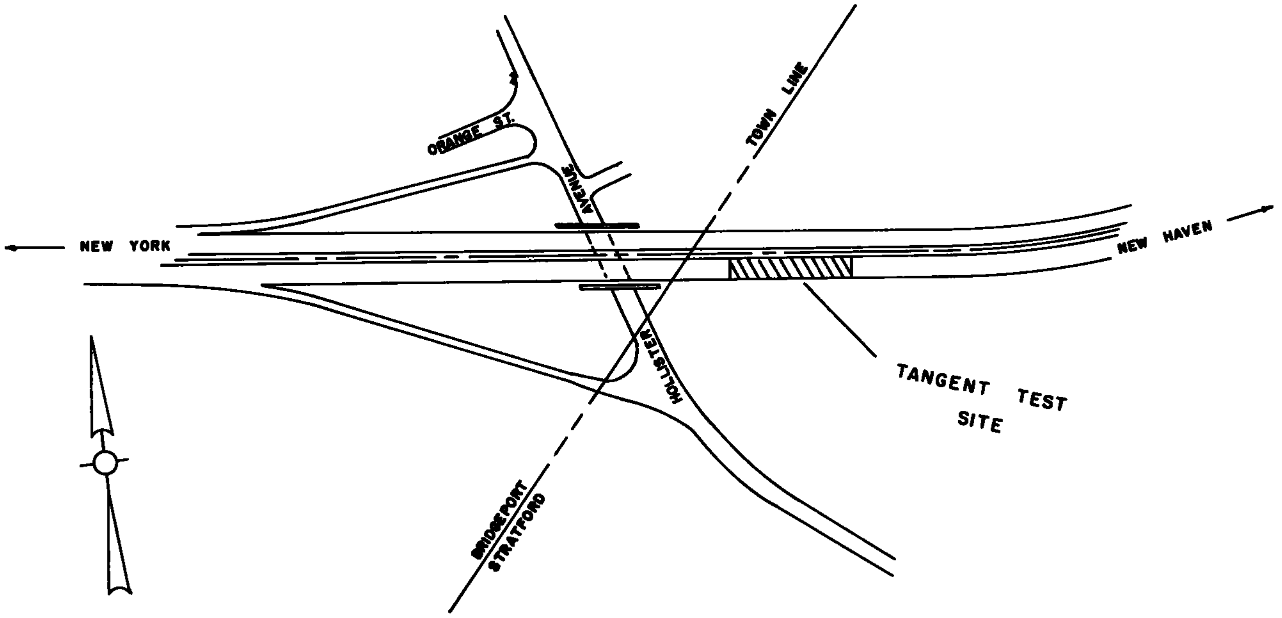


Figure 3. Tangent test site.

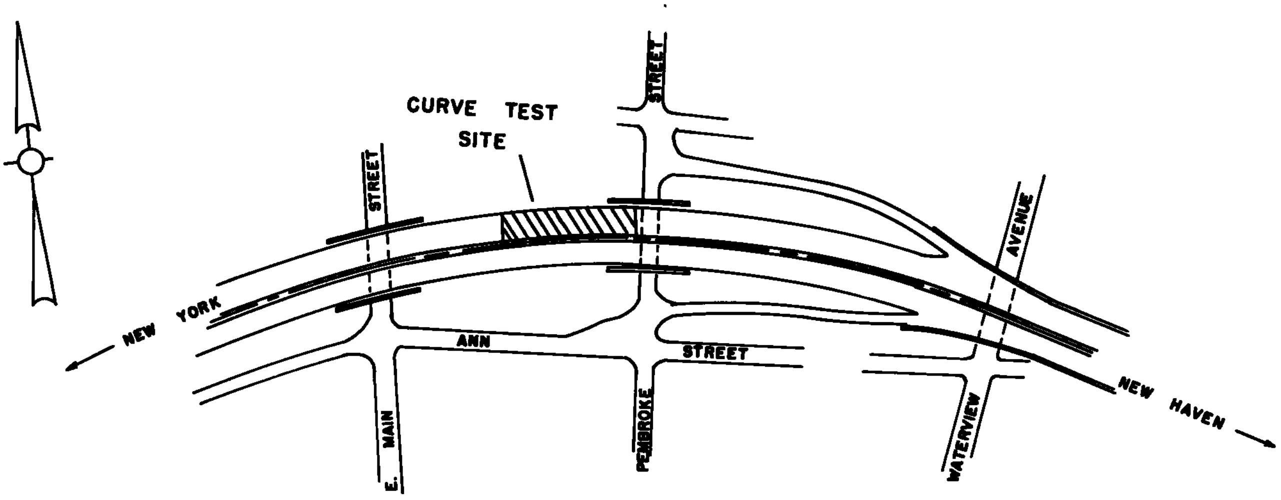


Figure 4. Curve test site.

spacing is 100 ft with a staggered arrangement. Spacing on the ramps varies with geometrics.

The lower intensity of illumination was achieved by using specially constructed lamps with the existing ballasts. These lamps were designed with power consumptive characteristics of a 400-w mercury-vapor lamp. This was accomplished by shunting the 175-w mercury-vapor arc tube within the bulb with an incandescent filament that will by-pass approximately 1.75 amp from the arc tube. The lamp will pass a total of 3.2 amp from the secondary of the 400-w mercury-vapor ballast.

The lamps were designed with an initial rating of 7,000 lumens with a mean of 6,500 lumens for a minimum of 6,000 burning hours. Nominal operating voltage and current is 135 and 1.45, respectively. The actual values measured at the two intensities of illumination and the calculated average foot-candles of illumination are given in Table 2.

Data Collection

The initial study plan called for four sets of observations made during the peak period of flow, under each of the nighttime lighting conditions. One set of observations was made during the daytime at each of the sites for comparison with nighttime observations. Mechanical breakdowns and

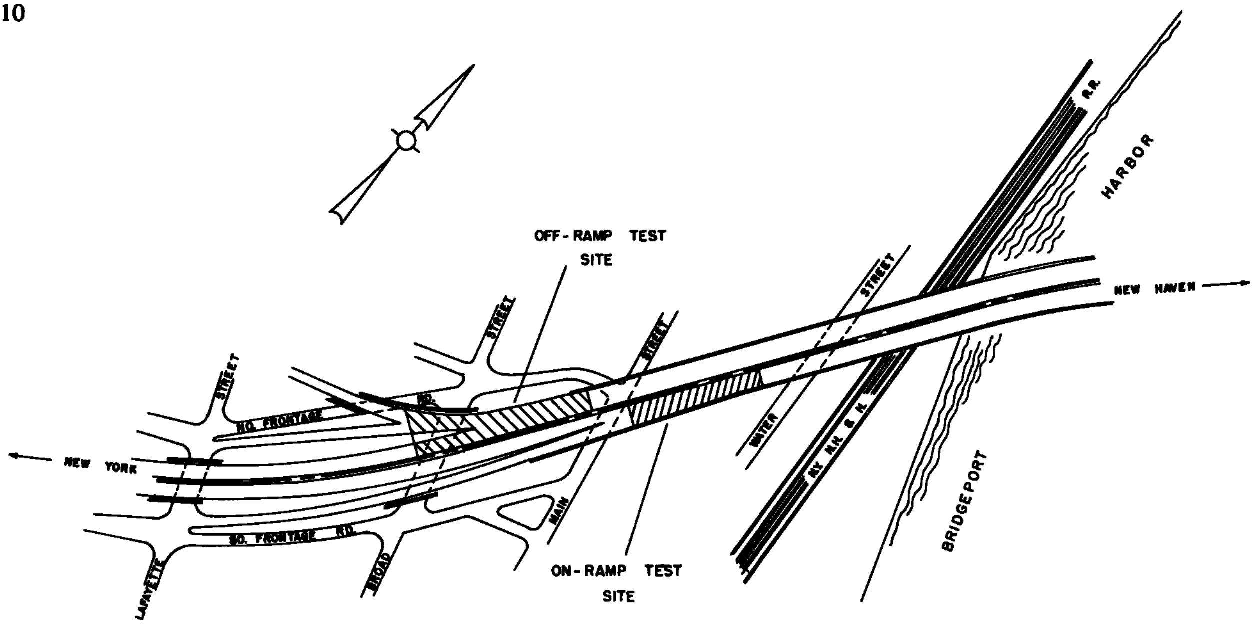


Figure 5. On-ramp and off-ramp test sites.

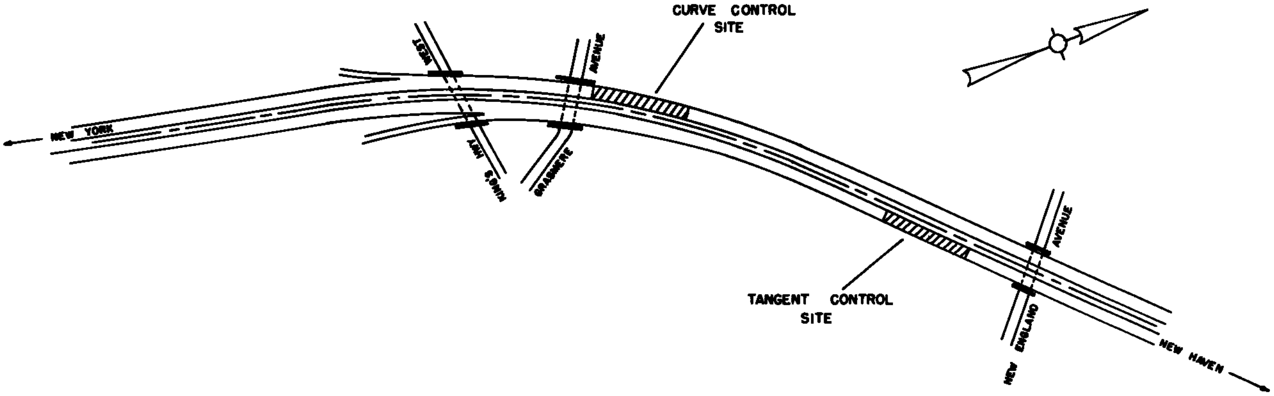


Figure 6. Tangent and curve control sites.

TABLE 1

GEOMETRIC DESIGN FEATURES OF STUDY SITES

SITE	LANES [a]	SHOULDER WIDTH (FT) OUTSIDE	SHOULDER WIDTH (FT) MEDIAN	GRADE (%)	CROSS-SLOPE (%)	*D*	MEDIAN (FT)	BARRIER [b]	ADT [a] 1964
Tangent, test	3	10	2	−0.97	1.04	—	30, grass	None	28,500
Tangent, control	3	10	2	+0.74	1.04	—	30, grass	None	33,100
Curve, test	4	10	2	−0.36	6.25	3°00′L	4, concrete	GR	34,800
Curve, control	3	10	2	−0.72	6.25	2°30′L	30, grass	None	33,500
On-ramp	3 T 2 R	—	2	+3.00	1.04	—	4, concrete	GR	32,100 T 9,400 R
Off-ramp	3 T 2 R	10	2	−3.00	1.04	—	4, concrete	GR	31,000 T 10,700 R

[a] T = through lanes; R = ramp lanes. [b] GR = guide rail.

TABLE 2

FIELD MEASUREMENTS OF PAVEMENT ILLUMINATION

STATION OF MEAS.	MEASURED ILLUSTRATION (FOOT-CANDLES)															
	FOR 0.62-FC AVERAGE								FOR 0.22-FC AVERAGE							
	WESTBOUND [a]				EASTBOUND [a]				WESTBOUND [a]				EASTBOUND [a]			
	OUTER EDGE LANE 1	LANE 1- LANE 2	LANE 2- LANE 3	MEDIAN EDGE LANE 3	MEDIAN EDGE LANE 3	LANE 3- LANE 2	LANE 2- LANE 1	OUTER EDGE LANE 1	OUTER EDGE LANE 1	LANE 1- LANE 2	LANE 2- LANE 3	MEDIAN EDGE LANE 3	MEDIAN EDGE LANE 3	LANE 3- LANE 2	LANE 2- LANE 3	OUTER EDGE LANE 3
Pole No. SF-28 [b]	1.40	2.15	1.65	1.05	0.26	0.15	0.15	0.15	0.60	1.00	0.90	0.52	0.14	0.11	0.07	0.06
+10	0.85	1.55	1.40	0.85	0.26	0.18	0.15	0.15	0.41	0.80	0.82	0.49	0.12	0.08	0.08	0.07
+20	0.65	1.10	1.00	0.60	0.26	0.20	0.18	0.12	0.35	0.58	0.54	0.35	0.12	0.10	0.09	0.06
+30	0.45	0.90	0.78	0.49	0.28	0.28	0.20	0.12	0.23	0.42	0.41	0.29	0.10	0.10	0.10	0.09
+40	0.32	0.55	0.58	0.39	0.25	0.30	0.27	0.17	0.20	0.30	0.29	0.20	0.10	0.12	0.10	0.10
+50	0.20	0.35	0.44	0.30	0.38	0.39	0.40	0.21	0.13	0.21	0.20	0.15	0.12	0.18	0.19	0.10
+60	0.12	0.25	0.28	0.24	0.50	0.61	0.60	0.42	0.12	0.16	0.17	0.13	0.15	0.21	0.25	0.16
+70	0.12	0.20	0.20	0.21	0.61	0.85	0.90	0.65	0.10	0.12	0.13	0.11	0.19	0.30	0.39	0.22
+80	0.09	0.16	0.18	0.22	0.75	1.25	1.25	0.90	0.09	0.10	0.11	0.10	0.22	0.41	0.45	0.31
+90	0.09	0.18	0.20	0.23	1.00	1.75	1.85	0.95	0.08	0.09	0.10	0.10	0.34	0.62	0.65	0.38
Pole No. SF-29 [b]	0.10	0.15	0.19	0.22	1.15	2.10	2.50	1.55	0.07	0.10	0.10	0.10	0.38	0.68	0.91	0.55
+10	0.09	0.15	0.19	0.22	1.10	2.12	2.60	1.55	0.08	0.09	0.09	0.09	0.38	0.68	0.93	0.57
+20	0.09	0.15	0.22	0.25	1.00	1.92	1.85	1.08	0.08	0.10	0.07	0.09	0.33	0.61	0.70	0.42
+30	0.12	0.18	0.23	0.25	0.70	1.40	1.33	1.02	0.08	0.12	0.10	0.10	0.22	0.39	0.60	0.34
+40	0.14	0.30	0.31	0.29	0.59	1.08	0.97	0.81	0.10	0.14	0.10	0.12	0.21	0.28	0.50	0.25
+50	0.28	0.42	0.41	0.33	0.42	0.58	0.70	0.59	0.12	0.20	0.18	0.13	0.17	0.20	0.35	0.18
+60	0.50	0.65	0.67	0.42	0.30	0.43	0.55	0.35	0.19	0.30	0.24	0.15	0.12	0.15	0.25	0.12
+70	0.68	1.00	0.80	0.60	0.27	0.31	0.33	0.30	0.25	0.40	0.32	0.21	0.11	0.11	0.12	0.10
+80	0.70	1.15	1.08	0.69	0.25	0.21	0.28	0.22	0.29	0.48	0.41	0.25	0.10	0.08	0.07	0.07
+90	1.05	1.80	1.70	0.92	0.25	0.18	0.17	0.20	0.40	0.69	0.62	0.35	0.09	0.08	0.05	0.05
Pole No. SF-30 [b]	1.60	2.05	1.80	1.00	0.20	0.16	0.15	0.12	0.62	0.85	0.77	0.42	0.10	0.08	0.08	0.05

[a] Measurements made at longitudinal lane boundaries of 12-ft wide lanes.

[b] All lighting standards off edge of shoulder; even numbered on westbound side, odd numbered on eastbound side.

weather conditions reduced the observations to two sets at the tangent and three sets at the curve, at each of the two artificial illumination intensities. A combined total of more than 58,000 vehicles were analyzed at all sites at night and approximately 12,000 vehicles were analyzed for daytime conditions.

Observations of traffic characteristics at night were made during the winter months, at which time the beginning of darkness and the evening peak hour are most nearly coincident. Observations were made at 0.2 fc during October and November 1964; observations at the 0.6-fc level were conducted in December 1964, and January 1965. Daytime observations were made during May and June 1965.

Because most data collection was scheduled for late fall and early winter, it was anticipated that adverse weather conditions would be encountered. Monday through Wednesday of each week were scheduled for data collection days, with Thursday held open for possible rescheduling of data collection in the event of equipment failure or adverse weather conditions earlier in the week. Inasmuch as it was necessary to close a lane of the Turnpike in order to mount the study equipment, the Highway Department and the Bureau of Highway Traffic agreed not to operate on the Turnpike during the heavy traffic period from Friday through Monday.

In scheduling the time and date of data collection every effort was made to insure that observations made at the two nighttime intensities of illumination and daytime conditions were matched as to day-of-week and time of collection. This was done in order to minimize the differences in both the population of drivers being sampled and the flow rates on the Turnpike.

Data were collected by using time-lapse 35-mm cameras mounted on the light standards adjacent to the roadway. Use of the cameras minimized interference with the traffic being observed and provided a continuous record of events on the Turnpike. Figures 7 and 8 show various items of the camera installations. At the on-ramp an overhead sign bridge provided an excellent opportunity for locating the camera over the center of the lanes. Vehicles were filmed head-on as they approached the camera.

At each of the test and control sites a survey grid was established. Base lines were run along both the outside and median shoulders and the elevations and distances to various points (usually at 50-ft intervals) along each line were measured.

Two or three reference lights were placed along each base line at intervals of 50 or 100 ft. After the camera was placed in position, properly sighted, the camera mounting height above the pavement was measured. The displacement of the lens from the base line zero point was also recorded.

Based on a predetermined filming schedule, the cameras were turned on at each site at a specific time. Filming was continuous and required approximately 70 min of running time for each operation. Table 3 gives a summary of filming dates, lighting levels, number of observations, and hourly rates at each site.

Data Reduction

Each reel of film was reviewed and edited on a microfilm reader. Each camera was equipped with an external data box containing a clock with a sweep secondhand and a four-digit frame counter. The clock and frame counter images were recorded on each frame in the lower left-hand corner. During the editing phase the times and frame numbers were recorded in 4-min intervals in order to determine the camera operating speed (a nominal 90 frames per minute).

The recorded data, on 35-mm negative film, were transcribed by means of a semi-automatic film reading system. This system consists of three basic components—a reading unit, an analog-to-digital converter, and a keypunch. Trial runs on the system indicated that the best method for reducing the data was to read the film backwards. That is, the last time a vehicle was recorded on the film was the first time its position was measured (it was also the point at which the vehicle was nearest to the camera). For nighttime filming, the most distinguishable point on each vehicle was the headlights. Figure 9 shows a strip of film as recorded.

The operator mechanically recorded the coordinates of both headlights for each vehicle and one reference point for each frame. The film frame number, vehicle identification, and reference point identification were manually punched onto data processing cards. Electronic computers were used to edit the punched cards, calculate the coordinates of the vehicles in each frame, and then compute the path of each separate vehicle. Details of the process are included in Appendices B, C, and D.

The placement within lanes and the Y-displacement were calculated for each vehicle. The speed of each vehicle was a function of the distance traveled and the elapsed time between frames.

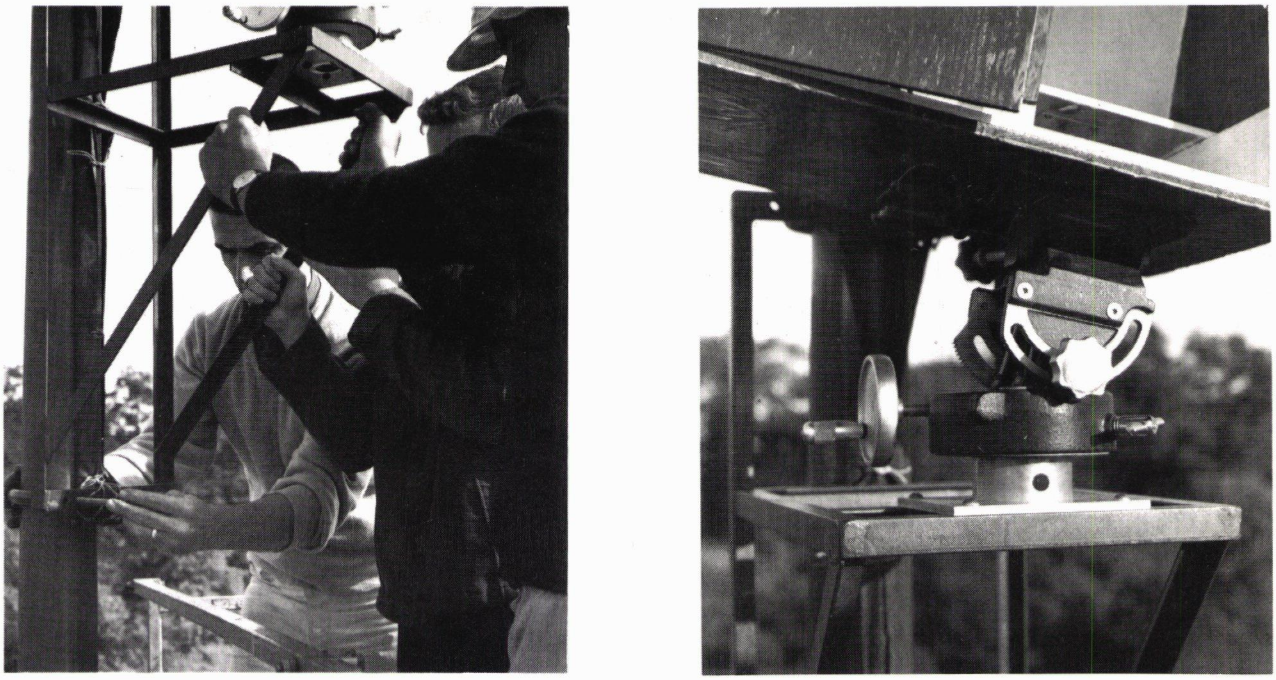
Because the cameras were battery powered, the camera speed was not constant over the duration of the filming interval. The adjustments in camera speed are described in Appendix E.

Analysis of Data

Some 44 separate camera runs were made, each including from 50 to 60 min of usable data. All but two of these runs were made on clear dry pavement; the remaining two were made at the tangent test and control sites at night during rain.

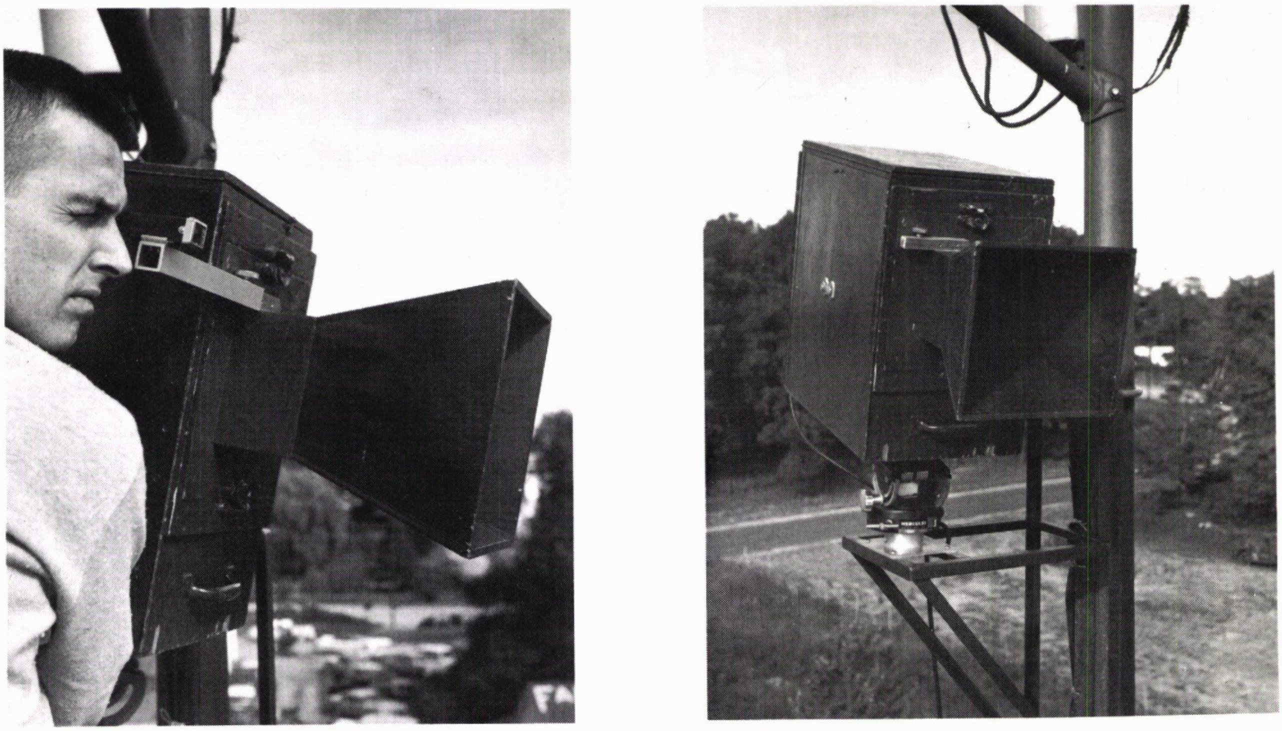
For each run the following tabulations were prepared:

1. Volume classification (full-size passenger vehicles, compact vehicles, commercial vehicles) by lanes.
2. Mean and standard deviation of velocities by vehicle type by lane. The velocities are based on the two observations of the vehicle when it was closest to the camera. The mean velocity is the time mean velocity.
3. Mean and standard deviation of placement by vehicle type by lane. Placements are based on the single observation made when the vehicle is closest to the camera.
4. Number of vehicles changing lanes within range of the camera (on-ramp only).



SECURING POLE BRACKET
TO LIGHTING STANDARD

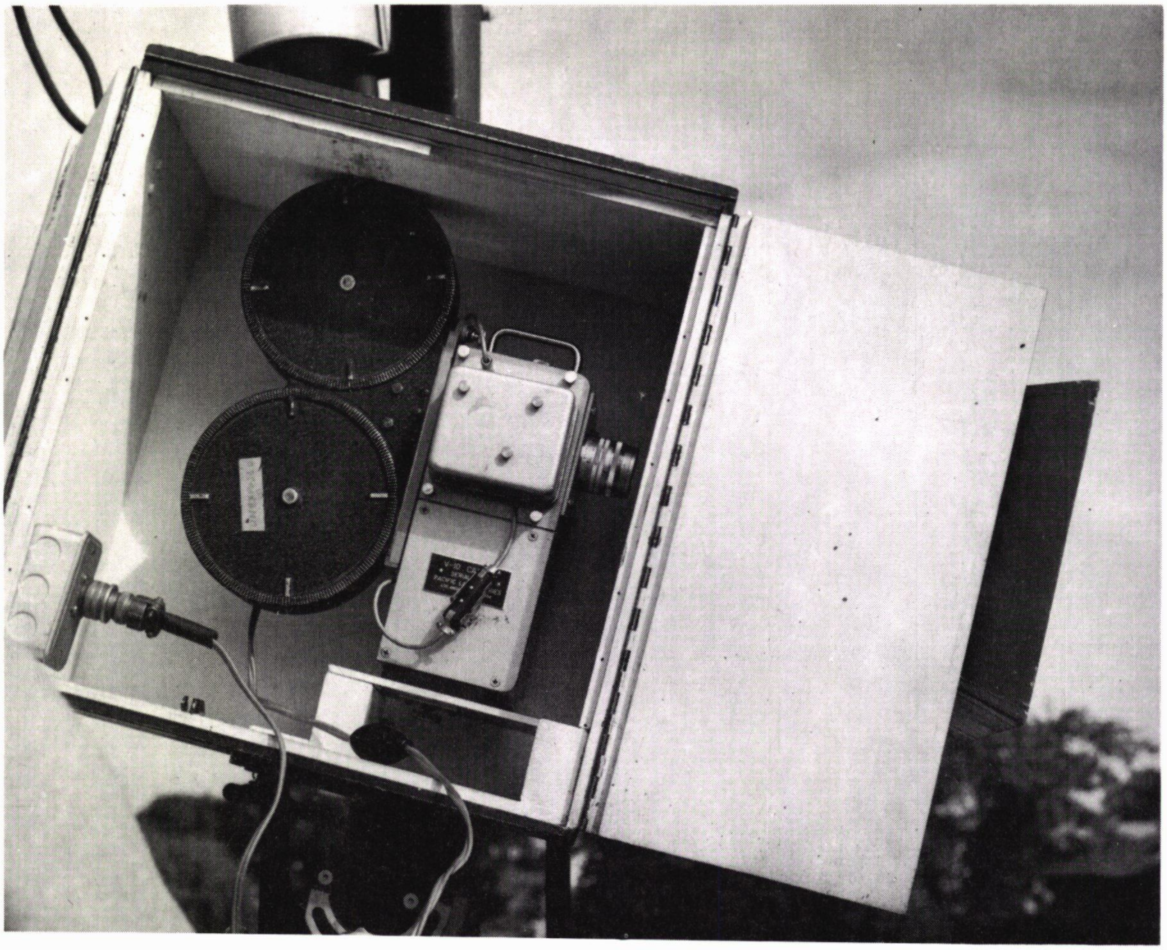
WEATHERPROOF CASE MOUNTED
TO POLE BRACKET BY MEANS
OF STANDARD TRIPOD HEAD



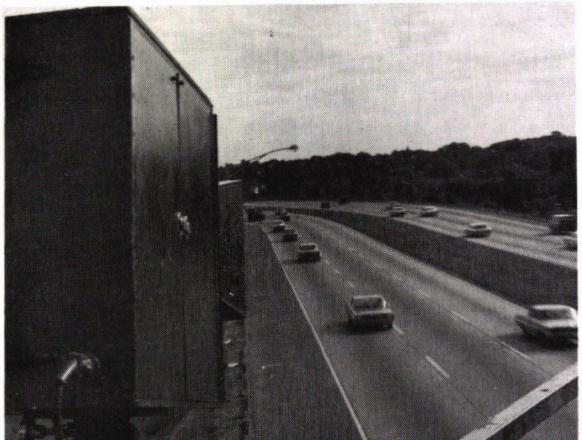
SIGHTING OF CAMERA WITH
EXTERNAL SIGHTING DEVICE

CLOSEUP VIEW OF COMPLETED
INSTALLATION

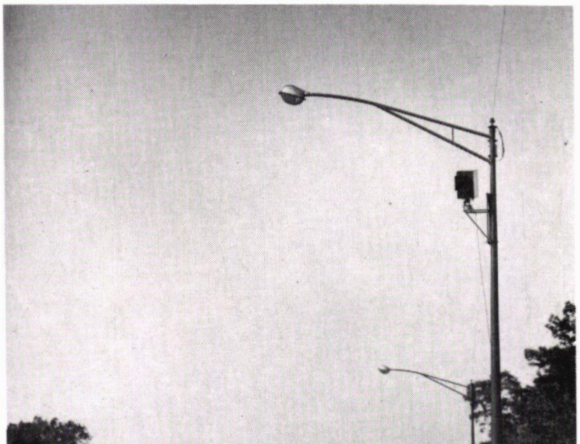
Figure 7. Installation of camera on lighting standard.



CAMERA WITH MAGAZINE
MOUNTED IN WEATHERPROOF CASE



VIEW OF ROADWAY FROM
BEHIND MOUNTED CAMERA



TYPICAL INSTALLATION AS SEEN
FROM PAVEMENT AT 150 FEET

Figure 8. Camera in use as mounted on lighting standard.

TABLE 3

DATA COLLECTION SCHEDULE

SITE	RUN	DATE	TIME [a]	LIGHTING LEVEL (FC)	NO. OF OBSERV.	HOURLY RATE (VPH)
Tangent, test	13	10/26/64	6:09–7:19	0.2	1332	1135
	21	11/12/64	5:49–6:49	0.2	1753	1497
	24	11/19/64	6:12–7:04	0.2	1067	1244
	29	12/ 9/64	5:48–6:39	0.6	1333	1572
	36	12/28/64	6:32–7:23	0.6	1059	1263
	44	6/16/65	5:34–6:28	Day	1913	2132
Tangent, control	13	10/26/64	6:22–7:14	0.6	1058	1227
	21	11/12/64	6:22–7:14	0.6	1574	1723
	24	11/19/64	6:03–6:57	0.6	1301	1429
	29	12/ 9/64	5:33–6:41	0.6	2014	1775
	36	12/28/64	6:28–7:19	0.6	1093	1274
	44	6/16/65	5:33–6:30	Day	1963	2075
Curve, test	12	10/21/64	7:27–8:21	0.2	883	989
	16	11/ 2/64	6:02–6:56	0.2	1468	1638
	20	11/10/64	6:06–7:02	0.2	1554	1661
	31	12/15/64	5:49–6:59	0.6	1922	1639
	34	12/21/64	6:06–7:00	0.6	1357	1507
	38	1/ 6/65	7:21–8:14	0.6	973	1093
	42	5/26/65	5:14–6:12	Day	225	2107
Curve, control	12	10/21/64	6:40–8:52	0.6	1335	1114
	16	11/ 2/64	6:03–6:57	0.6	1364	1522
	20	11/10/64	5:48–6:41	0.6	1455	1672
	31	12/15/64	5:56–6:41	0.6	1214	1627
	34	12/21/64	6:04–6:56	0.6	1269	1474
	38	1/ 6/65	6:31–7:40	0.6	1265	1115
	42	5/26/65	5:15–6:13	Day	2168	2229
On-ramp	11	10/20/64	6:41–7:36	0.2	1479	1627
	15	10/28/64	6:17–7:09	0.2	1689	1956
	17	11/ 4/64	5:48–6:41	0.2	1917	2142
	22	11/16/64	5:38–6:32	0.2	1867	2099
	27	21/ 7/64	5:39–6:31	0.6	1955	2220
	32	12/16/64	5:56–6:51	0.6	2004	2193
	37	12/29/64	6:46–7:39	0.6	1428	1624
	39	1/ 7/65	6:16–7:09	0.6	1444	1681
	43	6/ 3/65	6:10–6:56	Day	1780	2255
Off-ramp	10	10/19/64	6:13–7:06	0.2	1507	1693
	14	10/27/64	5:35–6:33	0.2	1959	2017
	19	11/ 9/64	5:58–6:49	0.2	1597	1862
	23	11/17/64	5:34–6:18	0.2	1858	2516
	28	12/ 8/64	5:16–6:27	0.6	2818	2392
	30	12/14/64	5:50–6:46	0.6	1885	2035
	35	12/22/64	5:39–6:32	0.6	1850	2091
	40	1/21/65	6:37–7:32	0.6	1587	1750
	41	5/24/65	5:54–6:49	Day	2025	2198

[a] Time for which data was actually reduced; not necessarily the starting or ending times of a film run.

5. Headway distribution within lanes and for the traffic stream as a whole. Inasmuch as headways are determined by time of arrival at a common point, it was necessary to calculate the speed and location of the vehicle in a given frame and then calculate the arrival time at the imaginary check point.

6. Analysis of the sequence in which vehicles were observed to follow each other, used to detect the tendency of commercial vehicles to travel in platoons.

At the on-ramp there were also analyses of the gaps accepted by merging vehicles and the point at which vehicles entered the through lane.

Summaries of these tabulations are given in Appendices F, G, and H.

In analyzing the data, the results of three or four studies under each level of nighttime lighting, for each site, were pooled, and comparisons were made on the basis of the pooled data.

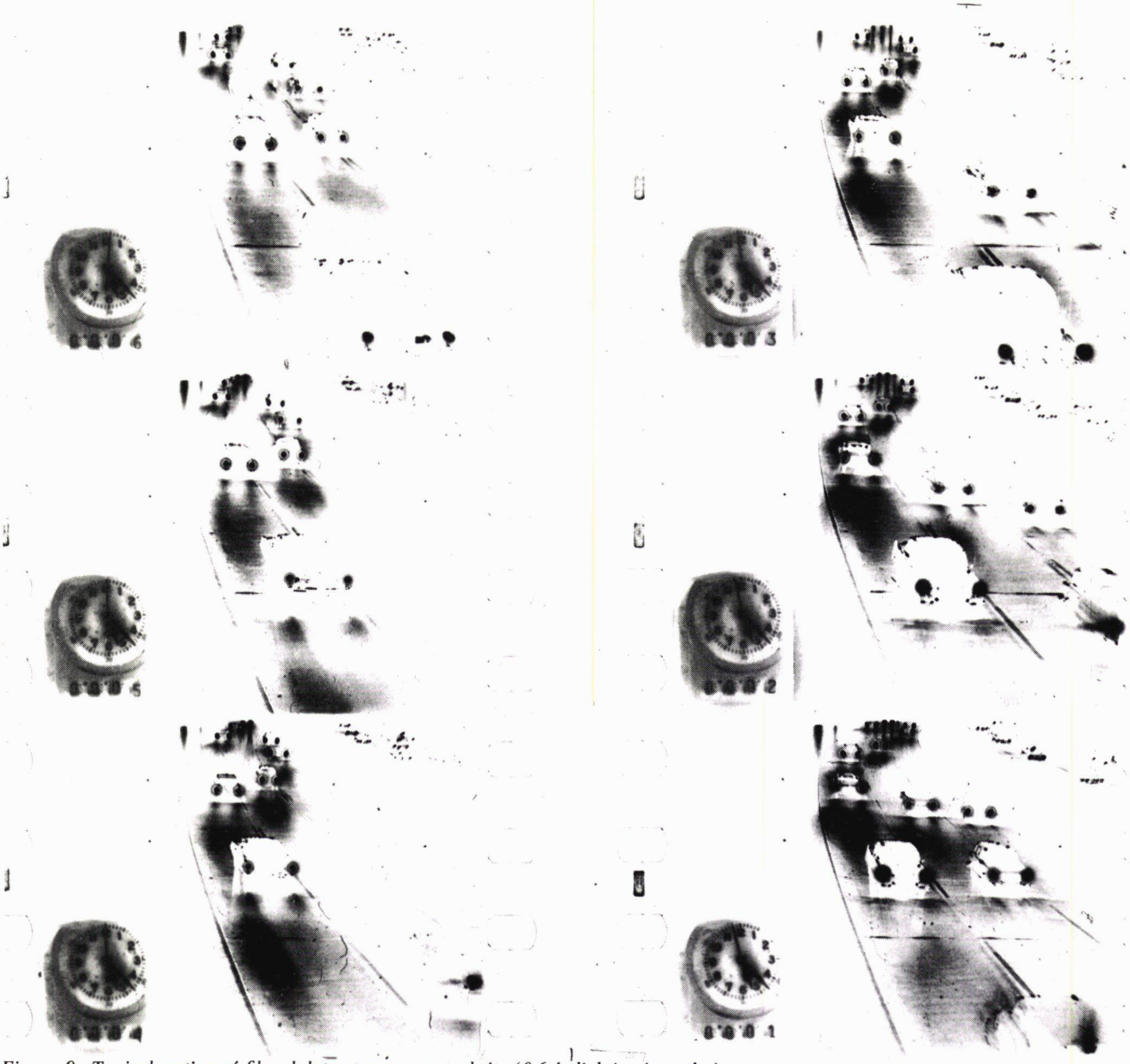


Figure 9. Typical section of filmed data at curve control site (0.6-fc lighting intensity).

CHAPTER TWO

ANALYSIS OF RESULTS

LANE USE

Does a change in lighting have an impact on lane use? Do vehicles distribute themselves in different lanes by vehicle types? What about the position within a lane or the scatter of position within a lane?

Lane use by location and run number is summarized in Table 4 and Figure 10. At no site is there a marked difference in lane distribution or commercial vehicle use within lanes. Observed volume rates over all lanes range from a low of 989 vph at the curve test site to a high of 2,516 vph at the off-ramp. Flow rates for the daytime

TABLE 4

VEHICLE DISTRIBUTION BY LANE

LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	TEST SECTION OBSERVATIONS	TEST SECTION RATE (VPH)	TEST SECTION % IN LANE	TEST SECTION TRUCKS (%)	CONTROL SECTION OBSERVATIONS	CONTROL SECTION RATE (VPH)	CONTROL SECTION % IN LANE	CONTROL SECTION TRUCKS (%)
(*a*) TANGENT SECTIONS										
0.2	13	1	455	388	34.2	16.5	471	546	44.5	13.4
		2	673	573	50.5	7.6	456	529	43.1	9.7
		3	204	174	15.3	3.9	131	152	12.4	3.1
		All	1332	1135	100.0	10.1	1058	1227	100.0	10.5
	21	1	564	482	32.2	16.9	637	697	40.5	15.9
		2	826	705	47.1	10.5	641	702	40.7	12.2
		3	363	310	20.7	3.9	296	324	18.8	4.7
		All	1753	1497	100.0	11.2	1574	1723	100.0	12.3
0.6	29	1	417	492	31.3	17.3	752	663	37.3	18.0
		2	644	759	48.3	12.6	870	767	43.2	13.0
		3	272	321	20.4	7.4	392	345	19.5	6.1
		All	1333	1572	100.0	13.0	2014	1775	100.0	13.5
	36	1	329	392	31.1	16.7	476	555	43.5	13.5
		2	521	622	49.2	6.9	462	539	42.3	10.8
		3	209	249	19.7	3.4	155	181	14.2	3.2
		All	1059	1263	100.0	9.3	1093	1275	100.0	10.9
Day	44	1	524	584	27.4	16.7	729	771	37.1	15.0
		2	879	979	45.9	8.1	792	837	40.4	7.5
		3	510	568	26.7	2.0	442	467	22.5	0.7
		All	1913	2132	100.0	8.8	1963	2075	100.0	8.7
(*b*) CURVE SECTIONS										
0.2	12	1	139	156	15.7	6.5	570	476	42.7	19.0
		2	307	344	34.8	20.9	539	450	40.1	10.6
		3	352	394	39.9	9.4	226	188	16.9	3.6
		4	85	95	9.6	4.7	—	—	—	—
		All	883	989	100.0	12.5	1335	1114	100.0	13.0
	16	1	202	225	13.8	8.5	546	609	40.0	15.8
		2	429	479	29.2	17.3	547	610	40.1	12.8
		3	593	662	40.4	10.3	271	302	19.9	4.1
		4	243	271	16.6	4.9	—	—	—	—
		All	1467	1638	100.0	11.2	1364	1522	100.0	12.2
	20	1	194	207	12.5	3.6	533	612	36.6	13.7
		2	472	505	30.4	19.9	593	681	40.8	9.8
		3	627	670	40.4	8.5	329	378	22.6	4.0
		4	261	279	16.8	3.5	—	—	—	—
		All	1554	1661	100.0	10.5	1455	1672	100.0	9.9
0.6	31	1	258	220	13.4	5.8	475	621	39.1	11.6
		2	575	490	29.9	16.2	500	670	41.2	10.0
		3	776	662	40.4	10.2	239	319	19.6	1.7
		4	313	267	16.3	2.6	—	—	—	—
		All	1922	1639	100.0	10.2	1214	1627	100.0	9.1
	34	1	149	165	11.0	6.9	493	573	38.9	12.4
		2	435	483	32.1	18.2	543	631	42.8	12.7
		3	560	622	41.3	10.9	233	271	18.4	6.0
		4	213	237	15.7	3.8	—	—	—	—
		All	1357	1507	100.0	11.6	2169	1474	100.0	11.4
	38	1	148	166	15.2	3.4	520	458	41.1	17.6
		2	332	373	34.1	19.6	541	477	42.8	9.4
		3	397	446	40.8	10.3	204	180	16.1	4.4
		4	96	108	9.9	1.0	—	—	—	—
		All	973	1093	100.0	11.5	1265	1115	100.0	11.9
Day	42	1	268	279	13.2	3.7	756	777	34.9	10.3
		2	572	595	28.3	11.9	823	846	37.9	10.8
		3	767	798	37.9	11.1	589	606	27.2	2.0
		4	418	435	20.6	2.4	—	—	—	—
		All	2025	2107	100.0	8.5	2168	2229	100.0	8.3
(*c*) ON-RAMP SECTION										
0.2	11	Ramp	363	399	24.5	1.4	—	—	—	—
		1	426	469	28.8	20.2	—	—	—	—
		2	489	538	33.1	13.5	—	—	—	—
		3	201	221	13.6	5.5	—	—	—	—
		All	1479	1627	100.0	11.4	—	—	—	—
	15	Ramp	329	381	19.5	2.4	—	—	—	—
		1	456	528	27.0	13.2	—	—	—	—
		2	603	698	35.7	12.6	—	—	—	—
		3	301	349	17.8	2.3	—	—	—	—
		All	1689	1956	100.0	8.9	—	—	—	—

TABLE 4—*Continued*

			TEST SECTION				CONTROL SECTION			
LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	OBSERVATIONS	RATE (VPH)	% IN LANE	TRUCKS (%)	OBSERVATIONS	RATE (VPH)	% IN LANE	TRUCKS (%)
	17	Ramp	437	488	22.8	3.7	—	—	—	—
		1	495	553	25.8	21.0	—	—	—	—
		2	645	721	33.7	10.4	—	—	—	—
		3	340	380	17.7	7.6	—	—	—	—
		All	1917	2142	100.0	11.1	—	—	—	—
	22	Ramp	463	521	24.8	6.5	—	—	—	—
		1	487	548	26.1	16.2	—	—	—	—
		2	624	702	33.4	11.9	—	—	—	—
		3	293	328	15.6	4.5	—	—	—	—
		All	1867	2099	100.0	10.5	—	—	—	—
0.6	27	Ramp	494	561	25.3	3.4	—	—	—	—
		1	543	617	27.8	14.6	—	—	—	—
		2	628	713	32.1	12.9	—	—	—	—
		3	290	329	14.8	7.6	—	—	—	—
		All	1955	2220	100.0	10.2	—	—	—	—
	32	Ramp	427	467	21.3	4.9	—	—	—	—
		1	544	595	27.2	15.3	—	—	—	—
		2	696	762	34.7	13.4	—	—	—	—
		3	337	369	16.8	5.9	—	—	—	—
		All	2004	2193	100.0	10.8	—	—	—	—
	37	Ramp	304	346	21.3	4.0	—	—	—	—
		1	379	431	26.5	20.1	—	—	—	—
		2	535	608	37.5	9.0	—	—	—	—
		3	210	239	14.7	4.3	—	—	—	—
		All	1428	1624	100.0	10.2	—	—	—	—
	39	Ramp	321	374	22.2	3.1	—	—	—	—
		1	391	455	27.1	17.9	—	—	—	—
		2	520	605	36.0	12.9	—	—	—	—
		3	212	247	14.7	4.7	—	—	—	—
		All	1444	1681	100.0	10.9	—	—	—	—
Day	43	Ramp	359	455	20.2	2.8	—	—	—	—
		1	457	579	25.7	18.4	—	—	—	—
		2	635	804	35.7	11.2	—	—	—	—
		3	329	417	18.4	3.3	—	—	—	—
		All	1780	2255	100.0	9.9	—	—	—	—
				(*d*) OFF-RAMP SECTION						
0.2	10	Ramp	554	622	36.8	0.7	—	—	—	—
		1	377	424	25.0	26.3	—	—	—	—
		2	450	506	29.9	11.1	—	—	—	—
		3	125	140	8.3	6.4	—	—	—	—
		All	1507	1693	100.0	10.7	—	—	—	—
	14	Ramp	560	577	28.6	2.1	—	—	—	—
		1	496	511	25.3	19.8	—	—	—	—
		2	651	670	33.2	7.5	—	—	—	—
		3	250	257	12.8	2.4	—	—	—	—
		All	1959	2017	100.0	8.4	—	—	—	—
	19	Ramp	459	535	28.7	2.8	—	—	—	—
		1	440	513	27.6	18.6	—	—	—	—
		2	510	595	31.9	10.8	—	—	—	—
		3	186	217	11.6	2.2	—	—	—	—
		All	1597	1862	100.0	9.6	—	—	—	—
	23	Ramp	557	754	30.0	3.9	—	—	—	—
		1	402	544	21.6	25.1	—	—	—	—
		2	612	829	32.9	8.3	—	—	—	—
		3	286	387	15.4	2.8	—	—	—	—
		All	1858	2516	100.0	9.8	—	—	—	—
0.6	28	Ramp	894	759	31.7	3.6	—	—	—	—
		1	644	547	22.9	19.2	—	—	—	—
		2	888	754	31.5	9.5	—	—	—	—
		3	391	332	13.9	3.1	—	—	—	—
		All	2818	2392	100.0	8.9	—	—	—	—
	30	Ramp	567	612	30.1	2.3	—	—	—	—
		1	487	526	25.8	22.6	—	—	—	—
		2	615	664	32.6	9.1	—	—	—	—
		3	216	233	11.5	3.7	—	—	—	—
		All	1885	2035	100.0	9.9	—	—	—	—
	35	Ramp	513	580	27.7	3.9	—	—	—	—
		1	433	489	23.4	20.6	—	—	—	—
		2	636	719	34.4	8.6	—	—	—	—
		3	264	298	14.3	3.8	—	—	—	—
		All	1850	2091	100.0	9.5	—	—	—	—

TABLE 4—*Continued*

			TEST SECTION				CONTROL SECTION			
LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	OBSERVATIONS	RATE (VPH)	% IN LANE	TRUCKS (%)	OBSERVATIONS	RATE (VPH)	% IN LANE	TRUCKS (%)
	40	Ramp	526	580	33.1	1.5	—	—	—	—
		1	407	449	25.7	23.3	—	—	—	—
		2	495	546	31.2	11.1	—	—	—	—
		3	159	175	10.0	5.0	—	—	—	—
		All	1587	1750	100.0	10.5	—	—	—	—
Day	41	Ramp	588	638	29.0	2.2	—	—	—	—
		1	486	528	24.0	22.0	—	—	—	—
		2	665	722	32.9	6.6	—	—	—	—
		3	286	310	14.1	3.9	—	—	—	—
		All	2025	2198	100.0	8.6	—	—	—	—

studies, made during the summer months, were about 30 to 40 percent higher than flow rates made during the winter months. Under these conditions there is a slight decrease in the percentage of commercial vehicles on the roadway. Except for the slight decrease in the percentage of trucks, no pattern is evident that would suggest that the level of illumination influences the distribution of vehicles between lanes or the distribution of commercial vehicles within the lanes.

MEAN PLACEMENT WITHIN LANES

The mean placements at the six test sites, with tests of like conditions averaged together, are given in Table 5 and shown in Figures 11 through 14. Test site placements during the "after" interval were made at 0.2 average foot-candles and during the "before" interval at 0.6 average foot-candles, whereas both "before" and "after" observations at the control sites were made at 0.6 average foot-candles. Daylight observations are also included. All placements are from the center of the vehicle to the right-hand edge of the through lanes (lane 1 from 0 to 12 ft, lane 2 from 12 to 24 ft, etc.) The changes in placement at the test site may be compared to changes in placement at the control site to isolate the differences due to lighting from the inherent day-to-day variation in placement. For example, passenger vehicles in lane 1 at the tangent test site moved from 6.7 ft to 6.2 ft a shift of 0.5 ft closer to the right-hand edge of pavement when the nighttime intensity was increased, but a similar shift was noted at the control site with no change in lighting. A shift of 0.5 ft to the right was also observed for commercial vehicles in lane 1 at the tangent test site, but this is compared with a lesser change (0.3 ft) at the control site.

No pattern of placement within lanes, as related to the lighting change, is apparent. With few exceptions other than the on-ramp site, mean daytime placements do not deviate by more than 0.2 ft from one or the other sets of nighttime observations. The pattern of agreement is random, so that daylight observations are consistently related with neither the observations made at 0.2 fc nor the observations made at 0.6 fc. (The daytime observations at the on-ramp were made from a vantage point closer to the gore of the merging ramp, so that vehicle placements, particularly on the merging ramp, are not directly comparable.) The greatest changes in placement with a change in lighting occurred in each of the three lanes at the tangent test site for passenger vehicles, but these differences are partially associated with a similar but somewhat smaller shift in placement of passenger vehicles at the tangent control site. With few exceptions, the placements in all lanes, at both the test and control sites, are closer to the right-hand edge of the pavement during the "before" study (0.6 fc). The greatest exception to this difference between before and after observations will be noted in lane 1 at the curve site, where for both passenger and commercial vehicles placements increased by more than 0.5 ft.

Three tests of statistical significance were applied to the mean nighttime placement data (Table H-1). The first two consisted of the application of the *t*-test to measure the significance of the difference in means between "before" and "after" studies. Where applicable, the difference in the means "before" and "after" at the control site were then used as a third test to further evaluate the significance of the differences at the test site.

For example, consider commercial vehicles in lane 1 at the two tangent sites. At both sites the placements "before" and "after" are significantly different, but the 0.5-ft decrease (6.3 ft to 5.8 ft) at the test site is not significantly different from the 0.3-ft decrease (6.6 ft to 6.3 ft) at the control site where there was no lighting change. (It is noted here that sample sizes for passenger vehicles almost always exceeded 1,000 units, but sample sizes in the high-speed lanes (lanes 3 and 4) were as small as 15 for commercial vehicles. The result is that the same physical difference may be statistically significant for passenger vehicles and show no statistically significant difference for commercial vehicles.)

When comparing the "differences-between-differences" the values for passenger vehicles in all lanes at the tangent and the curve sites tended to be 0.3 ft or less. The one exception was the mean placement values in lane 1 of the

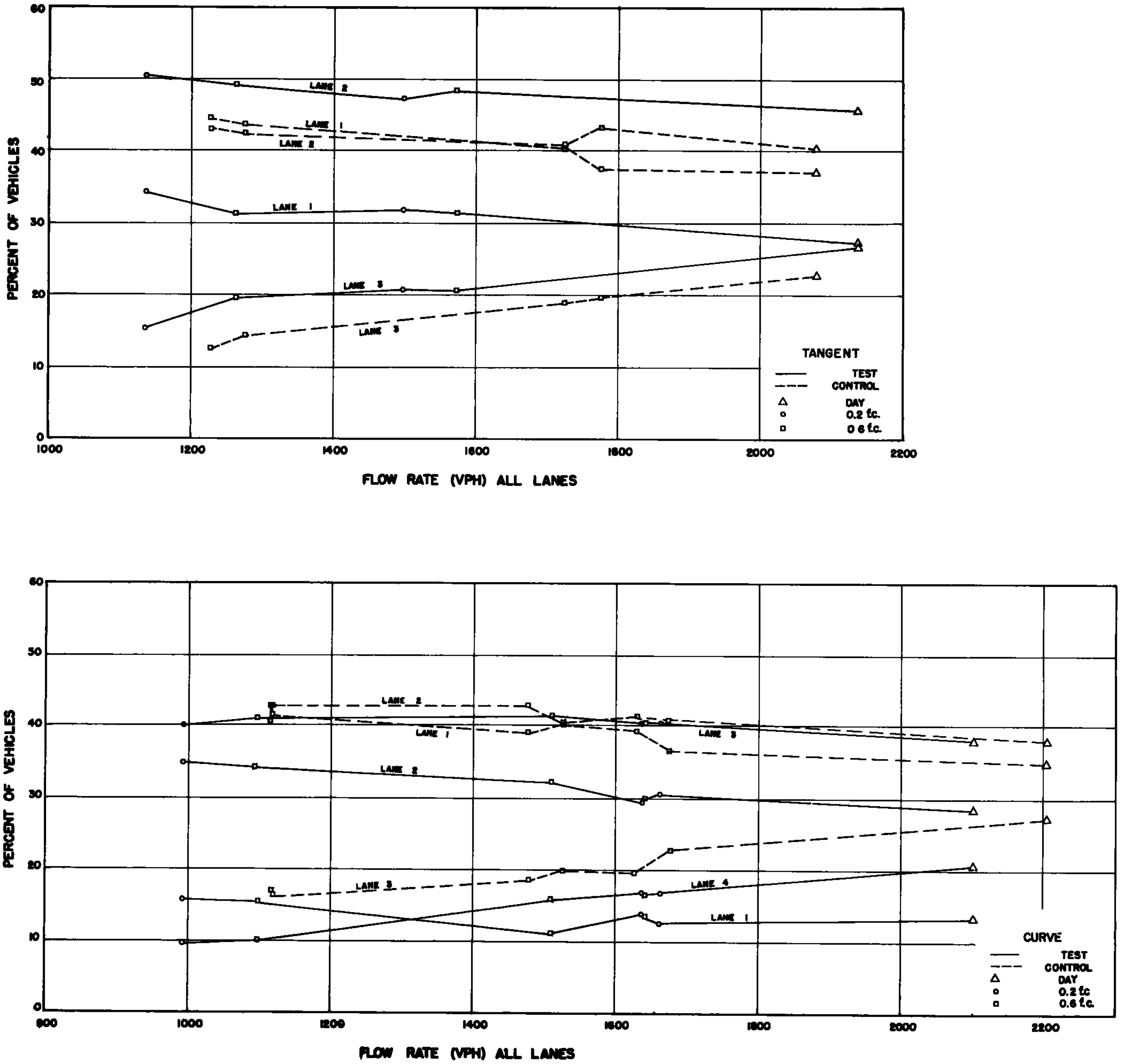


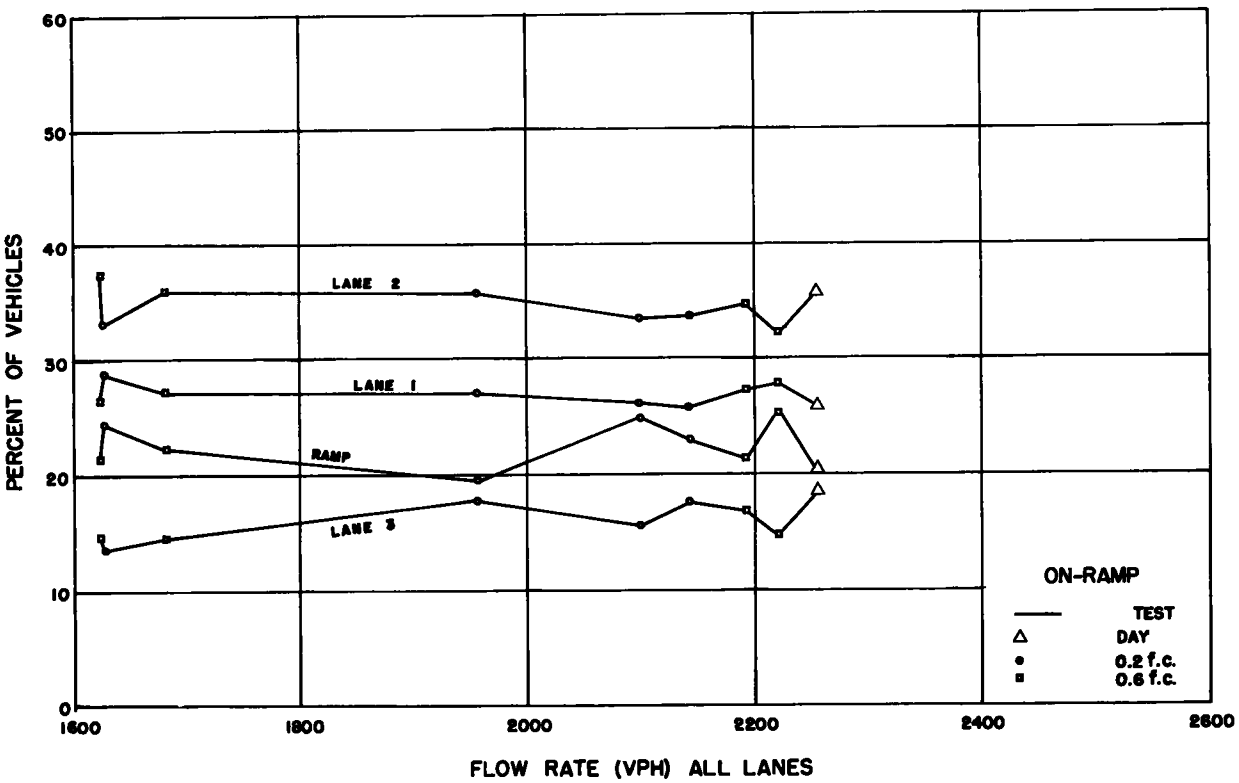
Figure 10. Lane distribution by lighting level.

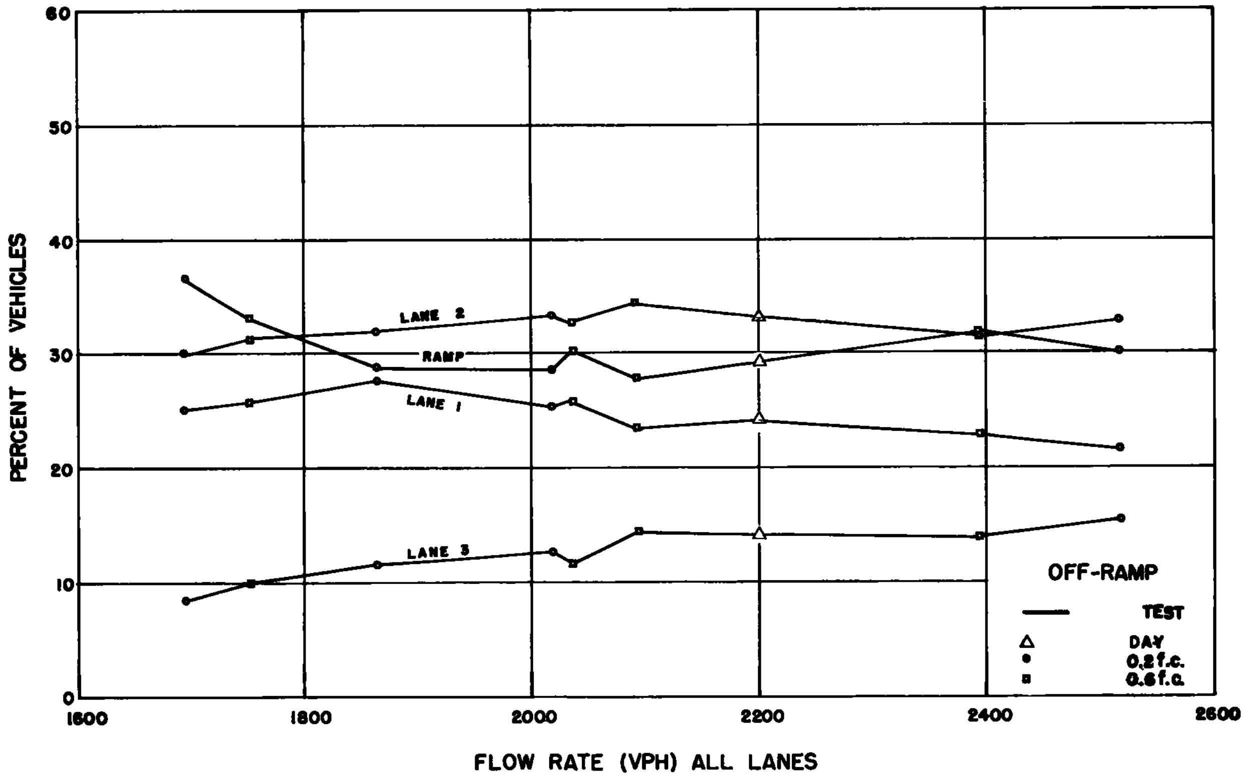
curve site, where an increase (further from right-hand pavement edge) of 0.6 ft at the test site is compared to a decrease (closer to right-hand pavement edge) of 0.2 ft at the control site.

VARIANCE OF PLACEMENT WITHIN LANES

It was hypothesized that a change in lighting may influence the variance of the placements within a lane, a lesser variance indicating that drivers tend to follow a common path and thus show less tendency to be "scattered" within a lane.

The standard deviations of placements are given in Table 6. Except for the ramp lanes the standard deviations are seldom greater than 2.0 ft. No consistent pattern related to the lighting change exists. For example, consider passenger vehicles at the tangent test site. There was an increase in variance in two of the three lanes when the nighttime lighting intensity was increased, whereas at the curve test site there was an increase in scatter in only one of the four lanes. At the on-ramp there was no change in variance in either the ramp lane or lane 1; decreases in scatter were observed in both lanes 2 and 3 with only lane 3 showing a significant change. Finally, at the off-ramp there was a significant increase in scatter in all through lanes with increased lighting; on the other hand, a


60
50
40
30
20
10
0
PERCENT OF VEHICLES
1600
1800
2000
2200
2400
2600
FLOW RATE (VPH) ALL LANES
LANE 2
LANE 1
RAMP
LANE 3
ON-RAMP
TEST
△ DAY
● 0.2 f.c.
▫ 0.6 f.c.


60
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0
PERCENT OF VEHICLES
1600
1800
2000
2200
2400
2600
FLOW RATE (VPH) ALL LANES
LANE 2
RAMP
LANE 1
LANE 3
OFF-RAMP
TEST
△ DAY
● 0.2 f.c.
▫ 0.6 f.c.

TABLE 5

MEAN PLACEMENT BY VEHICLE TYPE BY LANE BY LIGHTING CONDITION

			MEAN DISTANCE FROM PAVEMENT EDGE[a] (FT)					
			TEST SITE			CONTROL SITE		
SITE	VEHICLE TYPE	LANE	0.2 FC	0.6 FC	DAY	0.2 FC	0.6 FC	DAY
Tangent	Pass.	1	6.7	6.2	6.1	6.9	6.4	6.8
		2	19.0	18.4	18.5	19.6	19.3	19.6
		3	29.6	29.1	29.7	30.6	30.4	30.8
	Comm.	1	6.3	5.8	5.9	6.6	6.3	6.7
		2	18.8	18.4	18.0	19.6	19.2	19.8
		3	29.3	29.5	29.4	30.5	30.6	29.4
Curve	Pass.	1	7.4	8.0	7.3	7.8	7.6	7.1
		2	19.4	19.4	19.0	20.1	19.8	19.3
		3	31.2	31.1	30.9	31.4	31.2	31.3
		4	42.5	42.5	42.6	—	—	—
	Comm.	1	6.7	7.2	7.3	7.6	7.6	7.2
		2	19.2	19.3	19.4	19.8	19.9	19.2
		3	31.0	31.1	31.2	31.6	30.5	31.5
		4	41.9	40.9	42.2	—	—	—
On-ramp	Pass.	1	5.7	5.8	5.5	—	—	—
		2	19.4	19.4	18.4	—	—	—
		3	30.0	29.7	29.3	—	—	—
		Ramp	−7.8	−7.2	−11.0	—	—	—
	Comm.	1	6.1	5.9	6.3	—	—	—
		2	18.9	18.9	18.3	—	—	—
		3	29.7	29.5	29.7	—	—	—
		Ramp	−8.8	−7.9	−10.9	—	—	—
Off-ramp	Pass.	1	6.1	5.8	5.5	—	—	—
		2	19.7	19.7	19.8	—	—	—
		3	31.4	31.4	31.9	—	—	—
		Ramp	−30.8	−30.8	−31.2	—	—	—
	Comm.	1	6.1	5.8	5.6	—	—	—
		2	19.5	19.4	19.4	—	—	—
		3	31.0	31.0	31.5	—	—	—
		Ramp	−29.8	−28.8	−30.6	—	—	—

[a] Outside pavement edge at joint with shoulder.

TABLE 6

STANDARD DEVIATION OF PLACEMENT BY VEHICLE TYPE BY LANE BY LIGHTING CONDITION

			STANDARD DEVIATION (FT)					
			TEST SITE			CONTROL SITE		
SITE	VEHICLE TYPE	LANE	0.2 FC	0.6 FC	DAY	0.2 FC	0.6 FC	DAY
Tangent	Pass.	1	1.15	1.27	1.46	1.27	1.26	1.17
		2	1.17	1.20	1.45	1.43	1.35	1.41
		3	1.27	1.21	1.18	1.62	1.44	1.49
	Comm.	1	1.04	1.24	1.38	1.28	1.27	1.29
		2	1.37	1.48	1.84	1.30	1.45	1.10
		3	1.72	1.80	0.82	1.40	2.10	0.35
Curve	Pass.	1	1.42	1.30	1.29	1.22	1.39	1.21
		2	1.56	1.67	1.33	1.35	1.59	1.47
		3	1.61	1.55	1.48	1.35	1.54	1.48
		4	1.75	1.73	1.48	—	—	—
	Comm.	1	1.11	1.41	0.98	1.25	1.38	1.28
		2	1.64	1.42	1.35	1.50	1.24	1.11
		3	1.87	1.53	1.38	1.29	2.45	1.61
		4	2.08	2.46	1.61	—	—	—
On-ramp	Pass.	1	2.11	2.11	1.79	—	—	—
		2	1.46	1.45	1.42	—	—	—
		3	1.48	1.38	1.45	—	—	—
		Ramp	3.18	3.18	4.07	—	—	—
	Comm.	1	1.62	1.59	1.31	—	—	—
		2	1.41	1.36	1.66	—	—	—
		3	1.37	1.87	0.74	—	—	—
		Ramp	3.00	2.86	4.32	—	—	—
Off-ramp	Pass.	1	1.52	1.72	1.32	—	—	—
		2	1.58	1.74	1.47	—	—	—
		3	2.10	2.14	2.13	—	—	—
		Ramp	5.02	4.65	3.40	—	—	—
	Comm.	1	1.37	1.63	1.14	—	—	—
		2	1.76	1.75	2.10	—	—	—
		3	2.50	2.78	2.20	—	—	—
		Ramp	6.11	7.01	3.98	—	—	—

significant decrease was observed in the ramp lane. Again, the daytime variances do not appear to be related to either of the nighttime lighting conditions.

The ratio of the nighttime variances, before and after, were also calculated and the *F*-test was applied to test the significance of the change in variance. The results are given in Table H-1. Again, the results are mixed. There is no pattern of change evident with the change in lighting intensity.

VELOCITIES

Nighttime Velocities

Does a change in nighttime light intensity from 0.2 fc to 0.6 fc have any effect on the mean or variance of velocities? Is the effect different at a horizontal curve segment as compared to a tangent segment? If there is a difference is it related to the change in lighting? Are

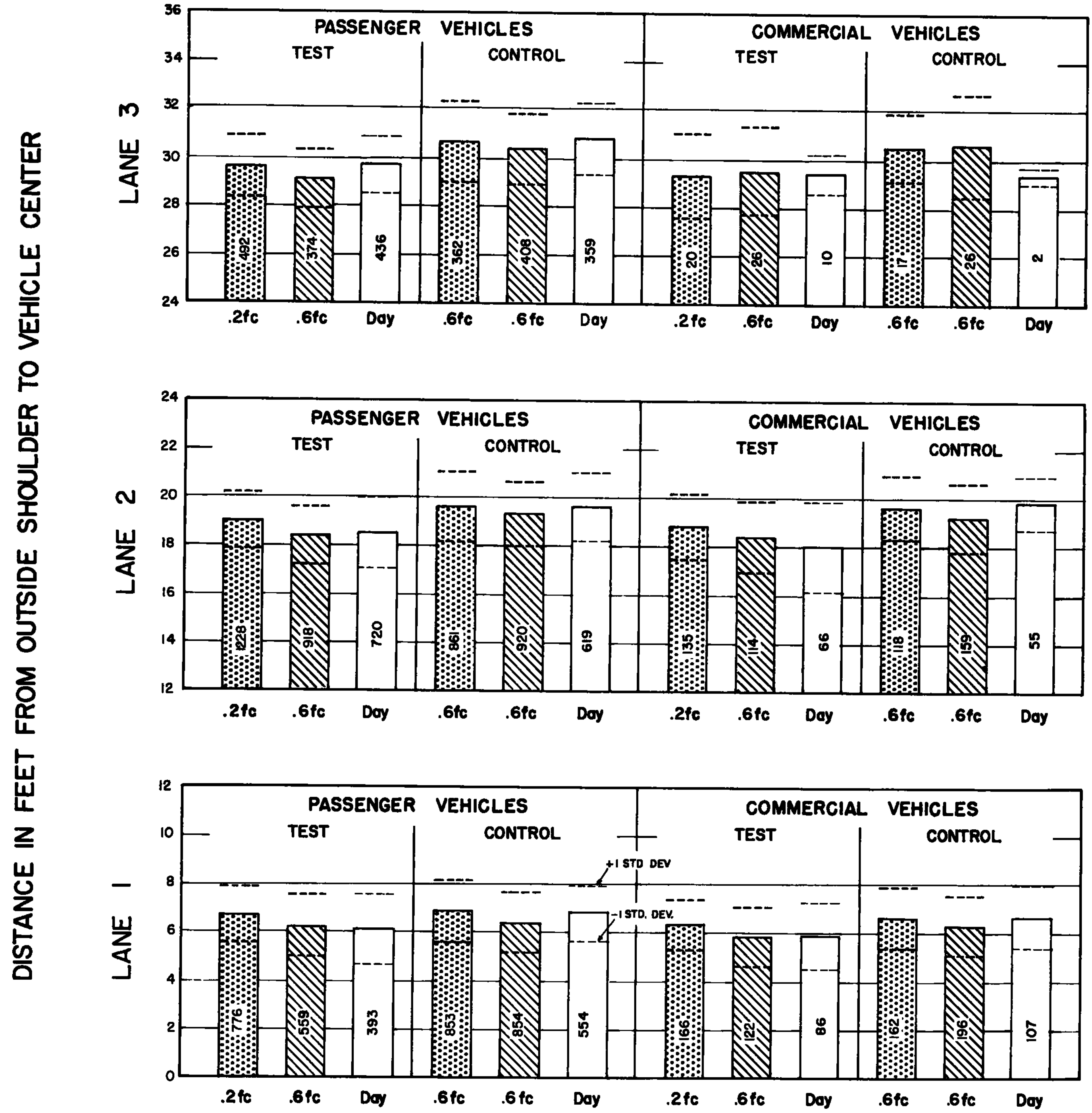

Figure 11. Mean placement by lane by vehicle type and lighting condition at tangent sites.

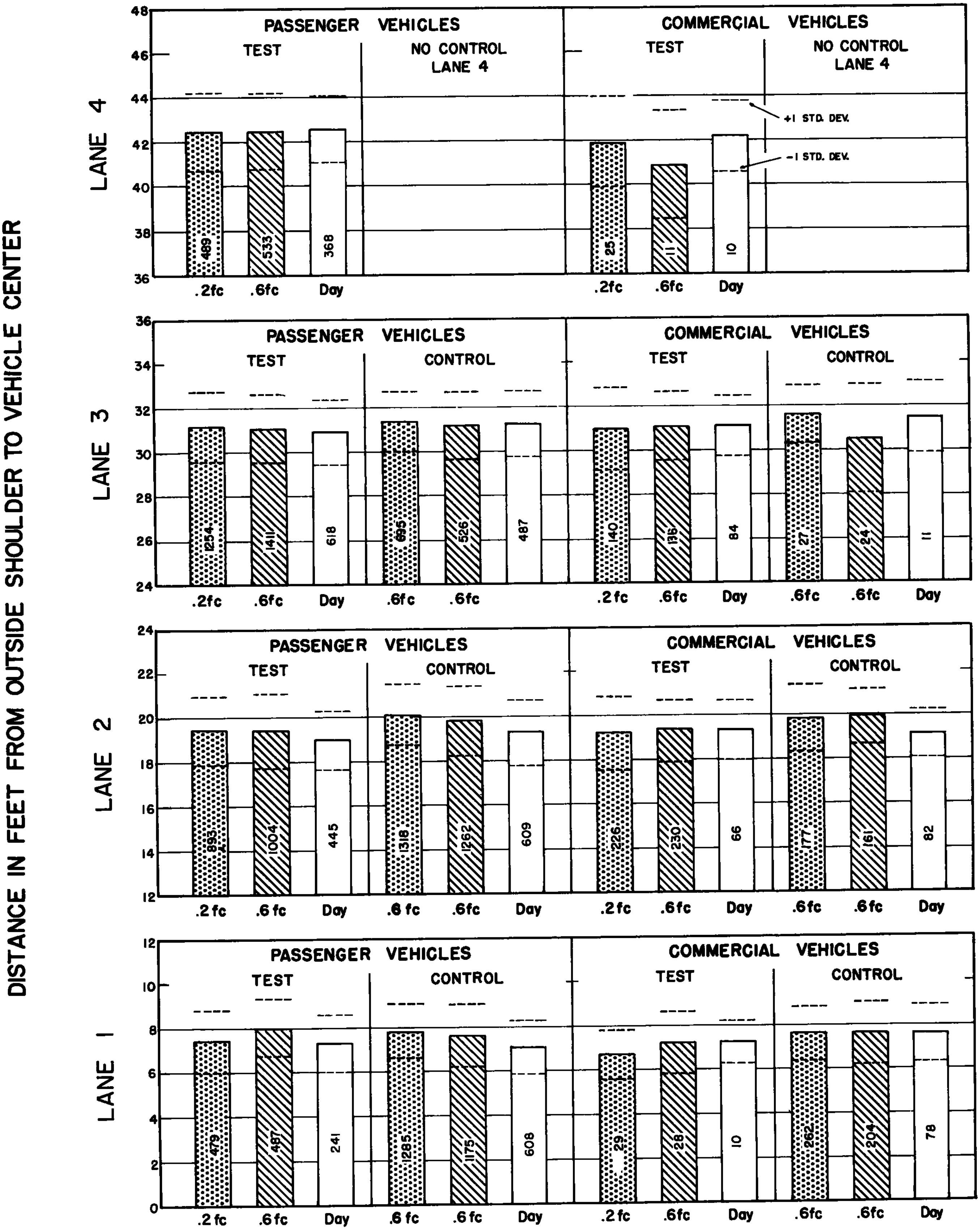

Figure 12. Mean placement by lane by vehicle type and lighting condition at curve sites.

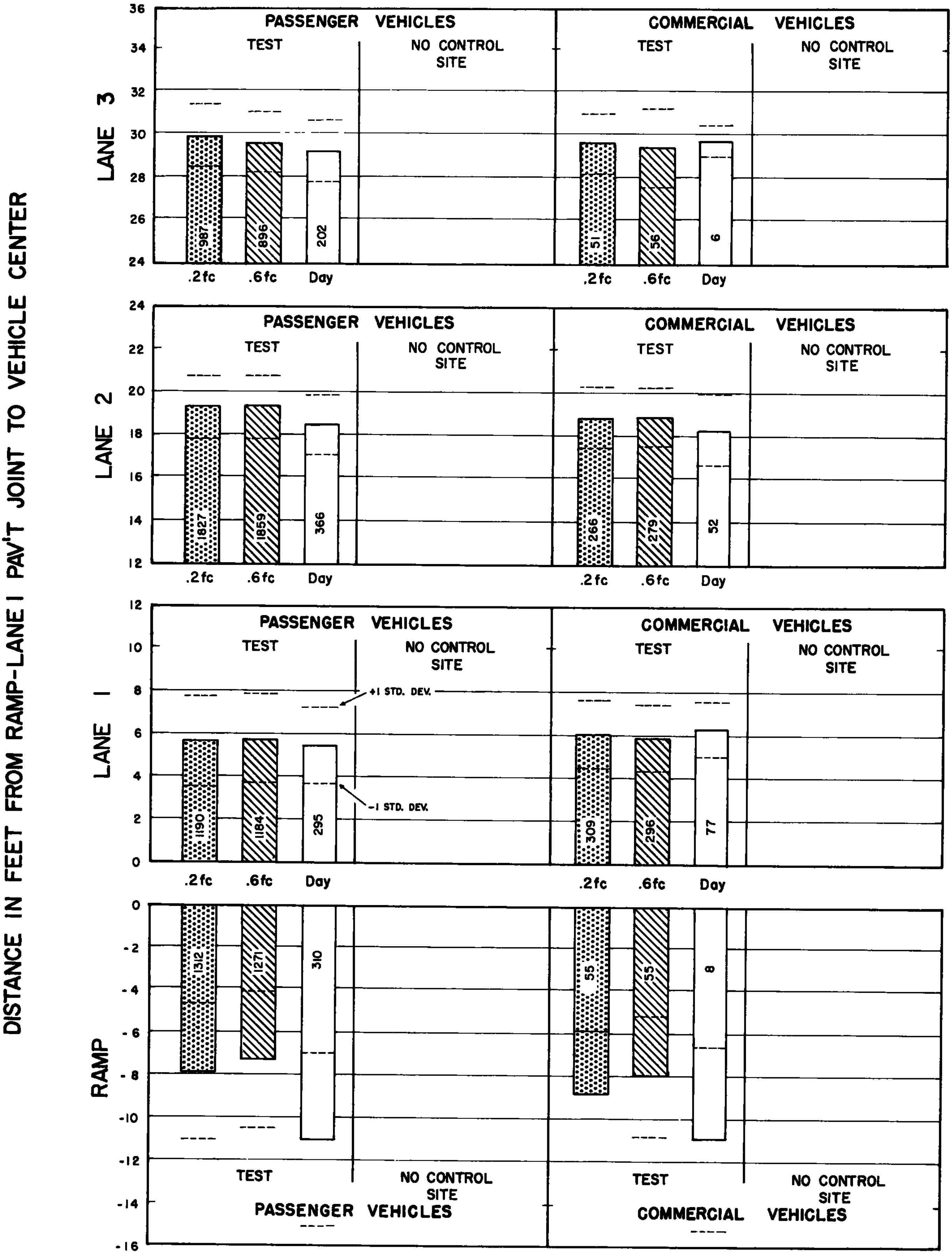

Figure 13. Mean placement by lane by vehicle type and lighting condition at on-ramp site.

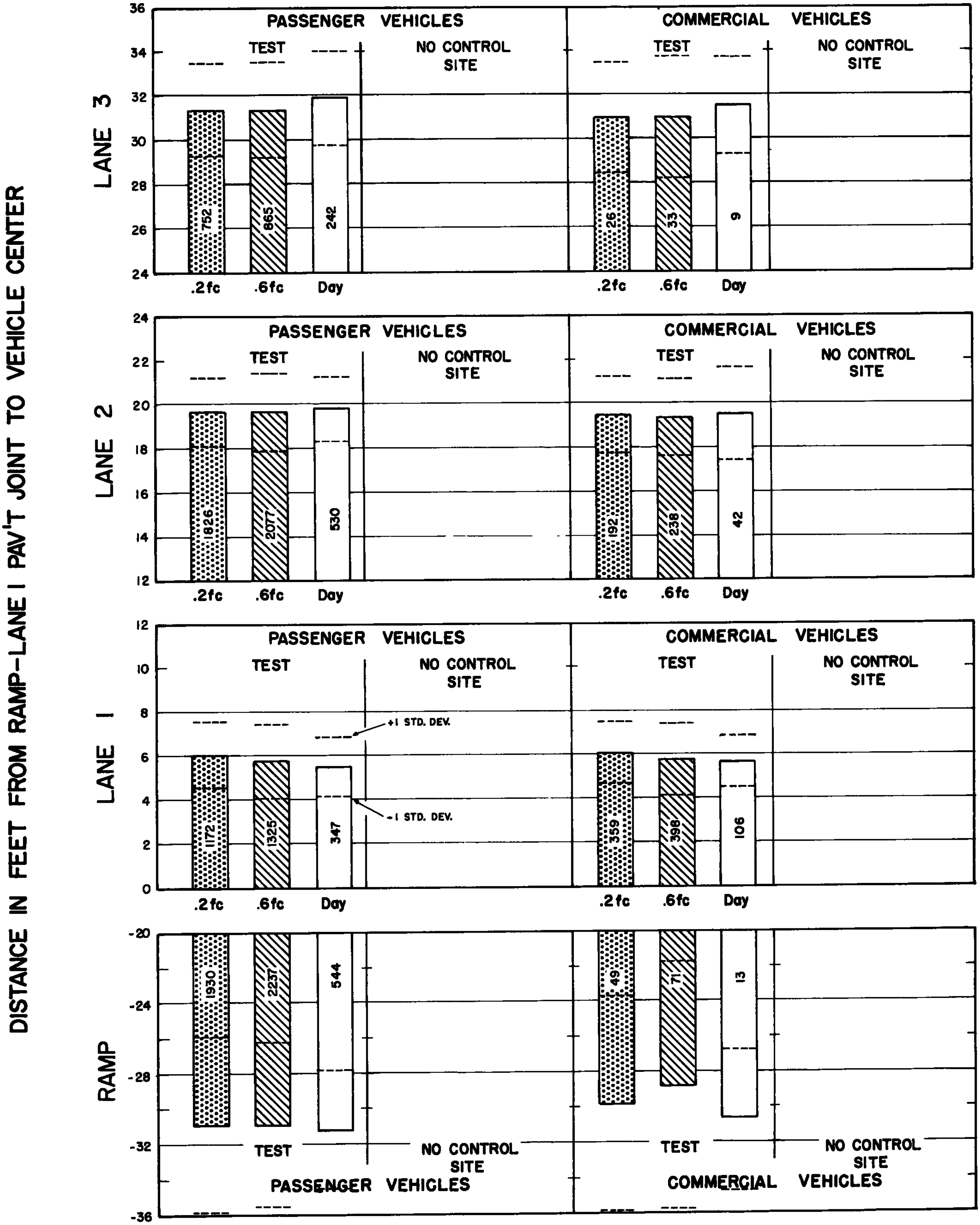

Figure 14. Mean placement by lane by vehicle type and lighting condition at off-ramp site.

the changes the same for passenger vehicles and commercial vehicles?

Mean velocities are given in Table 7 and Figure 15 through 18. Significance tests of differences are given in Table H-2. The posted speed limit is 50 mph at all sites. Mean velocities in the through lanes range from a low of 42 mph for commercial vehicles in lane 1 of the curve site to 65 mph for passenger vehicles in lane 3 of the on-ramp site. For passenger vehicles at the tangent test site and at the on-ramp test site (the three lanes of the on-ramp site are in a tangent segment also) the change in nighttime lighting causes a negligible change in velocities and only in lane 3 at the tangent site is the change for passenger vehicles greater than 1 mph. The changes in commercial vehicle velocities at the tangent sites are more pronounced, yet do not exceed 2 mph, and are not statistically significant except in lane 2. Further, the changes at the tangent test site showed a decrease in speed for both passenger and commercial vehicles with an increase in nighttime lighting intensity when the difference was significant.

A more pronounced pattern of change is evident at the curve test site and at the off-ramp test site. Both passenger and commercial vehicle velocities at these two sites decrease with the increase in nighttime lighting intensity, and for the passenger vehicles all decreases but one are statistically significant. There are no evident causes for these differences other than the lighting changes. The volume rates at the curve test site are given in Table 8 in order to emphasize the similarity of conditions.

Examination of the control sites, both tangent and curve, substantiates the results at the test sites. In general, the velocity changes at the tangent test site are no different from the changes at the tangent control site. At the curve control site it will be observed that there was little change in velocity (same lighting before and after) emphasizing the significance of the change in velocity at the curve test site.

Daylight Velocities

Daylight velocities at the tangent and curve test sites are similar to nighttime velocities in lanes 1 and 2 for both passenger and commercial vehicles. In lane 3 of the tangent test site and lanes 3 and 4 of the curve test site the daytime velocities are less than nighttime velocities

TABLE 7

MEAN VELOCITY BY VEHICLE TYPE BY LANE BY LIGHTING CONDITION

SITE	VEHICLE TYPE	LANE	MEAN VELOCITY (MPH)					
			TEST SITE			CONTROL SITE		
			0.2 FC	0.6 FC	DAY	0.2 FC	0.6 FC	DAY
Tangent	Pass.	1	51.84	52.00	51.91	48.75	48.81	49.51
		2	57.41	56.91	56.69	57.49	57.25	57.68
		3	60.79	59.62	58.90	62.68	60.42	64.10
	Comm.	1	52.66	51.72	50.18	47.16	45.58	47.40
		2	57.85	55.87	55.79	55.18	54.06	54.30
		3	59.71	58.35	57.24	58.53	57.60	59.45
Curve	Pass.	1	48.26	49.63	46.99	48.55	48.69	49.12
		2	46.69	48.63	48.88	55.10	55.70	56.44
		3	54.14	53.10	52.35	60.68	60.89	60.48
		4	58.46	56.75	55.26	—	—	—
	Comm.	1	43.66	42.10	42.66	50.56	50.51	50.49
		2	49.10	49.50	48.71	55.74	56.10	57.27
		3	54.23	52.94	51.68	59.22	59.44	62.92
		4	58.09	54.77	51.11	—	—	—
On-ramp	Pass.	1	49.54	59.75	51.00	—	—	—
		2	55.42	55.74	58.14	—	—	—
		3	61.57	62.23	64.55	—	—	—
		Ramp	48.09	47.88	46.97	—	—	—
	Comm.	1	46.88	47.07	48.03	—	—	—
		2	53.30	53.60	55.10	—	—	—
		3	58.21	58.49	60.45	—	—	—
		Ramp	41.03	41.40	38.39	—	—	—
Off-ramp	Pass.	1	49.81	48.93	50.25	—	—	—
		2	55.35	54.14	56.30	—	—	—
		3	59.63	59.34	61.09	—	—	—
		Ramp	37.56	35.84	37.27	—	—	—
	Comm.	1	50.29	49.35	51.46	—	—	—
		2	54.89	52.94	55.02	—	—	—
		3	58.21	57.37	60.87	—	—	—
		Ramp	36.72	35.26	41.62	—	—	—

TABLE 8

VOLUME RATES AT CURVE TEST SITE

LIGHTING LEVEL (FC)	RUN	DATE	TIME (PM)	VOLUME (VPH)	TRUCKS (%)
0.2	12	10/21/64	7:27-8:21	989	12.5
	16	11/ 2/64	6:02-6:56	1638	11.2
	20	11/10/64	6:06-7:02	1661	10.5
0.6	38	1/ 6/65	7:21-8:14	1093	10.2
	34	12/21/64	6:06-7:00	1507	11.6
	31	12/15/64	5:49-6:59	1639	11.5
Day	42	5/26/65	5:14-6:12	2107	8.5

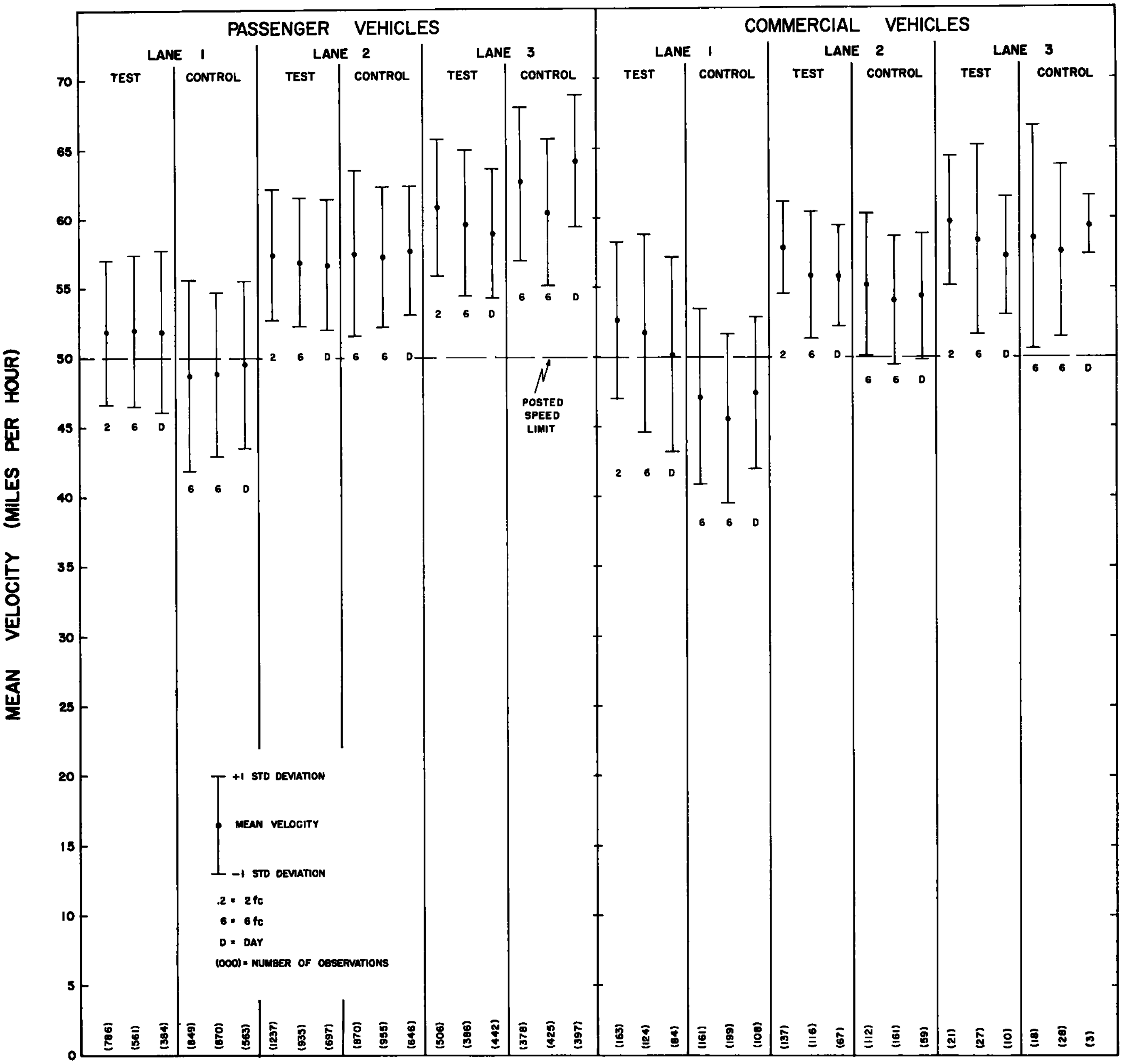

Figure 15. Mean velocity by lane by vehicle type and lighting condition at tangent sites.

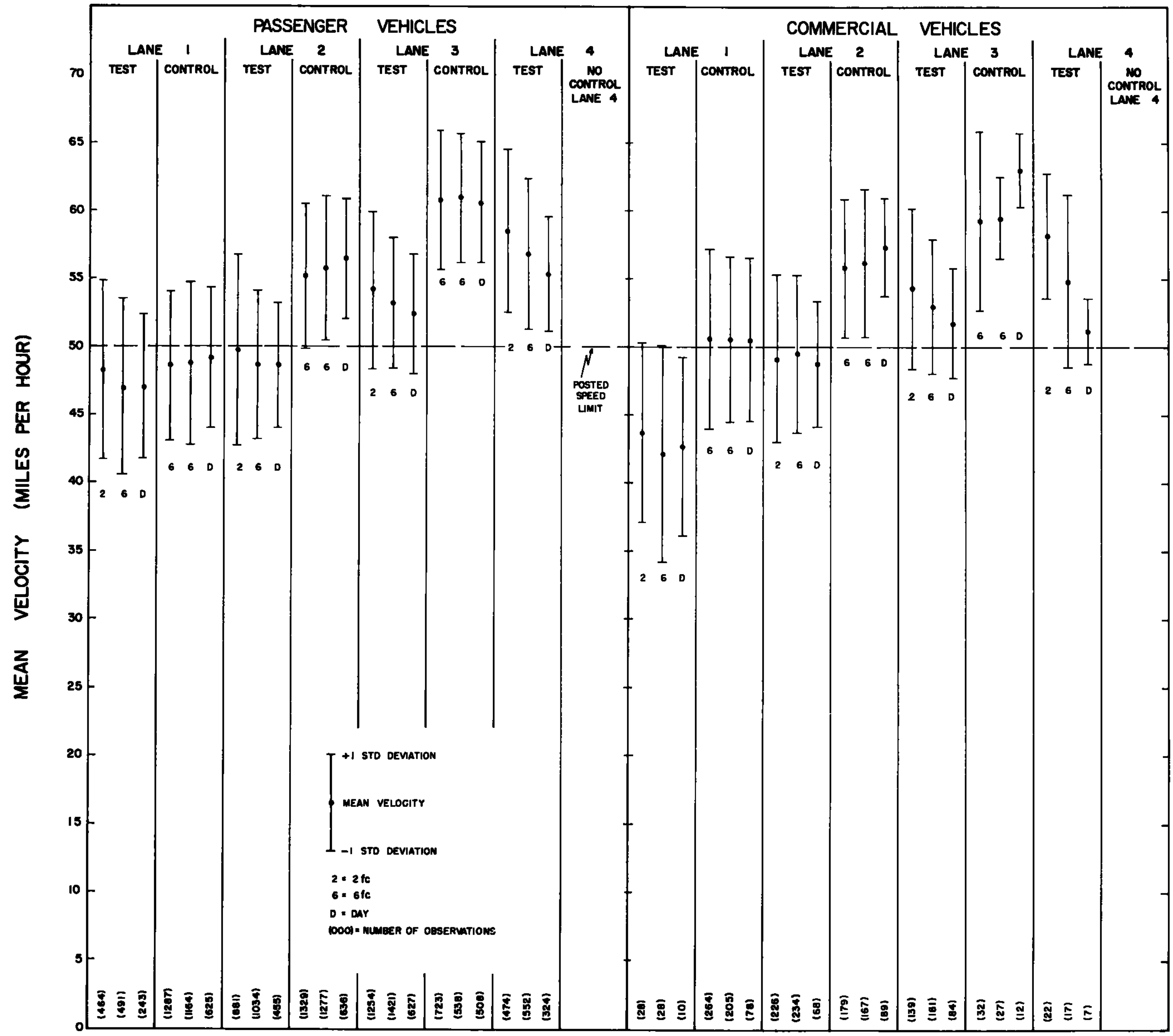

Figure 16. Mean velocity by lane by vehicle type and lighting condition at curve sites.

for both passenger and commercial vehicles. At the tangent and curve control sites and at the off-ramp and on-ramp sites the daytime velocities tend to be higher than nighttime velocities, but in only nine instances (lanes 2 and 3 at the on-ramp) do the differences between nighttime and daytime velocities for passenger vehicles exceed 2.0 mph on any of the through lanes.

The differences between day and night velocities for commercial vehicles on the ramp lanes at the on-ramp and off-ramp sites are based on fewer than 15 observations and are not statistically significant. (Less than 3.0 percent of the vehicles on either ramp are commercial vehicles.)

When comparing daylight velocities to nighttime velocities there is no pattern evident to suggest that daytime velocities more nearly represent the velocities under either of the two nighttime lighting conditions.

Variation in Velocity

The standard deviations of the velocity measurements at the six study sites are given in Table 9. The *F*-test for the ratio of variances was used to test the significance of the differences in the standard deviations before and after nighttime lighting changes (Table H-2).

Considering passenger vehicles only, there were no significant changes in variance at the tangent test site, three out of four lanes showed significant decreases at the curve test site, and two out of the three through lanes at the on-ramp test site showed a significant increase in scatter when the nighttime lighting was changed from 0.2 to 0.6 fc. Only one of the through lanes at the off-ramp shows a significant change in scatter. Clearly, there is no

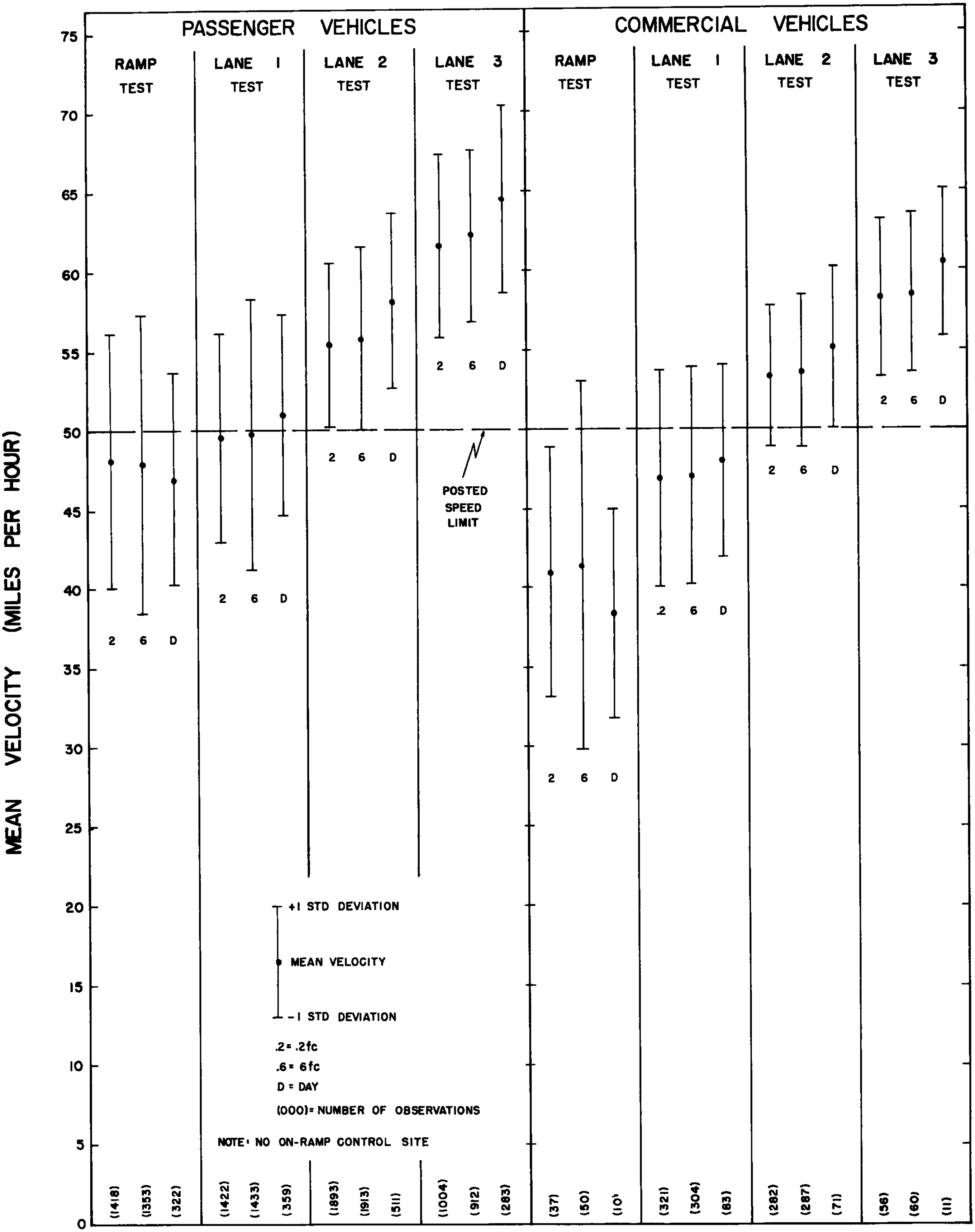

Figure 17. Mean velocity by lane by vehicle type and lighting condition at on-ramp site.

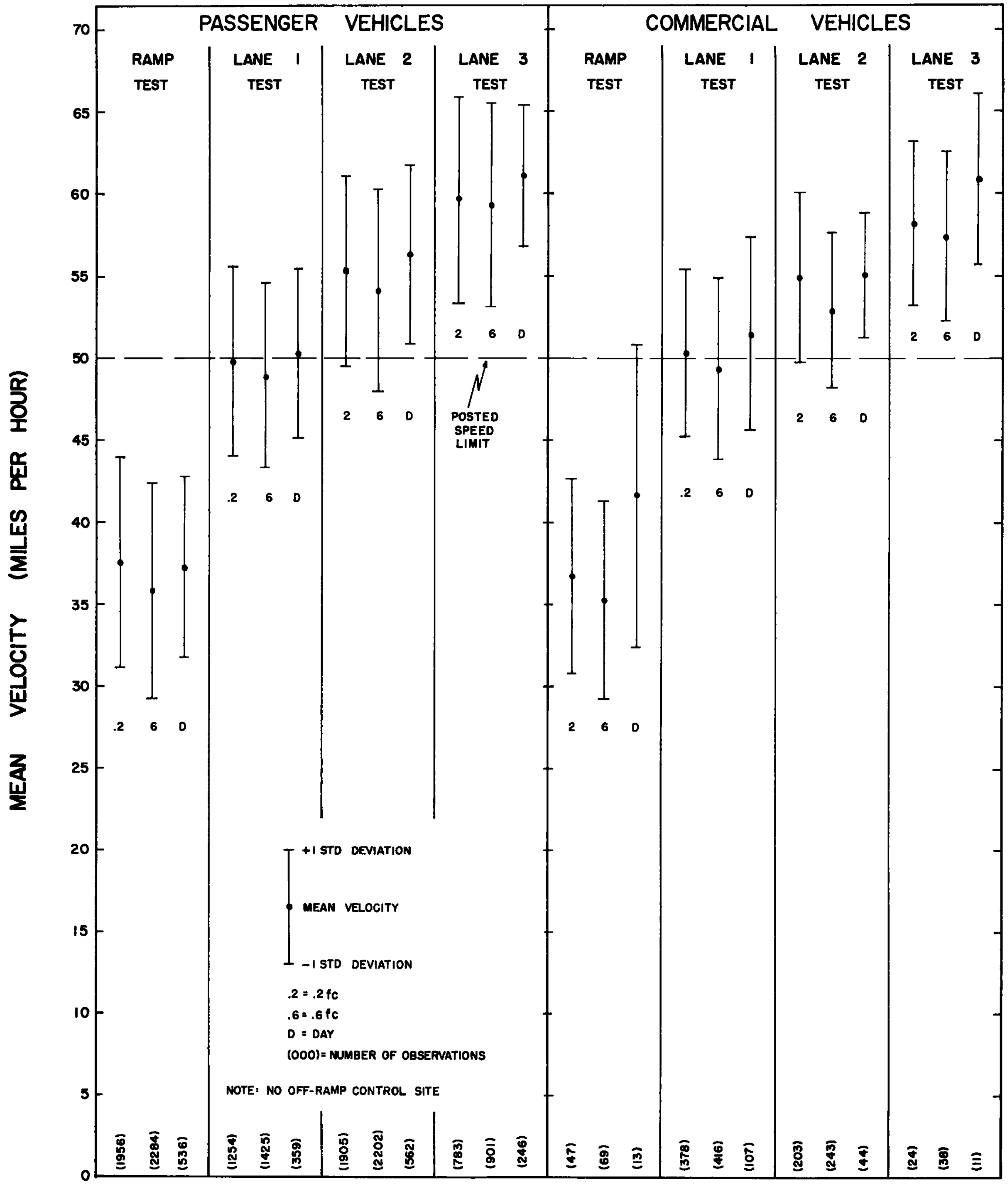

Figure 18. Mean velocity by lane by vehicle type and lighting condition at off-ramp site.

TABLE 9

STANDARD DEVIATION OF VELOCITY BY VEHICLE TYPE BY LANE BY LIGHTING CONDITION

SITE	VEHICLE TYPE	LANE	STANDARD DEVIATION (MPH)					
			TEST SITE			CONTROL SITE		
			0.2 FC	0.6 FC	DAY	0.2 FC	0.6 FC	DAY
Tangent	Pass.	1	5.22	5.44	5.80	6.87	5.88	6.00
		2	4.74	4.65	4.75	5.95	5.07	4.73
		3	4.88	5.28	4.65	5.79	5.25	4.68
	Comm.	1	5.62	7.10	7.00	6.23	6.06	5.42
		2	3.31	4.60	3.65	5.11	4.58	4.52
		3	4.64	6.77	4.26	8.00	6.14	2.11
Curve	Pass.	1	6.60	6.51	5.30	5.47	6.00	5.16
		2	6.99	5.43	4.57	5.32	5.30	4.39
		3	5.77	4.80	4.31	5.17	4.71	4.45
		4	5.98	5.54	4.22	—	—	—
	Comm.	1	6.61	7.97	6.59	6.63	6.07	6.01
		2	6.17	5.77	4.55	5.06	5.41	3.63
		3	5.89	4.90	4.01	6.58	3.03	2.72
		4	4.60	6.35	2.43	—	—	—
On-ramp	Pass.	1	6.59	8.50	6.36	—	—	—
		2	5.15	5.78	5.51	—	—	—
		3	5.73	5.43	5.83	—	—	—
		Ramp	8.08	9.47	6.74	—	—	—
	Comm.	1	6.87	6.83	6.05	—	—	—
		2	4.43	4.82	5.03	—	—	—
		3	4.94	4.95	4.62	—	—	—
		Ramp	7.93	11.62	6.63	—	—	—
Off-ramp	Pass.	1	5.73	5.63	5.16	—	—	—
		2	5.74	6.15	5.46	—	—	—
		3	6.30	6.16	4.32	—	—	—
		Ramp	6.42	6.58	5.51	—	—	—
	Comm.	1	5.10	5.50	5.86	—	—	—
		2	5.13	4.69	3.76	—	—	—
		3	4.96	5.13	5.20	—	—	—
		Ramp	5.96	6.05	9.20	—	—	—

pattern to the changes in the variation in velocity caused by the change in lighting at the test sites.

Only six of the comparisons for commercial vehicles at the test sites indicated a significant change between the two nighttime intensities of lighting. Four of the six comparisons show an increase in speed variation associated with an increase in lighting.

At the control sites the differences are again mixed. In all three lanes of the tangent the standard deviation for passenger vehicles decreased, and at the curve there is one observed increase and one decrease for passenger vehicles. With one exception, a decrease in lane 3 of the curve, commercial vehicles show no significant changes.

When comparing daytime to nighttime variances it will be observed that the variances are generally decreased during the daytime. For all runs and locations there are 31 instances in which the daytime variation in velocity is less, 7 in which it is greater, and 4 in which it lies between the nighttime values. In comparing nighttime variances only, it will be observed that the variations in velocities are randomly mixed (18 instances of greater variation at 0.6 fc and 12 of greater variation at 0.2 fc) in a difference which is not statistically significant. The daytime velocity variations are unrelated to the differences in the nighttime velocity variations.

Velocity Distribution Curves

A further comparison of the velocity distributions is shown in Figure 19 (tangent) and Figure 20 (curve). The cumulative frequency distributions of velocities by lanes for passenger vehicles only are compared at the two nighttime illumination levels.

It is evident from the curves that the level of nighttime illumination has little or no effect on the distribution of velocities about the mean. The differences in mean velocity are evident from the location of the curves, but the similarity in slope and curvature indicates that there is no tendency for a "bunching" of velocities under either level of nighttime illumination.

ANALYSIS OF HEADWAYS

The distribution of headways is a function of the rate of flow at which vehicles are passing a point. As the volume increases the likelihood of short headways increases, but extremely short headways (less than 0.5 sec) are not likely to occur within a lane because of the intervehicular interference between two vehicles in the same lane. In order to assess the influence of nighttime lighting changes on headways it is first necessary to determine the headways expected at the observed rate of flow. The deviation of the observed headway values from the expected values (as determined by the exponential distribution) was taken as a measure of the influence of nighttime lighting changes on headways.

Two tests were applied. In the first test all lanes were considered as one stream of traffic and the expected and observed headways as a function of the time a vehicle in any lane passes a given point in the roadway. In the second test each lane was separately analyzed and headways were accumulated by lane independent of the others. The results for the curve test site (run 16) are given in Table 10 and Figure 21.

The headways for the four lanes treated as one stream are based on a flow rate of 1,638 vph; the headways for the separate lanes of curve run 16 are based on the following flow rates: lane 1, 224 vph; lane 2, 479 vph; lane 3, 662 vph; lane 4, 271 vph. The expected headways are based on the relationship:

$$\text{Probability of a headway less than } t \text{ sec} = 1 - e^{-qt} \tag{1}$$

in which

e = base of natural logarithms;

q = flow rate, headways per sec; and

t = time, in seconds.

Although this relationship of expected headways does not exactly duplicate the observed headways, particularly for headways less than 2.0 sec, it provides a base from which to make comparisons. It was hypothesized that a change in artificial illumination would have a greater effect on small headways (less than 2.0 sec) and that the changes can be tested in this range of headway. It will be observed that for both stream and lane headways there are fewer observed than expected headways less than 1 sec and more observed than expected headways between 1.0 and 2.0 sec.

TABLE 10

OBSERVED AND EXPECTED HEADWAYS, CURVE TEST SITE (RUN 16)

HEADWAY (SEC)	STREAM		BY SEPARATE LANES	
	OBS.	EXP.	OBS.	EXP.
0-0.5	245	298.1	6	94.6
0.5-1.0	248	237.5	49	87.9
1.0-2.0	401	339.9	207	157.1
2.0-3.0	223	215.7	182	135.6
3.0-4.0	121	136.9	127	117.2
4.0-6.0	127	142.1	207	189.5
6.0-8.0	59	57.2	161	143.3
8.0-10.0	27	23.0	110	109.2
10.0-15.0	13	13.9	180	176.2
15.0-20.0	2	1.4	95	96.4
20.0+	0	0.2	138	155.1
All	1466	1466.0	1462	1462.0

Is there a relationship between the discrepancies in headways under 2.0 sec and the nighttime lighting condition? As the lighting intensity is increased are drivers more likely to follow at headways of 0 to 0.5 sec or 0.5 to 1.0 sec (thereby decreasing the discrepancy between observed and expected headways)?

The discrepancy was measured by calculating the value of the ratio [(Observed-Expected)^2/(Expected)] for each headway category. The sum of all such values, for all categories of a distribution, is, of course, the χ^2 value.

The discrepancies were arrayed in rank size order and tested by the Wilcoxon-Mann-Whitney test to see if there was a significant difference in ranking between those tests at 0.6 fc and those at 0.2 fc. As an example, consider the discrepancies in headways between 1 and 2 sec for the lane analysis at the off-ramp (Table 11).

TABLE 11

RANK DISCREPANCY IN HEADWAYS BETWEEN 1.0 AND 2.0 SEC AT THE OFF-RAMP

RUN NO.	LIGHTING INTENSITY (FC)	EXPECTED	OBSERVED	DISCREPANCY	RANK
19	0.2	181.07	245	22.58	1
10	0.2	166.93	232	25.37	2
40	0.6	175.70	248	29.75	3
35	0.6	226.22	310	31.03	4
30	0.6	230.46	333	45.63	5
23	0.2	259.63	376	52.16	6
14	0.2	235.45	352	57.69	7
28	0.6	382.63	582	103.88	8
41	Day	249.56	375	63.05	[a]

[a] Not included in rank-sum test.

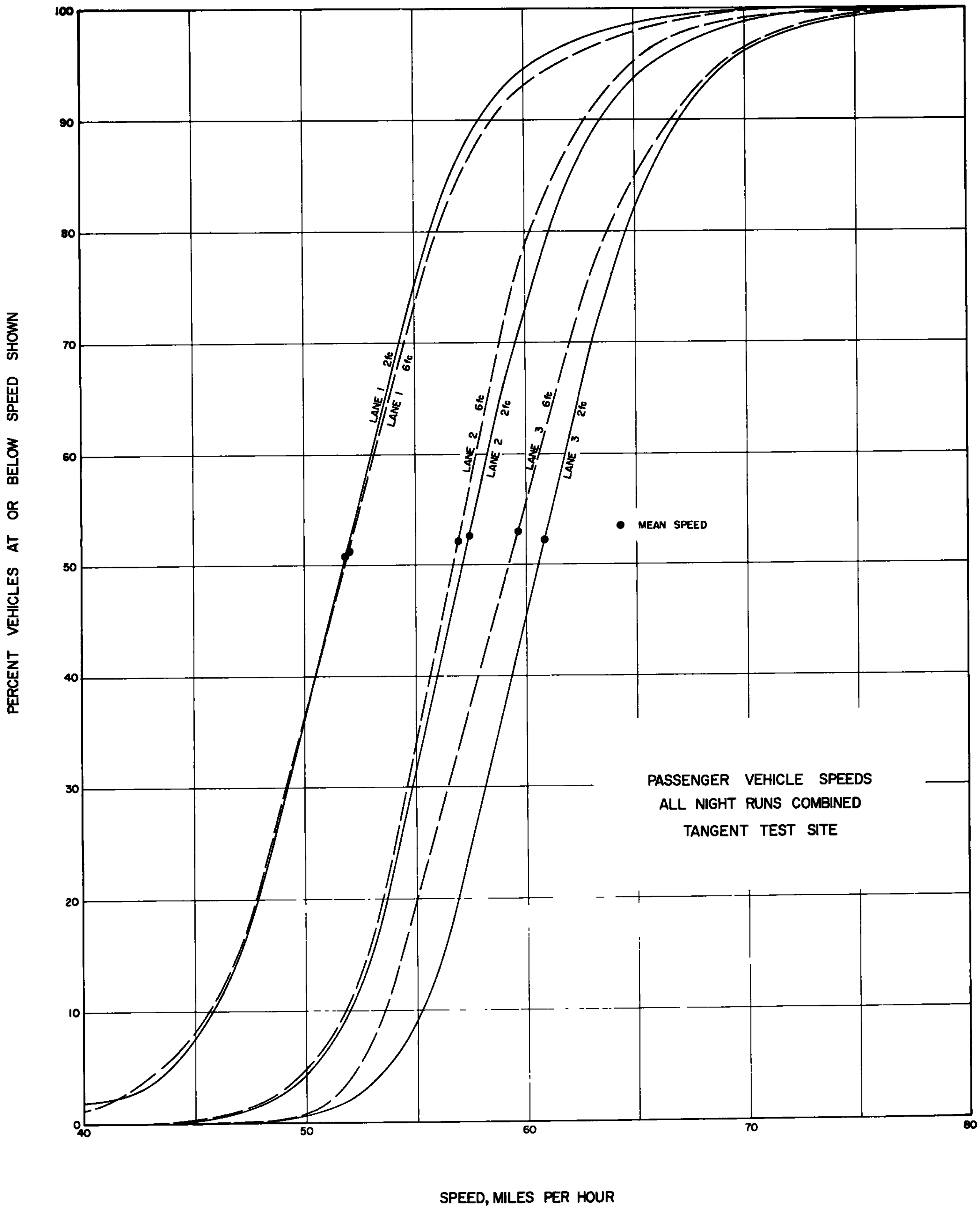

Figure 19. Cumulative frequency distribution—speed curves, tangent test site.

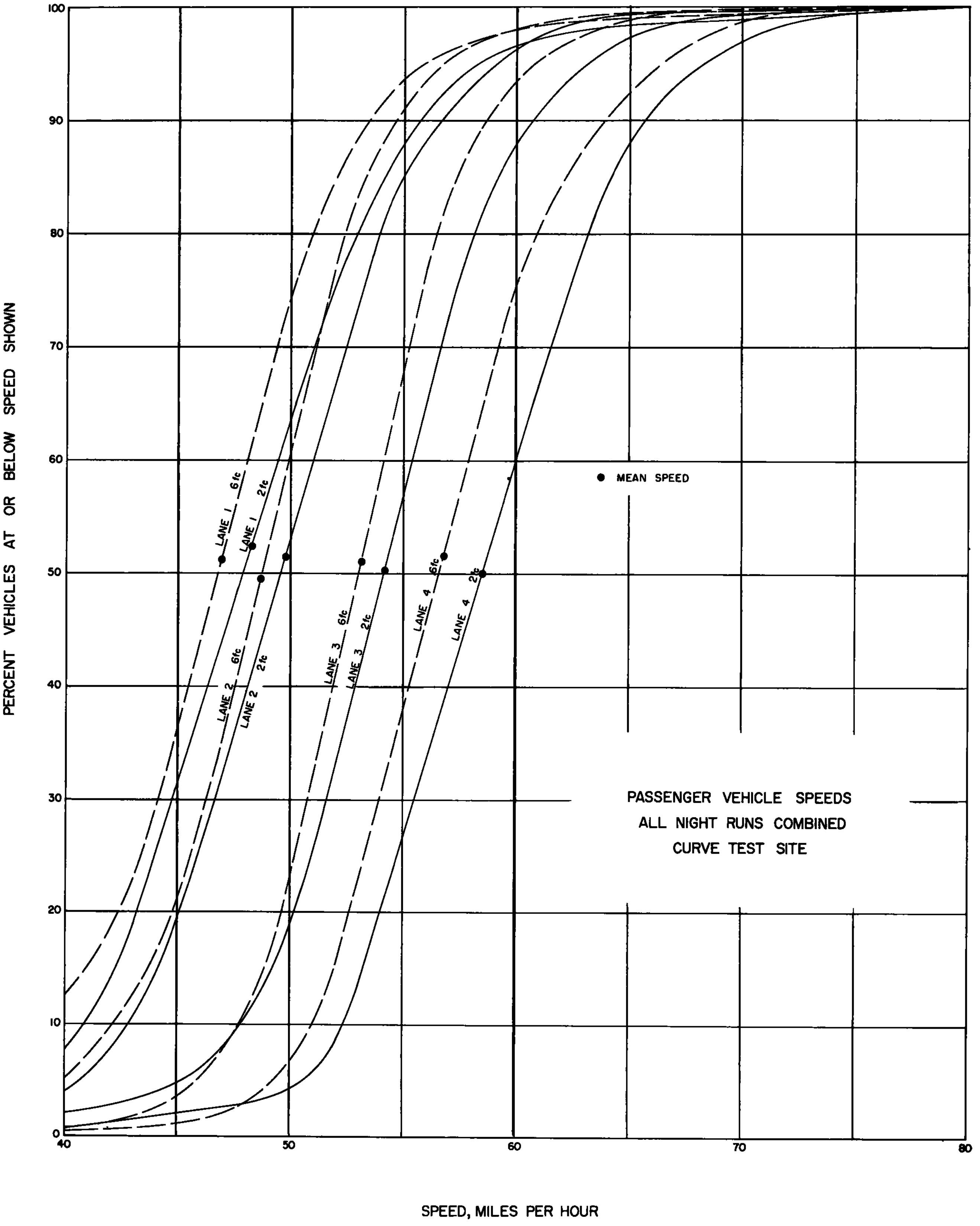

Figure 20. Cumulative frequency distribution—speed curves, curve test site.

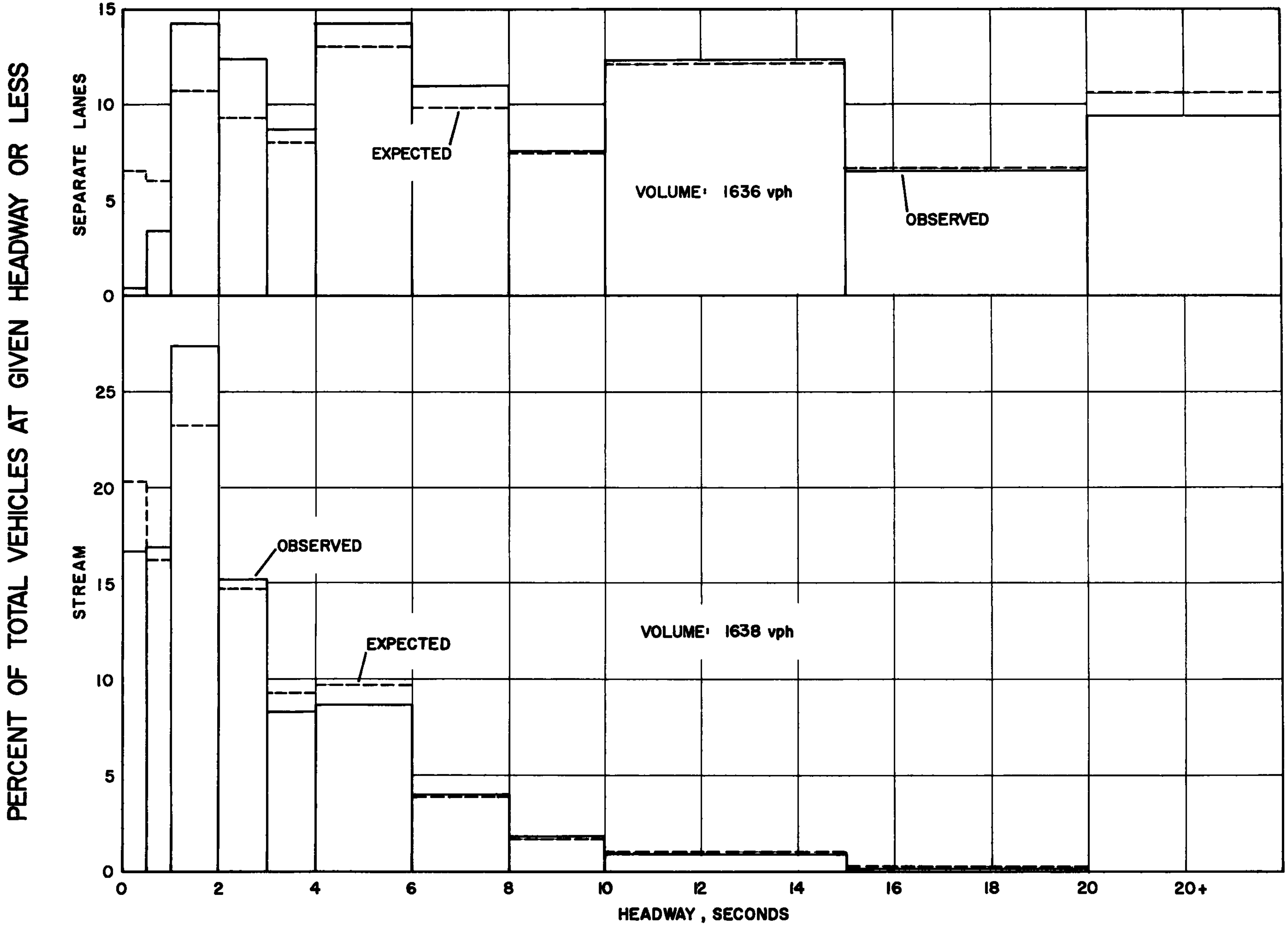

Figure 21. Distribution of observed and expected headways, curve test (run 16).

The Wilcoxon-Mann-Whitney test consists of totaling the ranks by category and testing the rank-sum against a probability table, in this instance:

	0.2 fc	0.6 fc
	1	3
	2	4
	6	5
	7	8
rank-sum	16	20

The rank-sums are not significantly different from what can be found by chance, so there was no basis for rejecting the hypothesis that the nighttime lighting has not influenced the discrepancies between expected and observed headways in the 1.0- to 2.0-sec range. If the low magnitude of discrepancy had been associated with 0.6 fc (i.e., ranks 1, 2, 3, and 4) the rank sum would have been 10 for 0.6 fc and 26 for 0.2 fc and the hypothesis that the lighting level and the amount of discrepancy are randomly distributed would obviously be rejected. This test was applied to the following groupings:

1. Four headway classifications:
    - (a) 0 to 0.5 sec.
    - (b) 0.5 to 1.0 sec.
    - (c) 1.0 to 2.0 sec.
    - (d) Sum of these three categories.
2. Two methods of calculating headway distribution:
    - (a) All lanes treated as one stream.
    - (b) Headways within lanes only.
3. Six sets of comparisons between lighting intensities:
    - (a) All 0.2-fc tests compared to all 0.6-fc tests (including control sites held constant at 0.6 fc).
    - (b) All 0.2-fc tests compared to all 0.6-fc tests, eliminating 0.6-fc control sites.
    - (c) 0.2-fc tangent test versus 0.6-fc tangent test.
    - (d) 0.2-fc curve test versus 0.6-fc curve test.
    - (e) 0.2-fc on-ramp site versus 0.6-fc on-ramp site.
    - (f) 0.2-fc off-ramp site versus 0.6-fc off-ramp.

This results in 48 comparisons (4 × 2 × 6) by the Wilcoxon-Mann-Whitney test. The significance levels are given in Table 12.

Except for one condition, stream headways at the tangent, there appears to be no relationship between intensity of the nighttime lighting and headway discrepancy. In the case of the tangent there are only two studies made at 0.6 fc and 3 at 0.2 fc and with this small sample it was not possible to state a likelihood of occurrence beyond the 0.20 level.

Table 13 contains the expected and observed stream headways for the daytime observations. Again the pattern of fewer than the expected number of small (0.0 to 0.5 sec) headways is evident at all sites in the daytime. The observed headways "bunch" more than the expected values in the 0.5- to 1.0-sec and 1.0- to 2.0-sec headway groups and occur less often than expected at the greater headways. This pattern is similar to that found for nighttime stream headways.

Stream Flow Characteristics vs Headway

Further tests were made to determine if the headway of vehicles had any effect on vehicle performance as related to headway. For purposes of this analysis it was arbitrarily decided that a 6-sec headway would be used as a measure of intervehicular influence. A 6-sec headway is the mean headway at a flow rate of 600 vehicles-per-hour, about the median flow rate for all lanes at all sites, and, at 55 mph, corresponds to a spacing of 484 ft. between vehicles.

The preceding and following headway of each vehicle was examined and the headway class determined. The categories, shown in Figure 22, were as follows:

GG = headway before and after greater than 6 sec;
GL = headway before greater than 6 sec, after less than 6 sec;
LG = headway before less than 6 sec, after greater than 6 sec;
LL = headway before and after less than 6 sec.

Mean velocities of passenger vehicles by lane and headway category for each site are given in Table G-1 and mean placements of passenger vehicles by lane and head-

TABLE 12

SIGNIFICANCE LEVELS OF LANE AND STREAM HEADWAY DISCREPANCIES

LIGHTING INTENSITY (FC)	LOCATION COMPARED	SIGNIFICANCE LEVEL [a]							
		WITHIN-LANE HEADWAY OF				STREAM HEADWAY OF			
		0-0.5 SEC	0.5-1.0 SEC	1.0-2.0 SEC	0-2.0 SEC	0-0.5 SEC	0.5-1.0 SEC	1.0-2.0 SEC	0-2.0 SEC
0.2 vs 0.6	All	NS	NS	NS	NS	NS	NS	NS	NS
0.2 vs 0.6	Test	NS	NS	NS	NS	NS	NS	NS	NS
0.2 vs 0.6	Tangent	NS	NS	NS	NS	0.20	NS	0.20	0.20
0.2 vs 0.6	Curve	NS	NS	NS	NS	NS	NS	NS	NS
0.2 vs 0.6	Off-ramp	NS	0.10	NS	NS	NS	NS	NS	NS
0.2 vs 0.6	On-ramp	NS	NS	NS	0.10	NS	0.20	NS	NS

[a] NS = not significant

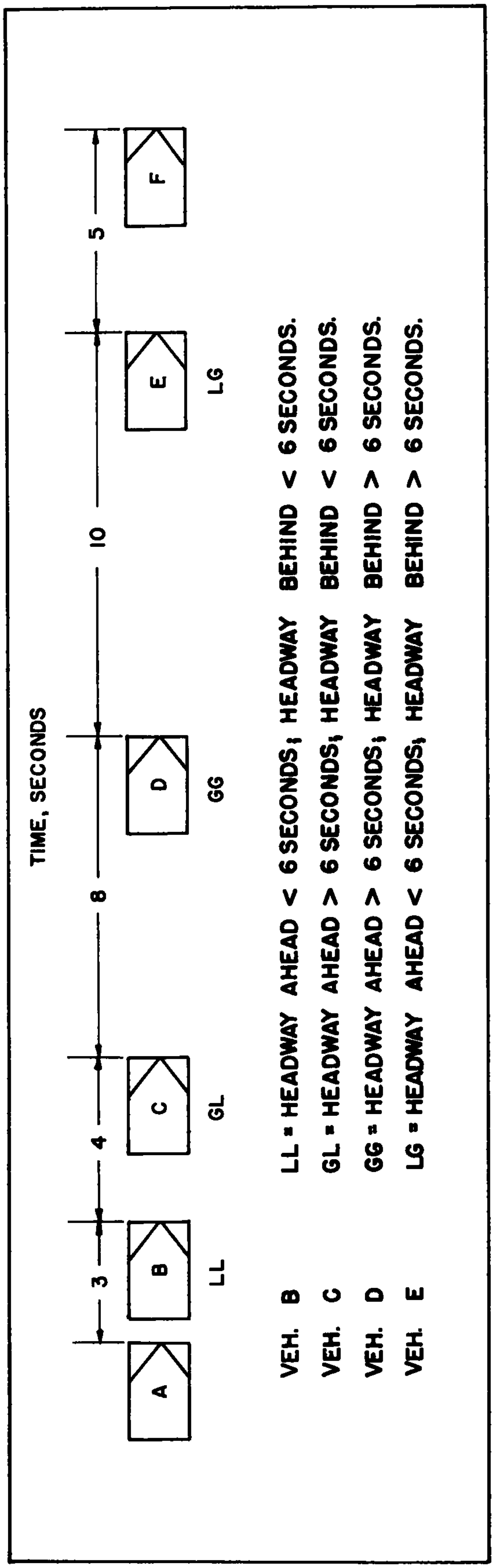

Figure 22. Definitions of headway categories.

way category in Table G-2. The velocities and placements by headway categories were examined to determine if there was any interrelationship between headway groups, illumination level, and stream-flow characteristics. Consider in detail the mean velocities of run 13 at the tangent test site by headway groups:

Lane	GG	GL	LG	LL
1	52.77	52.14	51.92	51.53
2	58.97	57.80	58.02	57.02
3	61.77	60.10	61.33	59.27

It is apparent that those vehicles with fore and aft headways greater than 6 sec have greater velocities than any other category of headway classification. Inspection will also show that vehicles that have headways both fore and aft which are less than 6 sec consistently tend to have the lowest velocities. A χ^2-test was applied to the rankings of the velocities by lanes to determine if the high velocities associated with headways greater than 6 sec occurred by chance alone. The hypothesis checked was that by chance alone a GG headway should be equally likely to rank 1, 2, 3, or 4. Similarly for categories GL, LG, and LL.

The same χ^2-test was applied to the hypothesis that ranks of placements were independently distributed when related to headway classification. The results are summarized in Table 14. It is evident that velocities are significantly different by headway categories but that placements tend not to be related to headway groupings as classified in this study.

It is evident that vehicles which have headways greater than 6 sec both ahead and behind tend to travel faster than vehicles that are in a platoon (LL) or vehicles leading a platoon (GL). Placements are not affected by the "free flow" of a vehicle, but rather appear to be independent of the type of gap which a vehicle occupies.

Because there was a relationship between headway category and velocity, a further test was made to determine if this relationship was related to the level of illumination. The hypothesis tested was that the distribution of velocity by headway groupings was independent of the three lighting levels (daylight, 0.6 fc, and 0.2 fc). The chi-square statistic was again used; the results are given in Table 15. At none of the locations was there cause to reject the hypothesis that lighting levels and velocities by headway groups were independently distributed. The level of illumination does not change the relationship between headway groups and velocity.

Inasmuch as placements were independent of headway groupings no further tests of this relationship were made.

DISTRIBUTION OF CAR-FOLLOWING PATTERNS

Related to the headway of a following vehicle is the pattern of type of vehicle related to the preceding vehicle. Do trucks tend to cluster in groups when lighting conditions change? A contingency table, based on observed following patterns, was used to determine the clustering effect. As an example, consider the observations at the curve control site, run 16, as given in Table 16.

A total of 1,360 vehicles, the great majority of them

TABLE 13

EXPECTED VS OBSERVED HEADWAYS IN DAYLIGHT

	TANGENT				CURVE							
	TEST		CONTROL		TEST		CONTROL		ON-RAMP		OFF-RAMP	
HEADWAY	EXP.	OBS.	EXP.	OBS.	EXP.	OBS.	EXP.	OBS.	EXP.	OBS.	EXP.	OBS.
0.0-0.5	453	448	465	412	494	410	561	478	393	387	494	450
0.5-1.0	333	432	365	414	374	395	416	494	295	391	374	441
1.0-2.0	464	510	473	564	496	644	538	630	429	550	496	585
2.0-3.0	272	221	278	243	286	279	297	263	256	218	286	262
3.0-4.0	161	111	159	146	161	122	160	123	160	93	161	122
4.0-6.0	151	120	147	113	144	108	136	114	152	87	144	102
6.0-8.0	51	39	49	53	47	41	42	41	60	39	47	42
8.0-10.0	17	20	18	9	14	18	13	12	22	8	14	12
>10.0	10	11	8	8	8	7	4	12	12	6	8	8

passenger cars, are following and being followed. Eighty-two percent (1,118/1,360) of the following vehicles are passenger cars and 12.2 percent (166/1,360) of the followed vehicles are trucks. If the vehicle following patterns are random it would be expected that the likelihood of a passenger car following a truck is equal to the probability of a following passenger vehicle (1,118/1,360) multiplied by the probability the followed vehicle is a truck (166/1,360). This likelihood (1,118/1,360 × 166/1,360) multiplied by the total following maneuvers (1,360) is the expected number of passenger cars following trucks if the pattern of following is random. The expected value becomes (1,118 × 166)/1,360, or 136.46, which can be compared to the observed 120. The expected following pattern for all types of vehicles is given in Table 17.

The chi-square values—(Observed-Expected)^2/Expected—for the following pattern are given in Table 18. This chi-square is significant at the 0.01 level, so the hypothesis of random following, based on the observed vehicle type, is rejected. The tendency of the trucks and buses to follow each other more than expected is the major cause for rejecting the hypothesis.

This chi-square test was applied to each run, and the chi-square values ranked in ascending order and compared by the Wilcoxon-Mann-Whitney test. There was no evidence that variation in vehicle following patterns are related to the change in nighttime lighting. There was evidence that the vehicle following pattern changes between sites. At the tangent and curve tests seven out of eleven following patterns were what would be expected by chance, one pattern was rejected at the 0.05 level, and three at the 0.01 level.

At the two interchanges, the on-ramp and off-ramp, trucks were under-represented in the ramp lanes and the patterns of following were not random in 14 out of 16 sets of observations; but, as previously noted, the relationship is independent of the lighting change.

Daytime vehicle following patterns also indicated a clustering effect for commercial vehicles. At five of the six study locations the variation from a random following

TABLE 14

CHI-SQUARE VALUES, HYPOTHESIS OF RANDOM RANK

		CHI-SQUARE VALUE	
LOCATION	LANE	VELOCITY	PLACEMENT
Tangent, test	1	24.10[a]	10.40
	2	30.95[a]	5.60
	3	36.90[a]	12.00
Tangent, control	1	34.05[a]	13.60
	2	31.30[a]	4.30
	3	16.80	10.40
Curve, test	1	8.56	25.43[a]
	2	38.93[a]	7.45
	3	30.29[a]	6.30
	4	25.71[a]	9.73
Curve, control	1	45.79[a]	30.27[a]
	2	43.49[a]	13.14
	3	11.99	14.29
On-ramp	1	28.83[a]	12.03
	2	31.55[a]	6.70
	3	40.33[a]	32.43[a]
	Ramp	27.12[a]	14.67
Off-ramp	1	52.03[a]	15.58
	2	42.24[a]	15.56
	3	13.80	15.12
	Ramp	45.75[a]	25.32[a]

[a] Significant at 0.01 level of probability.

TABLE 15

CHI-SQUARE VALUES, ILLUMINATION LEVEL SPEED BY HEADWAY GROUPS

LOCATION	CHI-SQUARE VALUE [a]
Tangent, test	18.70
Tangent, control	24.01
Curve, test	37.83
Curve, control	19.47
On-ramp	22.81
Off-ramp	9.91

[a] Chi-square (0.05) = 43.77; chi-square (0.01) = 50.89.

TABLE 16

OBSERVED VEHICLE FOLLOWING PATTERN, CURVE CONTROL SITE (RUN 16)

	VEHICLE TYPE, FOLLOWING			
VEHICLE TYPE BEING FOLLOWED	PASS. CAR	COM-PACT	TRUCK-BUS	TOTAL
Pass. car	938	58	121	1117
Compact	60	8	9	77
Truck-bus	120	10	36	166
All	1118	76	166	1360

TABLE 17

EXPECTED VEHICLE FOLLOWING PATTERN, CURVE CONTROL SITE (RUN 16)

	VEHICLE TYPE, FOLLOWING		
VEHICLE TYPE BEING FOLLOWED	PASS. CAR	COM-PACT	TRUCK-BUS
Pass. car	918.2	62.4	136.3
Compact	63.3	4.3	9.4
Truck-bus	136.5	9.3	20.3

TABLE 18

CHI-SQUARE VALUES[a] OF VEHICLE FOLLOWING PATTERNS, CURVE CONTROL SITE (RUN 16)

	VEHICLE TYPE, FOLLOWING		
VEHICLE TYPE BEING FOLLOWED	PASS. CAR	COM-PACT	TRUCK-BUS
Pass. car	0.425	0.313	1.726
Compact	0.172	3.176	0.017
Truck-bus	1.986	0.056	12.225

[a] Total chi-square = 20.096 with 4 d.f.

pattern was evident at the 0.01 level of significance. Only at the tangent control site was the following pattern the same as would be expected by chance.

MERGING

Behavior of Merging Vehicles

Three variables—percent merging, gaps accepted, and point of merger—were analyzed in comparing the merging behavior of vehicles at the on-ramp site. The geometry of the site (an added lane) permitted ramp vehicles to enter and continue on the Turnpike without interfering with through traffic, thereby limiting conflict between the streams of traffic. A summary of findings is given in Table 19 for the ramp lane and through lane 1, adjacent to the on-ramp.

Runs number 11, 15, 17, and 22 were made at a lighting intensity of 0.2-fc; runs number 27, 32, 37, and 39 at 0.6 fc; and run number 43 during daylight. The volume rates for the ramp lane and lane 1 are similar under the three conditions, as are the velocities observed during the nine runs.

It should be noted that the daylight filming at the on-ramp was not at the same location as that of the nighttime filming, but from a vantage point 125 ft closer to the gore. During all filming runs two cameras were in operation on the ramp. Because of a mechanical failure during the daylight filming, the camera located directly over the roadway on the sign bridge failed to function properly. As a result the ramp daylight data were analyzed from the alternate location, whereas all the nighttime data were analyzed from the sign bridge.

The analysis based on the alternate location had no effect on lane distributions, placements, or velocities. However, the behavior of merging vehicles was affected in terms of

TABLE 19

BEHAVIOR OF MERGING VEHICLES AT THE ON-RAMP

LIGHTING INTEN-SITY (FC)	RUN NO.	OBSERVATIONS		VOL. RATE (VPH)		MEAN SPEED (MPH)		MERGING VEHICLES		MEAN GAP ACCEPTED (SEC)	MEAN LOC. OF CROSS-ING (FT)
		ON-RAMP	LANE 1	ON-RAMP	LANE 1	ON-RAMP	LANE 1	NO.	%		
0.2	11	363	426	399	469	47.8	48.2	36	9.5	16.03	162
	15	329	456	381	528	47.8	48.9	29	8.9	14.30	150
	17	437	495	488	553	48.6	49.2	57	13.1	12.86	167
	22	463	487	521	548	47.4	50.1	66	13.7	11.97	164
0.6	27	494	543	561	617	46.8	48.0	76	14.8	10.78	167
	32	427	544	467	595	49.7	49.9	79	17.2	12.72	156
	37	304	379	346	431	47.6	49.5	25	8.2	17.68	147
	39	321	374	391	455	46.3	49.9	38	11.7	17.34	171
Day	43	359	457	455	579	46.6	50.4	9	2.5	10.76	262

the variables analyzed; namely, percent merging, gaps accepted, and point of merge. This is quite evident when comparing the results with the nighttime data in Table 19. Many ramp vehicles were, however, suspected of merging immediately beyond the alternate location, as indicated by the initial data. To extrapolate the point of merge of these vehicles by means of path projection would be erroneous because of the ramp geometry, existing traffic conditions, and individual desires and judgments. Therefore, the following analysis of merging vehicles is restricted only to those observed during the nighttime filming.

Comparisons of Percent of Merging Vehicles

The number of merging vehicles reported was the number observed changing from the ramp lane to through lane 1 at any point between the gore and the camera field of view 370 ft from the gore. Vehicles entering at the on-ramp site can continue in the entering ramp lane for 1,900 ft before the geometry of the site requires that they merge with the through traffic, so that the percentage changing is influenced primarily by traffic conditions in lane 1 and the drivers' own desires and judgments. Because volume rates and mean speeds were virtually similar at the two nighttime lighting intensities, the possibility exists that the number merging was a function of the lighting intensity. The results of combining the runs at the two different intensities are given in Table 20.

TABLE 20

COMBINED NUMBER OF MERGING VEHICLES AT THE ON-RAMP FOR BOTH INTENSITIES OF LIGHTING[a]

LIGHTING INTENSITY (FC)	ON-RAMP VEHICLES (NO.)	VEHICLES MOVING TO LANE 1	VEHICLES MERGING (%)
0.2	1592	188	11.8
0.6	1546	218	14.1

[a] Chi-square = 3.66 with 1 d.f. (nighttime values only).

The difference in percent observed changing lanes was not significant at the 0.5 level [$\chi^2_{0.90} = 2.71$; $\chi^2_{0.95} = 3.84$], indicating that the change in illumination did not influence the number changing lanes within 370 ft of the gore of the ramp.

Gaps Accepted by Merging Vehicles

As previously noted, merging vehicles were free to enter the through lane over a distance of 1,900 ft and observations were limited to the first 370 ft. The gaps accepted within this segment of the ramp are given in Table 21. (When more than one vehicle from the on-ramp merged into lane 1, only the gap of the last vehicle is considered, and the time was the time from the next to the last merging vehicle to the arrival of the next through vehicle in lane 1.)

There are no evident differences in the gaps accepted as related to the nighttime lighting conditions. When the studies are combined the results are as follows:

Lighting Condition (fc)	No. of Gaps	Mean Gap (sec)
0.2	131	13.4
0.6	119	13.2

The nighttime differences are minor and not significant.

Location of Lane Change

The point at which the center of each vehicle crossed the lane line between the ramp and through lane 1 (measured from the camera location 370 ft ahead of the gore) is given in Table 22.

TABLE 21

DISTRIBUTION OF ACCEPTED GAPS OF MERGING VEHICLES AT THE ON-RAMP

LIGHTING INTENSITY (FC)	RUN NO.	GAPS ACCEPTED (NO.) 0-5 SEC	5-10 SEC	10-15 SEC	15-20 SEC	20+ SEC	TOTAL	MEAN GAP (SEC)
0.2	11	1	8	4	5	8	26	16.03
	15	3	5	5	5	4	22	14.30
	17	4	13	6	10	6	39	12.86
	22	7	19	6	6	6	44	11.97
0.6	27	11	14	13	5	5	48	10.78
	32	2	13	3	7	3	28	12.72
	37	1	4	5	4	3	17	14.68
	39	3	5	4	5	9	26	17.34

TABLE 22

LOCATION AT WHICH RAMP VEHICLES MERGED INTO LANE 1

DISTANCE FROM CAMERA TO POINT OF MERGE (FT)	VEHICLES MERGING (NO.)								
	0.2 FC				0.6 FC				DAY[a]
	RUN 11	RUN 15	RUN 17	RUN 22	RUN 27	RUN 32	RUN 37	RUN 39	RUN 43
60-80	0	0	0	5	0	1	0	0	0
80-100	1	5	1	8	3	13	1	1	0
100-120	5	4	11	8	11	4	5	3	0
120-140	6	7	9	6	13	15	8	5	0
140-160	6	2	6	7	12	14	3	9	0
160-180	6	5	9	9	12	5	4	3	0
180-200	6	3	6	4	7	10	2	7	1
200-220	4	0	5	2	8	8	1	4	1
220-240	0	0	5	6	5	6	0	3	0
240-260	1	1	2	4	1	1	1	2	3
260-280	1	1	2	6	1	2	0	0	2
280-300	0	0	0	1	1	0	0	0	0
300-320	0	1	0	0	0	0	0	0	0
320-340	0	0	1	0	0	0	0	1	2
340-360	0	0	0	0	1	0	0	0	0
360-380	0	0	0	0	1	0	0	0	0
All	36	29	57	66	76	79	25	38	9
Mean	162	150	167	164	167	156	147	171	262

[a] Mean location for daylight data referenced to nighttime camera location.

The scatter is large, but the mean point of all lane-changing vehicles is nearly the same under both nighttime lighting conditions, as summarized in the following:

Lighting Condition (fc)	No. of Lane Changes	Mean Location (ft)
0.2	188	162
0.6	218	161

The difference is slight and not significant. The change in nighttime lighting had no apparent effect on the location at which merging drivers entered the through lane.

Comparisons of Vehicle Paths

Although a direct comparison could not be made of the mean crossing location between day and night, the possibility existed that the actual vehicle paths within the camera field of view are a function of the lighting condition.

Combining the runs at the two different nighttime intensities and comparing against daylight gives the results shown in Figure 23. In the daytime, at a distance of 360 ft from the overhead camera position, vehicles were observed to move closer to the left side of the ramp as compared to nighttime vehicles. This point is still on the ramp proper, where ramp and through lane continue to be separated by the painted gore. At a point 150 ft farther along the ramp (210 ft from the camera position) the mean path of the day observations is only slightly (0.2 ft) below the nighttime path at 0.6 fc, whereas the 15-percentile path (day) is midway between the equivalent paths observed at the two nighttime levels of illumination. Only at the 85-percentile path do the daytime observations continue to differ from nighttime observations, indicating slightly less variance in placement of daytime as compared to nighttime. The evidence suggested that the placement of vehicles within the acceleration lane is very similar day and night, but that in the daytime vehicles follow a path which is to the left of, and less scattered than the nighttime path when operating on the ramp. It is not possible to explain the differences observed at the point closest to the gore entrance; however, as the vehicles approach the merge point the differences are slight and unrelated to the level of lighting.

Summarizing the use of the on-ramp; the change in nighttime lighting had no significant effect on the percentage changing lanes, the gap accepted by the merging vehicles, or the point of entering the through lane. A comparison of vehicle paths on the ramp indicates that placement is very similar day and night, but that in the daytime vehicles follow a path which is left of and less scattered than the nighttime path.

EFFECT OF RAIN ON FLOW

Only one filming run was made during rain and wet weather. The data were collected at the tangent test site at 0.2 fc and the tangent control site at 0.6 fc. The mean and standard deviation of placement and velocity during rain are compared in Table 23 with the same variables, under the same lighting conditions, on dry pavement, at the same location.

At both the test and control sites under wet pavement

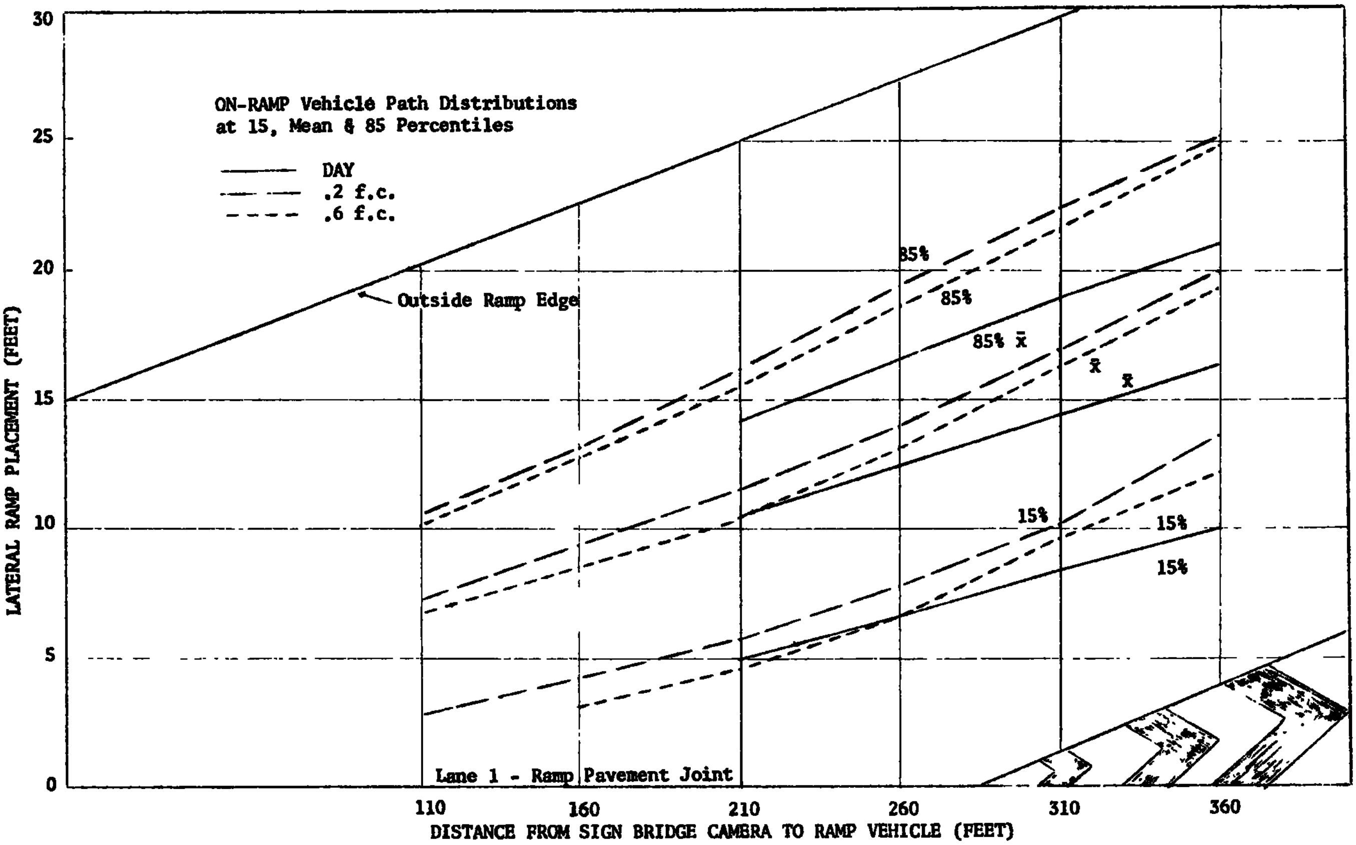

Figure 23. Lateral placement distributions related to lighting condition, on-ramp.

conditions there was a decrease in velocity and a tendency for the vehicles to move closer to the right-hand edge of the pavement. The changes in mean placement and velocity are greater because of rain than those observed because of the change in lighting.

The differences in mean placement are greater at the test site than at the control site, but there was a more pronounced change in mean velocities at the control site. Because it was not possible to run a similar "rain" test, with the test site lighted at 0.6 fc, it is difficult to draw

TABLE 23

EFFECT OF RAIN ON TRAFFIC FLOW AT TANGENT SITES BY VEHICLE TYPE AND LANE

				PLACEMENT (FT)				VELOCITY (MPH)			
				MEAN		STD. DEV.		MEAN		STD. DEV.	
SITE	ILLUM. (FC)	VEH. TYPE	LANE NO.	DRY	RAIN	DRY	RAIN	DRY	RAIN	DRY	RAIN
Test	0.2	Pass.	1	6.7	5.8	1.2	1.4	51.8	47.0	5.2	5.9
			2	19.0	18.3	1.2	1.4	57.4	52.1	4.7	5.0
			3	29.6	28.3	1.3	1.4	60.8	54.0	4.9	5.8
		Comm.	1	6.3	5.8	1.0	1.2	52.7	46.2	5.6	5.5
			2	18.8	18.4	1.4	1.3	57.9	51.5	3.3	5.2
			3	29.3	29.2	1.7	1.4	59.7	52.2	4.6	5.7
Control	0.6	Pass	1	6.9	6.4	1.3	1.5	48.8	41.7	6.9	5.2
			2	19.6	19.4	1.4	1.5	57.5	50.8	6.0	5.1
			3	30.6	29.8	1.6	1.4	62.7	54.0	5.8	5.3
		Comm.	1	6.6	6.6	1.3	1.4	47.1	39.4	6.2	4.8
			2	19.6	19.5	1.3	1.4	55.2	48.2	5.1	4.3
			3	30.5	30.1	1.4	1.8	58.5	51.7	8.0	4.7

conclusions from the observations. It may be that the "differences-in-the differences" are a function of the location or of the intensity of lighting, but further studies are required of lighting under bad-weather conditions.

ACCIDENT ANALYSIS

The possible effect of a change in lighting intensity upon the accident rate was determined by comparing the accident rates during the time interval of low-intensity lighting (0.2 fc) with the accident rate at the time of higher-intensity lighting (0.6 fc).

The Turnpike was divided into three geographical sections as follows:

1. West (27.6 miles)—milepost 0.0 (N.Y. State line) to milepost 27.57.
2. Test (4.1 miles)—milepost 27.57 to milepost 31.70 (limits of light change).
3. East (15.9 miles)—milepost 31.70 to milepost 47.62 (ramp to downtown New Haven).

The three geographical divisions, including the 4.1-mile test section, permitted evaluation of accident rates on different segments of the Turnpike, providing a control that would recognize effects peculiar to the test sites only.

Three natural lighting conditions were considered, (a) hours of daylight (from sunrise to sunset as determined from an almanac), (b) dusk (twilight period preceding sunrise or following sunset), and (c) night (the remaining hours of the day). Because the changes in artificial lighting will only affect nighttime accidents, the data for the other natural lighting conditions are included only to provide a control for isolating the effects of the changes on nighttime accident rates.

The historical data were divided into three time intervals (epochs), as follows:

1. Jan. 1, 1961 to Jan. 17, 1964—36 months—(0.6 fc).
2. Jan. 17, 1964 to Nov. 23, 1964—10 months—(0.2 fc, test section only).
3. Nov. 23, 1964 to Dec. 31, 1965—13 months—(0.6 fc).

Finally, the data were divided into six nearly equal two-month increments, reflecting (a) the dates of experimental changes, (b) "seasonal effects," and (c) changes in hours of darkness. The six time intervals were as follows:

1. Jan. 18 to Mar. 21 (63 days) (Jan. 18, date lighting reduced to 0.2 fc).
2. Mar. 22 to May 21 (61 days).
3. May 22 to July 10 (50 days).
4. July 11 to Sept. 11 (63 days).
5. Sept. 12 to Nov. 23 (73 days) (Nov. 24, date lighting returned to 0.6 fc).
6. Nov. 24 to Jan. 17 (55 days).

The total number of cells for the experimental design was: 3 (geography) × 3 (natural light) × 3 (epochs) × 6 (seasonal), or 162 possible entries. Because the change in lighting was conducted only during five of the six possible "seasonal" categories, the net number of data cells was reduced to 135.

For each of these cells the total of vehicle-miles was calculated and the total number of accidents was determined (Table 24). Only the total of accidents was considered, inasmuch as it was not possible to determine the separate number of vehicle-miles categorized by vehicle type, age or sex of driver, etc. The data on vehicle-miles and number of accidents are contained in Appendix A.

A Review of the Accident Rates

Table 25 summarizes accident rates on 47 miles of the Turnpike for the 5-year duration of the study. Consider the period Jan. 1, 1961 to Jan. 17, 1964, at which time the intensity of lighting was 0.6 fc. The overall accident rate is 1.00 accidents per million vehicle-miles. The test location has the highest accident rate (1.34 accidents/MVM) when considering total accidents over the three locations. For all locations, the nighttime accident rate (1.53) exceeds both the day (0.78) and dusk (1.35) accident rates.

Although the test section has day and dusk accident rates which are about 1½ times the mean for all locations, the night accident rate at the test section (1.87) is only about 22 percent more than the average night rate (1.53).

Table 25 further illustrates that during the 10-month period for which the lighting was lowered to 0.2 fc the overall accident rate increased to 1.19 accidents/MVM and then in the subsequent 14 months dropped to 1.09 accidents/MVM. Only during the hours of dusk is there a decrease in accident rates for the 10-month test period.

This overall increase in accident rate at all sites during the 10-month test period accounts for most of the increase in nighttime accident rates at the test site.

In the following statistical analysis, it was possible to consider only the effect of changing the lighting intensity from 0.2 to 0.6 fc. There was no information on nighttime accident rates in the absence of overhead illumination at the test location. Without this information it was not possible to determine if the relative improvement in the nighttime accident rate at the test location (as compared to day and dusk accident rates) was a function of the presence of illumination at night.

Statistical Analysis of Accident Data

Close scrutiny of Table 25 indicates apparent differences between accident rates east of, west of, and at the test section. Similarly there are differences in rates between day, night, and dusk, and between periods of the year. Are the differences significant as related to the level of nighttime illumination?

An analysis of variance test was applied to the accident data as follows. Consider the possible differential between accident rates averaged over day and dusk, and accident rates occurring at night. The *change* in this differential between the epochs before and after the test (averaged together) and the epoch of the test was investigated. In particular this *change* might be different during the summer and winter months, respectively. Further, to assure sym-

TABLE 24

ACCIDENT ANALYSIS, CONNECTICUT TURNPIKE

		DAY			NIGHT			DUSK		
LOCATION	TIME PERIOD [a]	ACCIDENTS	MILLION VEH.-MILES	RATE	ACCIDENTS	MILLION VEH.-MILES	RATE	ACCIDENTS	MILLION VEH.-MILES	RATE
(*a*) BEFORE LIGHTING INTENSITY REDUCED FROM 0.6 TO 0.2 FC (JAN. 1, 1961–JAN. 17, 1964)										
West of test section	1	138	118.90	1.161	109	53.51	2.037	44	25.12	1.752
	2	98	164.14	0.597	56	39.55	1.416	20	26.06	0.752
	3	90	168.08	0.535	35	30.47	1.149	12	21.80	0.550
	4	123	226.08	0.544	47	47.99	0.979	37	33.11	1.118
	5	107	180.84	0.592	110	81.24	1.354	70	34.90	2.006
	6	147	111.08	1.323	179	78.18	2.289	46	22.03	2.088
Test section	1	35	25.58	1.368	26	9.65	2.696	13	5.33	2.438
	2	31	34.41	0.901	18	7.02	2.563	5	4.89	1.023
	3	38	34.27	1.109	6	5.02	1.196	5	4.19	1.194
	4	31	46.57	0.666	2	7.92	0.252	4	5.98	0.669
	5	32	38.91	0.822	27	14.06	1.920	21	7.09	2.962
	6	52	24.84	2.094	27	13.16	2.052	23	5.14	4.471
East of test section	1	59	48.74	1.211	32	18.38	1.741	14	10.16	1.378
	2	59	65.33	0.903	11	13.33	0.825	4	9.28	0.431
	3	36	66.14	0.544	10	9.68	1.033	6	8.08	0.743
	4	67	91.44	0.733	11	15.54	0.708	1	11.72	0.085
	5	42	74.45	0.564	18	26.85	0.670	11	13.56	0.811
	6	38	47.18	0.805	35	25.00	1.400	12	9.77	1.228
(*b*) DURING TEST LIGHTING AT 0.2 FC (JAN. 18, 1964–NOV. 23, 1964)										
West of test section	1	58	46.25	1.254	53	20.75	2.254	22	9.74	2.259
	2	76	62.17	1.223	42	14.92	2.816	12	9.90	1.212
	3	46	65.05	0.707	23	11.97	1.951	8	8.84	0.948
	4	68	88.08	0.772	32	18.70	1.711	20	12.90	1.551
	5	56	69.40	0.807	54	30.94	1.745	11	13.39	0.822
	6	—	—	—	—	—	—	—	—	—
Test section	1	18	9.77	1.843	9	3 68	2.445	5	2.03	2.457
	2	18	12.83	1.403	7	2.61	2.685	2	1.82	1.098
	3	17	13.02	1.306	4	1.90	2.100	2	1.59	1.258
	4	15	17.89	0.838	2	3.04	0.657	6	2.30	2.614
	5	27	14.77	1.828	14	5.31	2.635	4	2.69	1.487
	6	—	—	—	—	—	—	—	—	—
East of test section	1	14	18.66	0.750	9	7.04	1.297	1	3.89	0.257
	2	10	24.56	0.407	17	4.99	3.407	1	3.49	0.287
	3	23	25.07	0.917	10	3.67	2.726	1	3.06	0.327
	4	25	35.19	0.710	8	5.98	1.337	6	4.51	1.330
	5	23	28.29	0.813	16	10.16	1.574	9	5.15	1.748
	6	—	—	—	—	—	—	—	—	—
(*c*) AFTER LIGHTING INTENSITY RESTORED FROM 0.2 TO 0.6 FC (NOV. 24, 1964–DEC. 31, 1965)										
West of test section	1	59	48.84	1.208	55	21.97	2.503	23	10.34	2.225
	2	33	67.67	0.488	30	16.24	1.848	9	10.74	0.838
	3	76	69.56	1.093	16	12.61	1.269	7	9.03	0.775
	4	63	95.24	0.661	33	20.25	1.630	12	13.96	0.860
	5	57	76.00	0.750	38	33.82	1.123	14	14.66	0.955
	6	91	77.44	1.175	113	54.49	2.074	28	15.34	1.826
Test section	1	9	10.26	0.877	13	3.88	3.353	7	2.15	3.260
	2	11	13.89	0.792	2	2.82	0.709	1	1.97	0.508
	3	10	13.82	0.724	5	2.02	2.473	4	1.69	2.371
	4	14	19.13	0.732	8	3.25	2 458	5	2.46	2.035
	5	17	15.83	1.074	5	5.69	0.879	3	2.88	1.041
	6	24	17.03	1.409	14	9.03	1.551	21	3.52	5.958
East of test section	1	13	20.19	0.644	13	7.63	1.704	6	4.22	1.420
	2	17	27.21	0.625	8	5.52	1.448	4	3.86	1.037
	3	18	27.45	0.656	6	4.02	1.494	1	3.35	0.298
	4	20	38.38	0.521	8	6.52	1.226	2	4.03	0.497
	5	17	31.39	0.541	8	11.27	0.710	2	5.71	0.350
	6	41	33.20	1.235	25	17.60	1.421	9	6.87	1.310

[a] Time period: 1 = Jan. 18 to Mar. 21; 2 = Mar. 22 to May 21; 3 = May 22 to July 10; 4 = July 11 to Sep. 11; 5 = Sep. 12 to Nov. 23; 6 = Nov. 24 to Jan. 17

TABLE 25

SUMMARY OF ACCIDENT RATES

			ACCIDENT RATE (/M VEH-MI)			
PERIOD	LOCATION	LENGTH (MI)	DAY HOURS	NIGHT HOURS	DUSK HOURS	ALL HOURS
1/1/61–1/17/64	West	27	0.72	1.62	1.40	1.00
	Test	4	1.07	1.87	2.18	1.34
	East	16	0.77	1.08	0.77	0.83
	All	47	0.78	1.53	1.35	1.00
1/18/64–11/23/64	West	27	0.92	2.10	1.33	1.20
	Test	4	1.39	2.18	1.82	1.58
	East	16	0.72	1.88	0.90	0.94
	All	47	0.93	2.06	1.29	1.19
11/24/64–12/31/65	West	27	0.87	1.79	1.26	1.13
	Test	4	0.95	1.76	2.80	1.32
	East	16	0.71	1.29	0.86	0.81
	All	47	0.84	1.68	1.35	1.09

metry in the analysis, the sixth time period was excluded from all epochs, before, during and after.

Accordingly, a full-dress linear (Gaussian) model was constructed to represent the (square root of the) accident rate in each observed subclassification. Briefly, a parameter β was introduced to measure:

1. The general mean (β_1).
2. Each of the two independent comparisons between the overall accident rates of "east," "west" and "test" (β_2, β_3).
3. Each of four independent comparisons between the five "season" results as a whole (β_4, β_5, β_6, β_7).
4. Each of the two independent comparisons between the "before," "test" and "after" accident rates β_8, β_9).
5. Each of the two independent comparisons between the overall accident rates during "day," "dusk" and "night" (β_{10}, β_{11}).
6. Each of the four "interactions" between the two effects measured under item 4 and the two measured under item 5 (β_{12}, β_{13}, β_{14}, β_{15}). In particular this becomes a measure of the change in accident rate as related to nighttime lighting conditions.

This produced a model with 15 parameters, one of which was a measure of the difference between the before-and-after accident differential and the test differential, where this "differential" represents the difference between the accident rates during the hours of daylight, dusk, and night, respectively. Clearly this difference (if really present) is a measure of the possible increase in nighttime accidents caused by reducing the lighting during the test period. Because of the likelihood that this increase would be different (i.e., larger) during the winter months a further (16th) parameter was added to measure this difference for season 1 (winter) only.

The analysis of variance indicated the following:

1. The difference in accident rates (day, night, and dusk combined) is significant.
2. There is a significant difference in the accident rates during the "seasons" of the year at all locations.
3. The difference in accident rates by location (east, west and test) is significant.
4. The difference in accident rates "before" and "after" the period of lighting at 0.2 fc is not significant, but the accident rate during the 10 months at 0.2-fc lighting is significantly different from the other two "epochs." This applies to day, dusk and night.
5. Finally, and most important, although the night accident rate in the test section (2.18) at 0.2 fc is higher than the night accident rate in the test before and after (1.87 and 1.76) the difference is *not* statistically significant. It will be observed in Table 25 that all rates, by lighting condition and location, went up during the 10 months of testing.

In reviewing the results of the accident analysis it is well to recall that there were only 36 reported accidents at the test section during the 10-month test interval. This is a very small sample from which to detect significant differences in accident rates. The relatively accident-free characteristics of the Turnpike make it difficult to detect significant differences in accident rates over a short time and distance as used for this analysis.

CHAPTER THREE

DISCUSSION OF RESULTS AND APPLICATIONS

Results have been presented for observations on the stream flow of a multilane limited-access roadway under two intensities of artificial illumination and during daylight. Analysis of lane use, placement within lanes, velocity by lanes, headway characteristics, vehicle following patterns, and the merging patterns indicated no great changes in these observed variables under any of the three conditions.

Examination of the accident rate at the two illumination intensities failed to indicate any relationship between accident rates and the changes in the artificial illumination.

Several observations can be made about the conditions under which the measurements were made, as follows:

1. The intensity of illumination varied from the maintained 0.6 fc to 0.2 fc, a change which was not readily detected by the human eye. It is possible that greater differences might be detected if a wider range in illumination, from no highway lighting to a level of 2.0 or 3.0 fc, were to take place.
2. The intent of the study was to make observations at the time the flow rate on the Turnpike was at its peak for dark hours. Even though observations were made as close to the evening rush hour as was permitted by the advent of darkness, the observed volume rates did not approach the capacity of the Turnpike. Hourly flow rates during the study ranged from a low of 989 vph at the curve test site to a high of 2,516 vph at the off-ramp site. The volumes were not high enough to provide sufficient information for determination of the highway capacity under the two lighting conditions. Thus, critical interactions between vehicles were at a minimum.
3. Although the volumes observed were not in the range of the critical capacity of the Turnpike, they were high enough to provide nearly continuous headlight illumination along the roadway. The average headways at the test sites ranged from a high of 3.7 sec at the 4-lane curve site to a low of 1.4 sec at the off-ramp site. At 55 mph (approximate mean speed), a vehicle travels about 80 ft/sec. At the lowest volume the average spacing between vehicles was about 300 ft, and at the highest volume about 112 ft. At these spacings, there can be little doubt that the headlights of the vehicles contributed to the illumination on the roadway. It may be that the influence of overhead roadway illumination is different when volumes are lower, because the vehicle headlights will have a lesser share in lighting the roadway as compared to the overhead illumination.
4. Another consequence of making observations during, or close to, the peak evening rush hour is the particular characteristics of the driver population being surveyed. How often do these drivers follow the same route under similar conditions? How familiar are they with the roadway, the ramps, and patterns of traffic? It seems logical that tourist traffic would be a small percentage of the traffic stream during the late fall months of the year. Does lighting have the same influence on commuter traffic that it has on a traffic stream of drivers less familiar with the roadway? A set of comparisons made at 10:00 PM may show results different from these made at 6:00 PM.

COMPARISON WITH TARAGIN-RUDY STUDY

Taragin and Rudy (*1*, pp. 21-22), in a study on the Connecticut Turnpike in 1958 and 1959, reported on observations of traffic operations as related to illumination and delineation. The studies were conducted at an on-ramp and an off-ramp located approximately 1 mile east of the east limits of this study.

An initial step of the present project was the review of the 1958-59 report for assistance in selecting sample sizes and study locations. A multivariate analysis of variance was made of the 1958-59 "raw" data obtained at the on-ramp. This analysis confirmed the findings of the authors, but indicated that fewer observations were required in order to establish significant differences in the observed variables.

The Taragin-Rudy study, made shortly after the opening of the Turnpike, included observations made at low volume rates (313 to 810 vph over all lanes). One purpose of the study reported herein was to make observations during conditions of higher volume (in the present study rates varied from 989 vph at the curve test site to 2,516 vph at the off-ramp site). To obtain these higher volumes it was necessary to select sites other than those chosen by Taragin and Rudy.

No consistent changes between day and night conditions by virtue of highway illumination or delineation were shown in the Taragin-Rudy study when considering average speed, placement, and headway. Similarily, in this study no consistent changes in the same three variables were related to changes in illumination, even though higher volumes were observed.

Taragin and Rudy reported that the nighttime use of the acceleration lane approached daytime use as illumination increased. In the present study no difference was observed in use of the acceleration lane under the two levels of artificial illumination or daylight; but it will be remembered that the geometry of the on-ramp did not require vehicles to merge into the through lanes for a distance of nearly 1,900 ft.

This study confirms the observations made by Taragin and Rudy on nighttime accident rates versus daytime accident rates within the Bridgeport area. In both instances it was found that the daytime accident rate within the Bridgeport area was substantially higher than the daytime accident rate over the entire illuminated section. Further, in both studies it was found that the nighttime accident rate within the study area compared favorably with the nighttime accident rate over the entire illuminated section. No estimate of expected accident rates without illumination is possible from the data available in either study.

In general, the present study, made at more locations, over all lanes, and at higher volumes, does not show any substantial differences from the conclusions of Taragin and Rudy.

APPLICATIONS

In order that the results of any study be applicable to a particular case or for a particular purpose, significant differences (of a practical nature) must be evident. As stated previously throughout the report, this was not the case. To apply the results of this study directly to the establishment of warrants and/or criteria for freeway lighting would be misleading.

Anticipated differences in operating characteristics were not forthcoming. Perhaps if a higher degree of illumination contrast, say from no overhead illumination to 2.0 or 3.0 fc, had been tested, the results might possibly be different and statistically significant. Further, the similarity of nighttime traffic characteristics to daytime traffic characteristics would suggest that the variables measured are not directly related to illumination levels.

Although the results obtained do not have an immediate application, it is believed that the methodology used in data collection, reduction and analysis is directly applicable to other problems. The procedures used will be of value to others wishing to apply time-lapse photographic techniques to traffic studies, and will tend to eliminate many of the cumbersome calculations and data reduction methods associated with this technique.

PART II

DRIVING PERFORMANCE

THOMAS H. ROCKWELL AND GLENN F. LINDSAY
SYSTEMS RESEARCH GROUP
DEPARTMENT OF INDUSTRIAL ENGINEERING
THE OHIO STATE UNIVERSITY

CONTENTS

PART II

DRIVING PERFORMANCE

SUMMARY

The second part of this report documents work completed by the Systems Research Group, Department of Industrial Engineering, The Ohio State University, under NCHRP Project 5-2. During this research the Systems Research Group joined other research agencies, together with the Connecticut State Highway Department, in a series of tests studying the effects of nighttime illumination levels on freeway traffic. The role of the Systems Research Group centered on the individual driver and his performance in controlling his vehicle under different nighttime illumination levels.

The tests were carried out on an illuminated section of the Connecticut Turnpike (I-95) near Bridgeport in November and December 1964 using volunteer local drivers. After familiarization with the vehicle, subjects were first tested under a reduced illumination level (0.22 fc). After the luminaires were returned to normal levels (0.62 fc) the testing on the same subjects was repeated. Subjects drove an instrumented vehicle equipped with an oscillograph recorder and sensors for velocity, steering, and gas pedal movements. Total testing time was about 2,400 min for all subjects, with data points available for each 0.5 sec when required by particular analysis. Testing was limited to the second lane from the median, and data for periods of car-following, lane changing, and entering and exiting were excluded. Analysis centered on driving data from 16 designated sampling zones along the test route; each zone was 1,000 ft in length and contained reasonably uniform geometric characteristics. Traffic volume in both directions was measured during test to relate headlight illumination effects.

Speeds were elected by the test subject and data for periods of containment due to car-following were deleted, so that elected speeds could be compared between the two lighting levels. It was found that under the normal lighting test subjects elected slightly higher speeds with significantly greater velocity variability than they did when the lighting levels were reduced.

Steering and gas pedal activity were measured in terms of control movements per 1,000 ft of highway, where a control movement is defined as change in the rate of movement (slope) of the steering wheel or gas pedal. Analysis of steering data showed that steering activity was essentially unaffected by the two lighting levels. Correlation between the steering measure and elected speed suggested that steering motions may be based on time as well as distance traveled, but conversion of the raw data to a time scale and subsequent analysis again failed to show any effect of lighting on steering activity.

Gas pedal movements, on the other hand, were found to be significantly affected by lighting level. Mean pedal activity was significantly reduced by the reduced lighting level, and variability in pedal activity also showed a decrease.

In general, subjects exhibited stable driving characteristics during all tests. This was evidenced by the lack of effect on velocity and control behavior, of horizontal curvature, traffic volume, lighting and cycle within the test period. Vertical curvature (as expected) did show significant effects on gas pedal activity and velocity

variance. Driving performance was much less affected by the lighting levels tested than by highway geometry. Neither the experimenter nor subjects could detect 0.22- to 0.62-fc level differences, and substantial lighting effects were not generally apparent from the data even when special analytic procedures were used to factor out geometry, traffic volume, and cycle effects.

Although evidence suggests that, if anything, lower illumination levels provide more stable performance (i.e., less velocity variability and less control movement), there are no present assurances that these measures have practical significant effects in highway safety and traffic flow. They represent the best measures possible under driver elected experimental conditions. Recent instrumentation at Ohio State now permits lane position measurement. Whether this would have been affected by the tested lighting levels is subject to speculation. One must also distinguish between what is statistically significant and that which is practically significant. This latter question is best measured by the traffic engineer rather than the human factors engineer.

Prior to the Connecticut tests, a set of small exploratory studies was conducted on Ohio test sites to study the effects of glare from oncoming vehicles on driver conrol activity. Daytime encounters were also tested for control purposes. Testing was limited to straight, flat, nonilluminated two-lane rural highways, where driver control movements were recorded for "open-road" situations as well as when headlights of oncoming vehicles were visible.

Control movement data for the steady-state (nonencounter) condition was examined for stochastic properties. This analysis led to the rejection of *a priori* hypotheses that control activity could be readily described as a Poisson process. Independence assumptions for the number of control movements in consecutive 3-sec intervals were also rejected, and autocorrelation coefficients of the order of 0.5 were found for both gas pedal and steering wheel activity with a time lag of 3 sec. The data did support hypotheses of independence between gas pedal and steering wheel movement.

Control activity during the encounter condition was examined for time-variate changes both before and immediately after encounters with oncoming vehicles. Distributions of control movements for time periods near the encounter were found to differ significantly from steady-state distributions. Although subject-to-subject variability was high, each subject showed some form of response to the encounter. In general, the data showed an increase in gas pedal activity and steering activity immediately before the encounter, whereas steering wheel activity tended to continue after the encounter. Driver corrective responses usually began 6 sec prior to encounter. Gas pedal activity resumed normal immediately after the encounter, whereas steering control (dither) continued for about 4 sec. This might be explained partly by light-dark adaptation.

CHAPTER FOUR

INTRODUCTION

Ever increasing importance is being given to highway safety in terms of modifications, improvements, and innovations of design and development procedures for modern expressways and peripheral hardware. Effective and efficient utilization of these new developments requires that concurrent and related information or theory be available to permit meaningful prediction of operational effectiveness prior to implementation. The cost and complexity of the modern expressway, together with rapid technological progress, have made traditional trial and error development of changes relating to highway safety impractical and in many cases unfeasible.

The alternative to evolutionary trial and error development is theory stemming from empirical records permitting some degree of methodical data-based assessment of the operating properties of proposed system changes prior to allocation and commitment of time and funds.

The research studies reported herein are addressed to such an objective. They represent initial investigations into relationships between the illumination of a highway and the performance of drivers using the highway.

Research in this area is new, important, and promising. Many data have been assembled about the effects of glare on the human eye, but very little is known about the impact of this glare on a driver's ability to control his vehicle. Recent and significant developments in photometry and visual measures permit assessment of the visibility of a distant object on a lighted expressway, but present theory does not allow relation of these luminaires to driving performance.

Growing support for studies of driver behavior has occurred only in recent years, permitting some advances in special areas. As is the case with many new and emerging areas of science, the frontier of knowledge is still at best spotty and any specialized investigation requires a considerable amount of basic research before practical questions may be approached.

The studies reported herein exemplify this situation. Studies of illumination and driving performance require (1) identification and specification of indicators of driving performance, (2) procedures and equipment to measure these indicators, and (3) methodology permitting meaningful and consistent reduction and analysis of these measures. Fulfilling these needs becomes of necessity an integral part of the research effort, and the content of these research results should accordingly reflect advances in the methodology and basic knowledge of the area as well as the specific topic under study.

Specifically, research into the effects of illumination on driving performance could be approached in a number of ways. Test subjects could be placed in a well-controlled environment in a laboratory and be asked to perform carefully designed tasks under different illumination levels. Although this approach offers a high degree of precise control over experimental variables (and more importantly over nonexperimental variables), its findings are valid only for the imposed laboratory conditions and may not be meaningful in an actual driving situation. Another possibility would use some analogue device to simulate the driving task. Here again, it is difficult to assume valid extrapolations and interpretations of research findings to real-world problems. One may continue along this scale, moving from a precise, simplified abstraction of the problem to the complexities of the problem itself, which occur on the road in daily traffic.

The approach taken by the Systems Research Group involves placing test subjects in an actual driving environment and recording their performance. In this way the abstractions imposed by the laboratory, the simulator, and the trafficless test track are avoided and performance recorded should be closely representative of that found in daily traffic. In general, the research approach taken should be a function of the interpretation one wishes to place on the results. The highway is obviously a poor place to study the general effect of illumination levels on human behavior, inasmuch as the many uncontrollable factors of traffic, motion, varying attention levels, etc., might fully obscure the effect of illumination. On the other hand, the highway is an advantageous place to study the effect of roadway illumination on driving performance, because in this instance one wishes to interpret research results in an on-the-road context leading to statements about *driving*.

The on-the-road approach to driving studies employed by SRG is made possible through several specially-constructed instrumented vehicles. Figure 24 shows the vehicle and recorder used in the illumination studies. A 1963 Chevrolet sedan was equipped with a 50-channel oscillograph recorder that produces continuous traces of signal inputs on 400-ft rolls of 12-in. photographic paper. This equipment has been used to record inputs such as vehicle dynamics (speed, vertical and horizontal acceleration), the driver's control activity (gas pedal, steering wheel, and brake pedal movements), headway and relative velocity with a leading vehicle, and lateral displacement. During experiments the vehicle travels as a self-contained instrument, with test subject driving and recorder and observer in the back seat. In this way, a driver's reactions and responses may be recorded as he drives on the highway in traffic with a minimum of bias or distraction imposed by the actual data-collection mechanisms.

The instrumented vehicle served as the major research tool to investigate the effect of overhead illumination on driver performance. The results of these studies form the content of Chapter Five, which is largely devoted to results obtained from data collected on the Connecticut Turnpike in November and December 1964, and Chapter Six, which reports a group of supporting studies performed in an investigation of driver response to nighttime encounters with oncoming vehicles. Supporting data are contained in Appendix I.

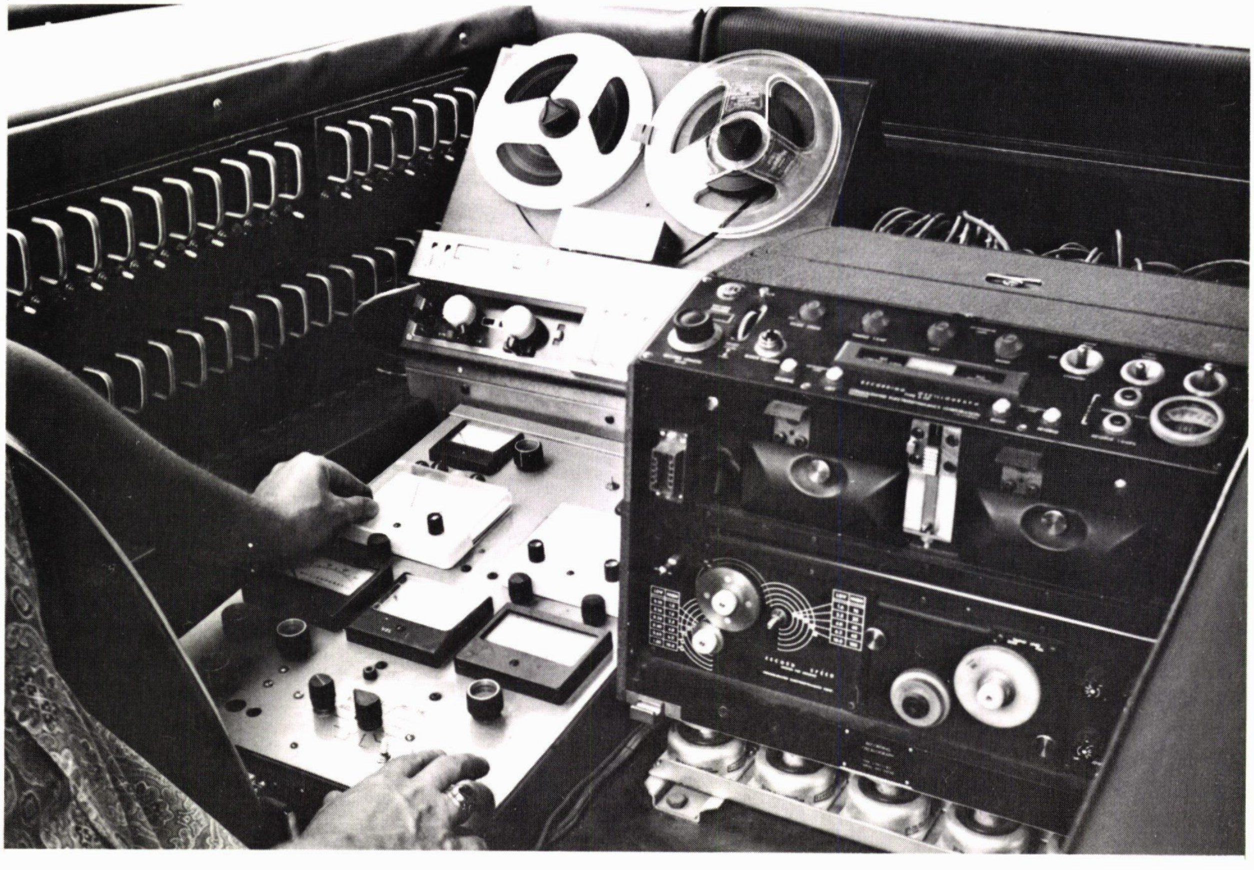

Figure 24. System Research Group's instrumented research vehicle (top) and oscillograph recorder (bottom).

CHAPTER FIVE

OVERHEAD ILLUMINATION AND DRIVING PERFORMANCE

The research into relationships between overhead illumination and driving has been the undertaking of several research groups working cooperatively with the Connecticut State Highway Department in the investigation of driver and traffic behavior on lighted sections of the Connecticut Turnpike. The problem was approached in several ways. The macroscopic viewpoint of the traffic engineer was taken by the Yale Bureau of Highway Traffic, which used time-lapse film techniques to obtain velocity profiles and headway distributions under different illumination levels (Part I). Motorists' attitudes were measured by questionnaires developed by The Institute for Research (Part IV). Ohio State's Institute for Research in Vision measured and analyzed such visual factors as disability glare on the Turnpike (Part III). The microscopic viewpoint concerning an individual driver's behavioral response was the concern of the Systems Research Group. It is the efforts in the latter area that are reported here.

The rationale for the study was straightforward. The Connecticut State Highway Department in early 1964 had dimmed the illumination on a section of the Connecticut Turnpike near Bridgeport, by lamp replacement yielding a nominal reduced lighting level of 0.22 foot-candles. Systems Research Group testing under this reduced illumination was completed during the week of November 16, 1964. During the following week (Thanksgiving) the luminaires were returned to the normal level measured at 0.62 foot-candles. Beginning November 30, 1964, and continuing through the first week in December, the ten experimental subjects that had driven under the reduced lighting were tested again under normal illumination. Analysis was to be based on a comparison of driving performance under the two lighting conditions.

Testing involved cycling over a section of the Turnpike extending eastward from the center of Bridgeport, and bounded on the east by the Stratford toll station. This area of Bridgeport is largely industrial, and the western part of the site varies between six and eight lanes elevated over the city. The Turnpike is illuminated by mercury-vapor luminaires suspended from posts on the shoulders. Traffic volumes are of the order of 68,00 vpd. Roadway geometry varies, and the test site includes several horizontal curves and many changes in vertical curvature. Figure 25 shows some of the salient geometric features.

CONNECTICUT TESTING PROCEDURE

While cycling between exits 25 and 32, subjects were instructed to drive in the second lane from the median, leaving this lane only when passing to avoid a car-following situation. Speeds were elected by the drivers. Two subjects were used each evening, and the subject not driving obtained a moving volume count of oncoming traffic. Drivers were changed after a coffee break midway through the 4-hr testing sessions. The ten test subjects were obtained from a national employment service, were both male and female, and ranged in age from 23 to 58.

For the Connecticut tests the Systems Research Group vehicle had been equipped by the Institute for Research in Vision with various photometers and flux integrators (see Figure 41, Part IV) permitting recording of directional glare and luminance levels while the vehicle was in motion. During the drive to the test site the nature of this equipment was briefly explained to the test subjects, who had been hired as "drivers and observers to assist in a traffic study." They served as "helpers" to the SRG experimenter, who remained in the back seat to operate the recording equipment. Inasmuch as the "purpose of the study was to measure glare and lighting," the requirements to drive in the second lane, avoid car-following (reflection), and count oncoming traffic were easily explained. This gentle deception was employed as an effort to reduce the experimental bias that is present in driving experiments, and to accordingly encourage subjects to drive as they normally would without directly instructing them to do so. Discussions with drivers after both phases of the experiment were completed indicated that this technique was successful.

Each subject at each test session was allowed to cycle twice around the site before actual data recording began. It was felt that this would permit familiarization as well as reducing transient effects.

During each cycle the experimenter used the recorder's stimulus marker to note periods of car-following, driving in other lanes, and other irregular events. Data from these periods were deleted from the analysis. Notations were also made of various landmarks on the site during each cycle. This allowed conversion of gas pedal, steering, and velocity traces from the time domain to a distance scale, permitting alignment with salient factors of roadway geometry.

The variations in roadway geometry which occurred on the test site had to be accounted for, because voiding data from periods of driver containment resulted in intermittent sampling along the route. Figure 26 shows the geometric variations schematically. Inspection of the geometric properties of the test site resulted in the selection of 18 sampling zones of 1,000 ft in length, each of which possessed reasonably constant geometric characteristics in terms of horizontal and vertical curvature. These are also shown in Figure 26. Analyses of the Connecticut tests were completed in terms of data from these sampling zones. (Data from zones 9 and 10 were influenced by transient driving conditions at the western terminal of the test site, and were not employed in the analysis.) This also permitted an

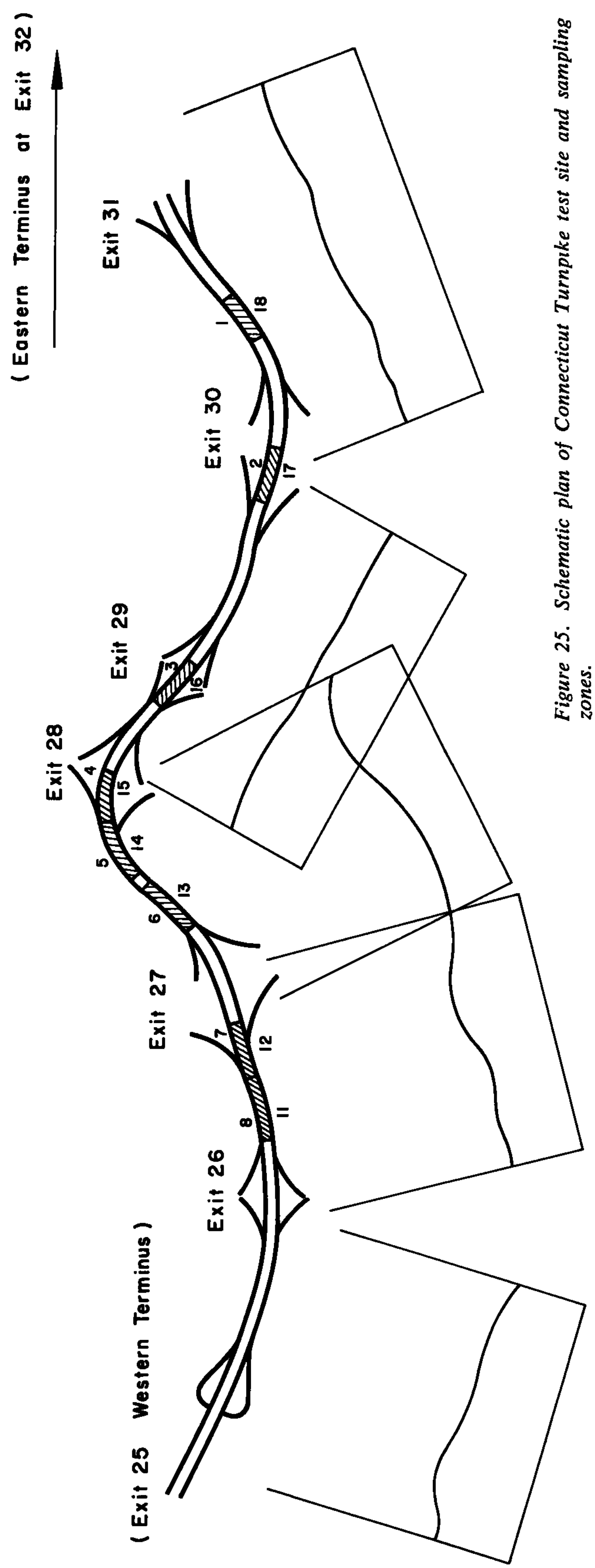

Figure 25. Schematic plan of Connecticut Turnpike test site and sampling zones.

analysis of driving performance on upgrades and downgrades as well as on level pavement.

Driving data for a given subject and cycle across a particular sampling zone represents one observation, for which the study measured and employed seven environmental or experimental variables, as follows:

1. Lighting level, recorded as reduced (first week's testing) or normal (second week's testing) and measured in foot-candles.
2. Subject and subject's age.
3. Cycle number for the subject and lighting level, as a scale for learning or transient behavior.
4. Oncoming traffic volume, in vehicles per minute, computed from the moving volume count adjusted for average test vehicle speed during the half-cycle.
5. Adjacent traffic volume, computed by averaging the oncoming traffic volumes of the preceding and following half-cycles. This provides a measure of the density of traffic in adjacent lanes.
6. Vertical curvature or grade, measured for the sampling zone in feet per 100 ft.
7. Horizontal curvature, measured for the sampling zone in degrees per 100 ft.

An example of the driving traces from the vehicle's oscillograph recorder is given in Figure 27. The gas pedal, steering, and velocity traces formed the dependent variables for the study. Analysis of the data in terms of these variables is reported in the following sections.

VELOCITY AND LIGHTING LEVEL

Elected Velocities

Driving velocities for the ten test subjects were recorded continuously during the trials. Data from periods of driving under nonelective speeds (such as car-following) were deleted, as were data during acceleration after entering, deceleration prior to exiting, and other perturbations. Reduction of the remaining data led to recording of the mean velocity during each 1,000-ft sampling zone as a measure of elected velocity. Thus, each data point should reflect that subject's elected speed for a given lighting level, replication, and set of geometric conditions.

Table 26 is a summary of the velocity data for all subjects and sampling zones. The over-all mean elected velocity of 50.98 mph pools trials under both lighting levels and is based on the total of 697 observations. This velocity data could be considered normally distributed, and the over-all standard deviation of 4.54 mph indicates that roughly 95 percent of all observations were between 42 and 60 mph.

Means and standard deviations of elected velocities for normal and reduced lighting levels are also given in Table 26. These results suggest that under reduced lighting levels subjects tended to drive at slightly lower but far more consistent speeds. The statistical implications that may be related to this statement are discussed in the following sections. If the data are assumed to be normally distributed, it is noted that approximately 95 percent of the elected speeds under "normal" lighting occurred between 41.2 and

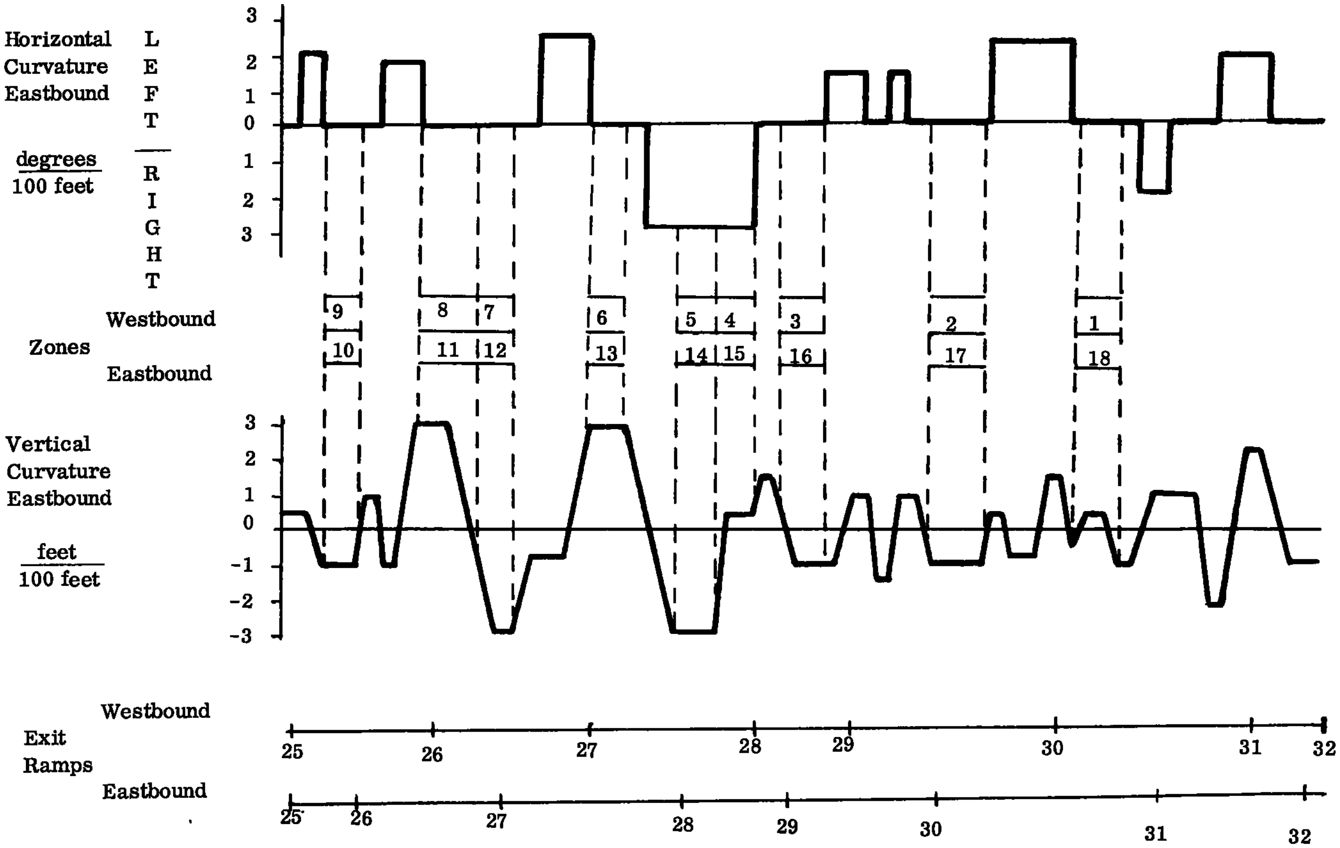

Figure 26. Connecticut Turnpike test site geometry and zoning.

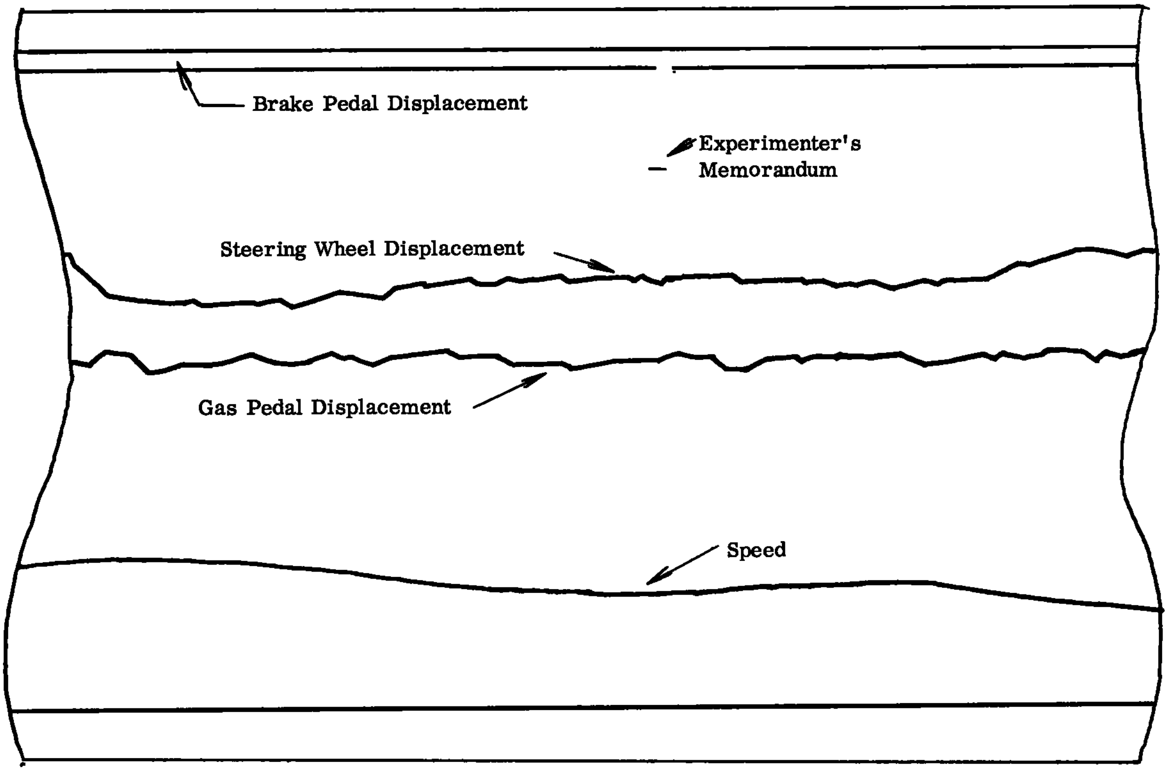

Figure 27. Example of oscillograph recording from Connecticut Turnpike test run.

TABLE 26

SUMMARY OF BRIDGEPORT NIGHTTIME VELOCITY DATA FOR ALL SUBJECTS AND ZONES

ITEM	VALUE
Mean velocity:	
All trials	50.98 mph
Normal lighting	51.48 mph
Reduced lighting	50.52 mph
Standard dev. of velocity:	
All trials	4.54 mph
Normal lighting	5.36 mph
Reduced lighting	3.56 mph
Correlation coefficients, all trials:	
Velocity—lighting level	0.105
Velocity—replication number	0.206
Velocity—highway grade	—0.144
Velocity—horizontal curvature [a]	—0.113
Velocity—subject's age	0.107
Velocity—adjacent traffic vol.	—0.089
Velocity—oncoming traffic vol.	—0.032

[a] Measured as an absolute value in degrees per 100 ft.

61.8 mph, whereas 95 percent of speeds under reduced lighting were grouped between 43.7 and 57.3 mph.

Table 26 also gives a number of over-all correlations between elected velocities and factors which partially describe the varying conditions under which the velocity was recorded. For example, the 0.206 correlation between replication and speed suggests that some subjects may have tended to drive more rapidly on each succeeding trial. This observation is explored in greater detail in a later section.

The correlation between velocity and lighting level is positive and small, as one would expect in view of the mean velocities previously noted. First-, second-, third-, and fourth-order partial correlations were computed to determine if a stronger, intrinsic relationship might exist between velocity and lighting level when other variables were held constant. Successive and cumulative exclusion of variation in adjacent traffic volume, oncoming traffic volume, horizontal curvature, and highway grade yielded first- to fourth-order partial correlations between velocity and lighting of 0.085, 0.093, 0.094, and 0.094, respectively, suggesting little change from the over-all correlation of 0.105.

Returning to Table 26, the negative correlation with highway grade reflects the tendency of drivers to allow increased speed on downgrades and/or reduced speed on upgrades. The negative correlation between horizontal curvature and speed is also unsurprising, as are the negative correlations with the traffic volumes.

Correlations as small as those given in Table 26 cannot be taken as evidence of underlying relationships in the data. These correlations do, however, suggest areas for further and more intensive investigations of the velocity data. For example, the very small correlations of velocity with traffic volumes in both directions suggest that serious errors are unlikely if traffic conditions are disregarded during subsequent work with the data. On the other hand, it would appear useful to undertake further study in terms of roadway geometry and replication number, for the correlation coefficients suggest this as fruitful ground. Accordingly, studies of velocity and lighting level as a function of roadway geometry are reported in the following. A later section describes the replication-to-replication effect on velocity under the two lighting levels.

Velocity, Lighting Level, and Highway Geometry

Effects of roadway geometry on elected velocities under the two lighting levels may be shown by investigating speeds in each of the sampling zones. Figure 28 shows elected velocities under normal and reduced lighting as a function of distance traveled since entering the Turnpike. Each point represents the mean velocity in that sampling zone for all subjects and replications under the given lighting level. Although a week separated testing under the two lighting levels, velocity patterns for the two test sessions were highly similar. That the eastbound pattern is not an inverted reversal of the westbound pattern suggests that velocities in the sampling zones may depend on roadway characteristics preceding the zone.

Mean velocities corresponding to Figure 28 are given in Table 27. The table also includes results of tests in each zone for significant differences between mean velocities under the two lighting levels. Of the 16 sampling zones, 2 showed statistical differences in mean velocity, and in both cases the difference was significant only at the 10 percent level.

Sample standard deviations of velocity for each lighting level and sampling zone are also given in Table 27, together with results of *F*-tests for significant differences in each sampling zone. As the table indicates, sample standard deviations for the two lighting levels tend to differ significantly in most of the sampling zones, usually at the 5 percent level or less.

The standard deviations are plotted against distance traveled in Figure 29. Here the similarity in pattern between the two testing sessions is again evident, and the difference in magnitude is substantial.

From the foregoing it is concluded that in general there was little difference in over-all mean velocity between the two lighting levels. Drivers did, however, display significantly more variation in electing their speeds under the normal lighting level than they did when the luminaires were dimmed.

Velocity, Lighting Level, and Replication

As was noted in Table 26, replication number had the highest over-all correlation with elected velocity among the seven environmental variables recorded. Replications (cycles) were numbered consecutively from one for each subject and lighting condition; thus, the correlation would suggest increasing elected speed with each cycle. It should be remembered, however, that the first replication in these data was actually preceded by two familiarization cycles during which data were not recorded.

Table 28 gives mean elected speeds for each replication

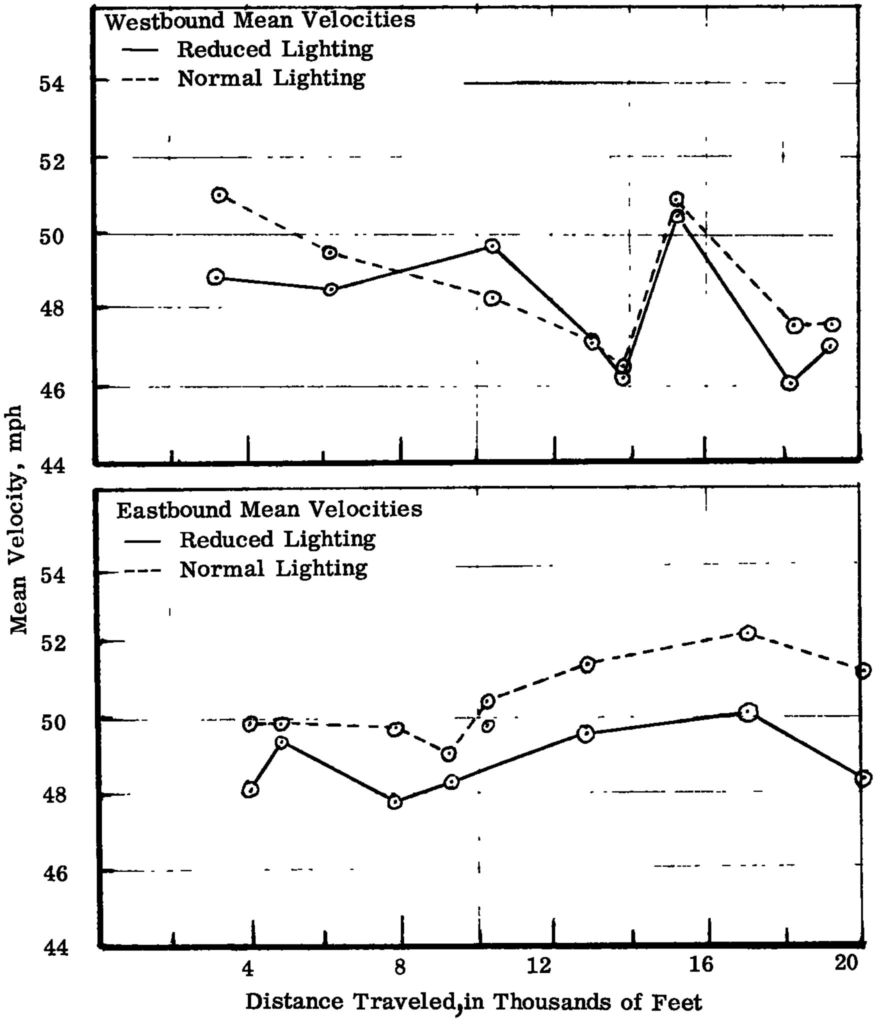

Figure 28. Mean velocities on Connecticut Turnpike test runs.

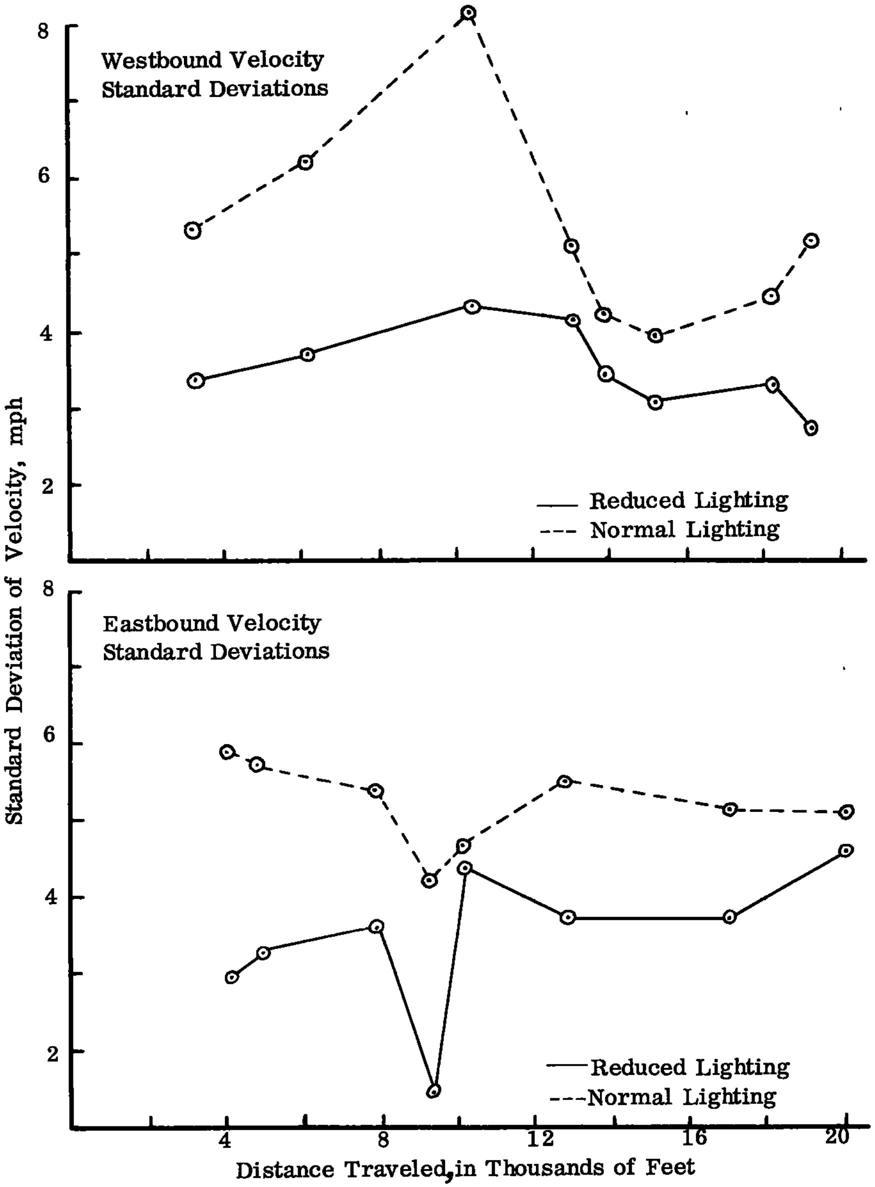

Figure 29. Standard deviation of velocities on Connecticut Turnpike test runs.

TABLE 27

VELOCITY MEANS AND STANDARD DEVIATIONS BY ZONE, WITH α-LEVELS FOR SIGNIFICANT DIFFERENCES DUE TO LIGHTING

		VELOCITY (MPH)					
		MEAN			STANDARD DEVIATION		
ZONE	GRADE	REDUCED	NORMAL	α	REDUCED	NORMAL	α
			(a) WESTBOUND				
1	−0.5	50.89	53.02	NS	3.34	5.40	0.050
2	1.0	50.60	51.55	NS	3.72	6.24	0.001
3	0.9	51.70	50.35	NS	3.38	8.22	0.005
4	−0.5[a]	49.37	49.19	NS	4.20	5.10	NS
5	3.0[a]	48.19	48.50	NS	3.45	4.23	NS
6	−3.0	52.99	52.64	NS	3.10	3.96	NS
7	3.0	48.16	49.63	0.100	3.31	4.47	0.100
8	−3.0	49.10	49.60	NS	2.76	5.17	0.005
			(b) EASTBOUND				
11	3.0	50.17	51.92	NS	3.00	5.99	0.001
12	−3.0	51.40	51.87	NS	3.32	5.76	0.050
13	3.0	49.78	51.70	NS	3.63	5.45	0.050
14	−3.0[b]	50.23	51.00	NS	1.50	4.26	0.001
15	0.5[b]	51.79	52.41	NS	4.43	4.77	NS
16	−0.9	51.55	53.36	NS	3.80	5.60	0.050
17	−1.0	52.16	54.18	NS	3.74	5.18	0.100
18	0.5	50.29	52.81	0.100	5.13	4.67	NS

[a] Combined with a left curve of 3° per 100 ft.
[b] Combined with a right curve of 3° per 100 ft.

under the two lighting levels. Means for 3 percent downgrades represent a pooling of sampling zones 6, 8, and 12; zones 7, 11, and 13 were combined for upgrade data.

The significantly higher speeds on downgrades as opposed to upgrades have been discussed earlier and are numerically clear in Table 28. Of special interest here, however, is the difference in pattern as a function of cycle. For both downgrades and upgrades the upward trend suggested by the correlation analysis is not evident under the reduced lighting condition. For the speeds elected under normal lighting, however, the trend is pronounced.

TABLE 28

MEAN ELECTED VELOCITIES BY REPLICATION ON 3 PERCENT UPGRADES AND DOWNGRADES

	REDUCED LIGHTING		NORMAL LIGHTING	
RELICATION	N	MEAN VEL. (MPH)	N	MEAN VEL. (MPH)
		(a) 3 PERCENT DOWNGRADES		
1	16	50.1	17	47.5
2	18	51.6	13	51.2
3	10	50.4	10	54.9
4	10	51.6	8	53.3
5+	14	51.4	4	56.7
		(b) 3 PERCENT UPGRADES		
1	16	48.9	16	46.6
2	17	50.4	11	49.8
3	14	48.6	11	54.0
4	12	50.4	10	51.3
5+	15	48.2	7	54.2

The data from Table 28 are presented graphically in Figure 30. Under normal lighting, speeds tend to increase through the third replication, after which there appears to be a leveling out. That speed changes concurrent with cycle number do not appear under the reduced lighting level is surprising when it is recalled that subjects drove under the reduced lighting first, driving under normal levels two weeks later. Accordingly, it seems unlikely that the increasing speed under the normal levels could be attributed to learning; i.e., familiarization with the vehicle and the test site. Learning effects would be expected to occur earlier in the study. In this case, however, subjects are found to be changing their speed very little during their first test session, and then returning to the site after essentially two weeks to begin at a lower velocity and rise on succeeding trials to higher speeds than they obtained before.

It is important that the over-all means and variances of elected speed discussed earlier be interpreted in the light of cycle variations. It was remarked earlier that there was no significant difference in mean velocities between the two lighting levels. Yet Figure 30 suggests (by extrapolation) that subjects would tend to drive more rapidly under normal lighting after the second cycle, and that the earlier failure to find a difference in mean speeds may have been attributed to low first-cycle speeds under normal lighting.

More important, the cyclic variations may explain the differences in standard deviations of speed which were found in both the over-all case and in terms of roadway geometry. Pooling cycles may well account for the large standard deviation under normal lighting.

Summary

The foregoing sections have described analyses of data on elected speeds for subjects driving under two lighting levels on the Connecticut Turnpike. Correlation of speed with variables describing the driving environment tended to be small, the largest being 0.206 between velocity and replication number and −0.144 between velocity and roadway grade. Over-all correlation between speed and lighting levels was 0.105.

When data for all subjects and replications were separated in terms of roadway geometry, it was found that subjects drove slightly but not significantly faster under normal lighting than under reduced lighting. Studies of sample standard deviations showed statistically significant differences between the two lighting levels, with the smaller variance in elective speed occurring under the reduced lighting condition. Analyses of replication-to-replication speeds indicate that the difference in variance may be partially attributable to subjects significantly increasing their speed on each of the first three cycles under normal lighting. Similar behavior did not occur under reduced lighting, where cycle-to-cycle variability was small and trends were not observed.

In general, then, subjects during the tests elected slightly higher speeds with significantly greater variability under normal lighting than they did when lighting levels were reduced. Extrapolation of the data on a time basis, however, suggests that higher speeds with reduced variability might occur under normal lighting if (a) additional replications had been attempted, or (b) a test site of greater length had been employed.

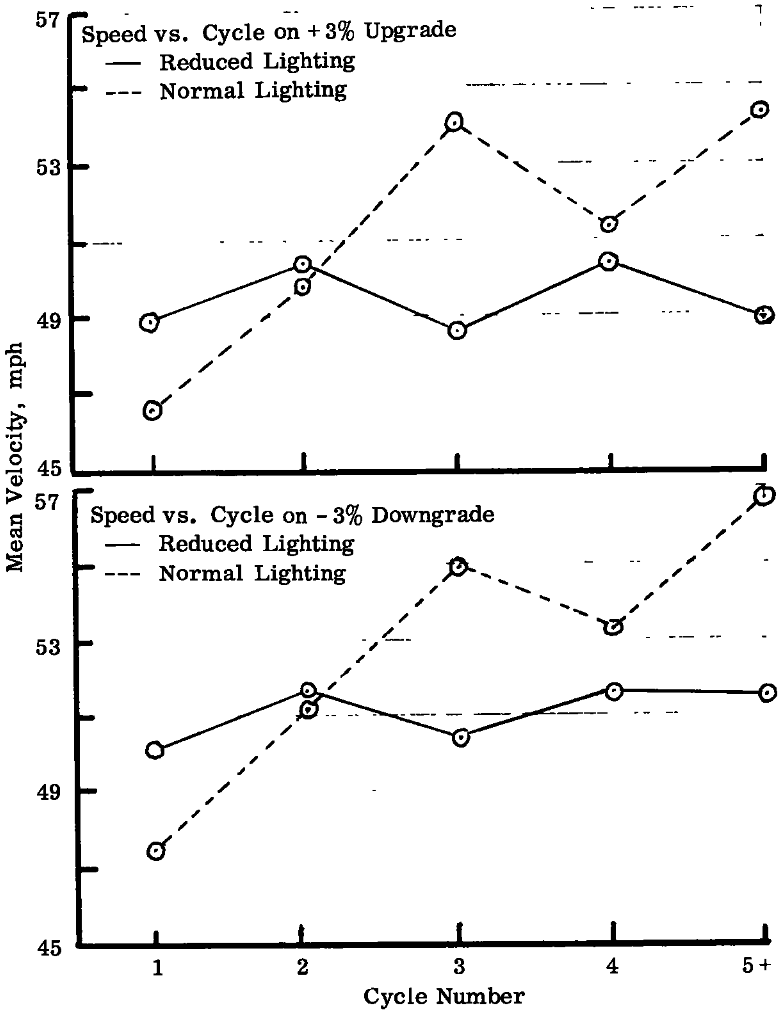

Figure 30. Speed vs cycle on grades on Connecticut Turnpike test runs.

STEERING CONTROL ACTIVITY AND LIGHTING LEVEL

Steering Wheel Control Movements

Steering activity during the Connecticut tests was initially measured in terms of the number of control movements per 1,000 ft of highway. A control movement is defined as change in the rate of steering wheel motion. Studies of many drivers have shown that plots or traces of steering wheel motion during freeway driving may be closely fitted by a series of connected straight-line segments, and each change in slope is counted as a control movement. Stated another way, the second derivative of a steering wheel trace appears as a series of spikes; steering activity is measured by the number of spikes per 1,000 ft of highway.

Steering activity was recorded for each subject, zone, lighting level, and replication during the Connecticut tests. Table 29 summarizes these data. When subjects, replications, and geometric zones are pooled there was no difference in either the mean or variance of steering activity between the two lighting conditions. Similarly, the computed correlation coefficient between steering activity and lighting level is 0.008. Partial correlations were also computed; successive and cumulative exclusion of adjacent traffic volume, oncoming traffic volume, horizontal curvature, and grade yielded −0.021, −0.032, − 0.034, −0.034, as first-, second-, third-, and fourth-order partial correlations, respectively, between steering activity and lighting level.

Table 29 also gives correlations between steering activity and variables partially describing the driving environment. The highest correlations occur positively with horizontal curvature and traffic volumes, as one would expect. As was the case with the velocity data, however, these correlations are too small to be meaningful in themselves.

Steering, Lighting, and Geometry

Mean steering activity for each sampling zone is shown graphically in Figure 31 as a function of distance traveled along the test route. Here again the patterns produced by the two lighting conditions are highly similar, although a week elapsed between the two week-long testing sessions. That roadway geometry may partially contribute to these patterns was suggested by the correlation between steering activity and horizontal curvature. Four of the sampling zones have nonzero horizontal curvature; zones 4 and 5 (westbound) include a left curve of 3° per 100 ft, and zones 14 and 15 (eastbound) a right curve of the same magnitude. Greater steering activity in or near these zones is indicated in the figures.

Analysis of the means in each of the sampling zones revealed no significant differences between steering activity under the two lighting levels. Table 30 gives the sample means, together with statistical results; none of the 16 zones showed a significant difference in mean steering activity due to lighting level.

The tables also gives sample standard deviations for the sampling zones. Here results of statistical testing tend to be mixed, although in general strong differences are not apparent. Of the 16 zones, 10 show no significant difference in steering variability and 4 show significant differences only at the 10 percent level. Zones 4 and 15 are across the median from one another on a long horizontal curve; both show differences in steering activity standard deviations at the 5 percent or better level (Fig. 32). One possible but incomplete explanation for the high steering variability in zone 4 might reflect the potential for oncoming headlight glare in this zone, as suggested by the test site schematic (Fig. 25). This hypothesis is supported by the correlation in Table 29 between steering activity and traffic volume, although left unexplained is the lower variance in zone 4 under reduced lighting and the high variability in zone 15 (which should have a low glare level in view of the angle of oncoming lights) under reduced lighting.

Another topic of particular interest with regard to steering behavior on the Connecticut test site concerns a possible relationship between steering and velocity. A study of cross correlations between variables designated as independent revealed a correlation coefficient for the data of −0.301 between steering activity and elected velocity. This indicates that steering movements per 1,000 ft decrease as speed increases, suggesting that steering activity might be measured more effectively in terms of time rather than distance. To explore this hypothesis, each steering observation was adjusted in terms of the concomitant velocity. This yielded a new body of steering activity data based on the measure of control movements per 10 sec. Figure 33 shows the zonal means for this measure. As was the case with the distance rate, no zones were found with significant differences between steering time rates under the two lighting levels. Also, comparison with Figure 31 shows highly similar patterns between the two measures, although the tendency on the part of the drivers to reduce speeds in zones 4 and 5 (see Fig. 28) is reflected in the time-based steering activity pattern in Figure 33. One consequence of this analysis should be a detailed evaluation of a time-based steering activity measure during future studies.

Summary

Analyses described in the preceding sections tend to indicate few differences in steering wheel activity between driving tests under the two lighting levels. Significant differences in mean steering activity (measured in control movements per 1000 feet of highway) between the illuminative conditions were not found in any of the sampling zones. The same results were obtained when the measure was changed to steering control movements per 10 seconds. Variability in steering rates showed only slight and inconsistent effect which might be attributed to lighting. The steering activity measure did not correlate highly with any of the environmental variables recorded in the study. A −0.3 correlation with velocity, however, suggests that steering wheel motions may be based upon time as well as distance traveled.

GAS PEDAL ACTIVITY AND LIGHTING LEVEL

Gas Pedal Control Movements

Inspection of the gas pedal traces recorded during the Connecticut tests showed that, as in the case of steering, the trace could be closely approximated by a series of straight-line segments. Accordingly, gas pedal activity was measured in the same manner as steering activity (i.e., in gas pedal control movements per 1,000 ft of highway. Table 31 summarizes the experimental data using this measure. Mean gas pedal activity differed considerably between the lighting conditions, with the lesser activity occurring under reduced illumination levels. Variability in gas pedal activity was also less under reduced lighting. Inasmuch as gas pedal activity best correlates with both lighting level and highway grade, statistical differences are examined in the next section.

First- through fourth-order partial correlations cumulatively eliminating the effect of adjacent traffic, oncoming traffic, horizontal curves, and grade were found to be 0.251, 0.257, 0.256, and 0.267, respectively. Of particular interest in Table 31 are the very low correlations between gas pedal activity and traffic volumes or horizontal curves. This is surprising, because one might expect, *a priori*, a rather high positive correlation between accelerator movement rates and adjacent traffic. Gas pedal activity and elected velocity during the study were found to correlate at 0.142 level, indicating little gain by converting the variables to a time scale.

TABLE 29

SUMMARY OF BRIDGEPORT NIGHTTIME STEERING WHEEL ACTIVITY DATA FOR ALL SUBJECTS AND ZONES

ITEM	VALUE
Mean steering activity:	
All trials	23.30[a]
Normal lighting	23.29[a]
Reduced lighting	23.31[a]
Standard deviation:	
All trials	6.50[a]
Normal lighting	6.64[a]
Reduced lighting	6.35[a]
Correlation coefficients, all trials:	
Steering activity—lighting level	0.008
Steering activity—horiz. curvature	0.189
Steering activity—oncoming traf. vol.	0.151
Steering activity—adjacent traf. vol.	0.109
Steering activity—replication No.	0.083
Steering activity—highway grade	0.034
Steering activity—subject age	0.028

[a] Steering wheel control movements per 1,000 ft of highway.

Gas Pedal Activity, Lighting, and Geometry

Mean gas pedal activity for each sampling zone under the two lighting conditions is plotted in Figure 34, which shows

TABLE 30

STEERING ACTIVITY MEANS AND STANDARD DEVIATION BY ZONES, WITH α-LEVELS OF SIGNIFICANT DIFFERENCES DUE TO LIGHTING

		STEERING MOVEMENTS (NO./1,000 FT)					
		MEAN			STANDARD DEVIATION		
ZONE	GRADE	REDUCED	NORMAL	α	REDUCED	NORMAL	α
			(*a*) WESTBOUND				
1	−0.5	24.50	24.07	NS	4.95	5.29	NS
2	1.0	21.50	22.83	NS	6.78	6.56	NS
3	0.9	22.89	23.18	NS	5.87	6.54	NS
4	−0.5[a]	28.38	26.78	NS	6.20	9.73	.025
5	3.0[a]	28.14	28.66	NS	6.64	7.53	NS
6	−3.0	25.36	28.28	NS	6.25	6.93	NS
7	3.0	22.43	25.81	NS	6.61	7.12	NS
8	−3.0	21.76	22.49	NS	5.98	6.79	NS
			(*b*) EASTBOUND				
11	3.0	22.20	21.90	NS	4.82	7.07	0.100
12	−3.0	21.24	19.42	NS	6.05	6.19	NS
13	3.0	21.85	21.81	NS	5.83	4.30	0.100
14	−3.0[b]	25.27	22.38	NS	7.55	5.81	0.100
15	0.5[b]	23.70	24.68	NS	8.32	5.15	0.050
16	−0.9	21.01	21.70	NS	5.19	6.60	NS
17	−1.0	20.77	17.90	NS	7.21	7.90	NS
18	0.5	22.00	20.71	NS	6.38	4.56	0.100

[a] Combined with a left curve of 3° per 100 ft

[b] Combined with a right curve of 3° per 100 ft

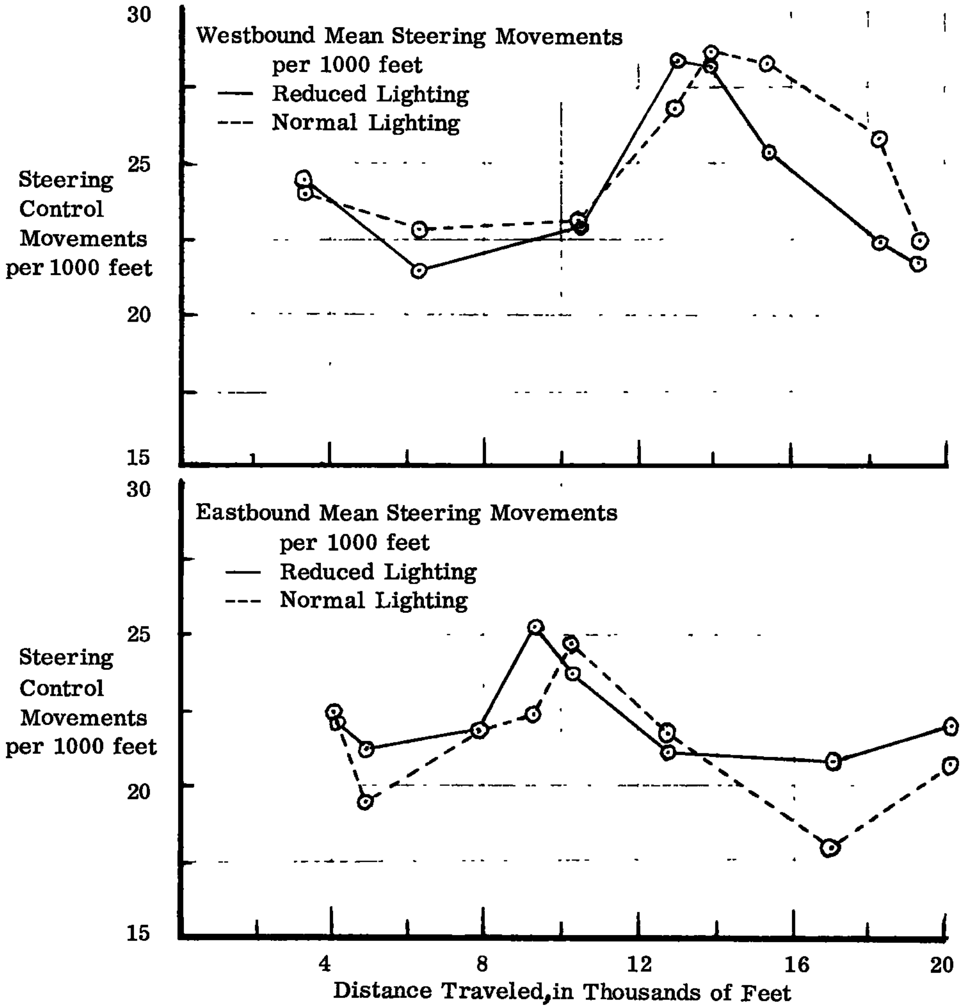

Figure 31. Mean steering control movements per 1,000 ft on Connecticut Turnpike test runs.

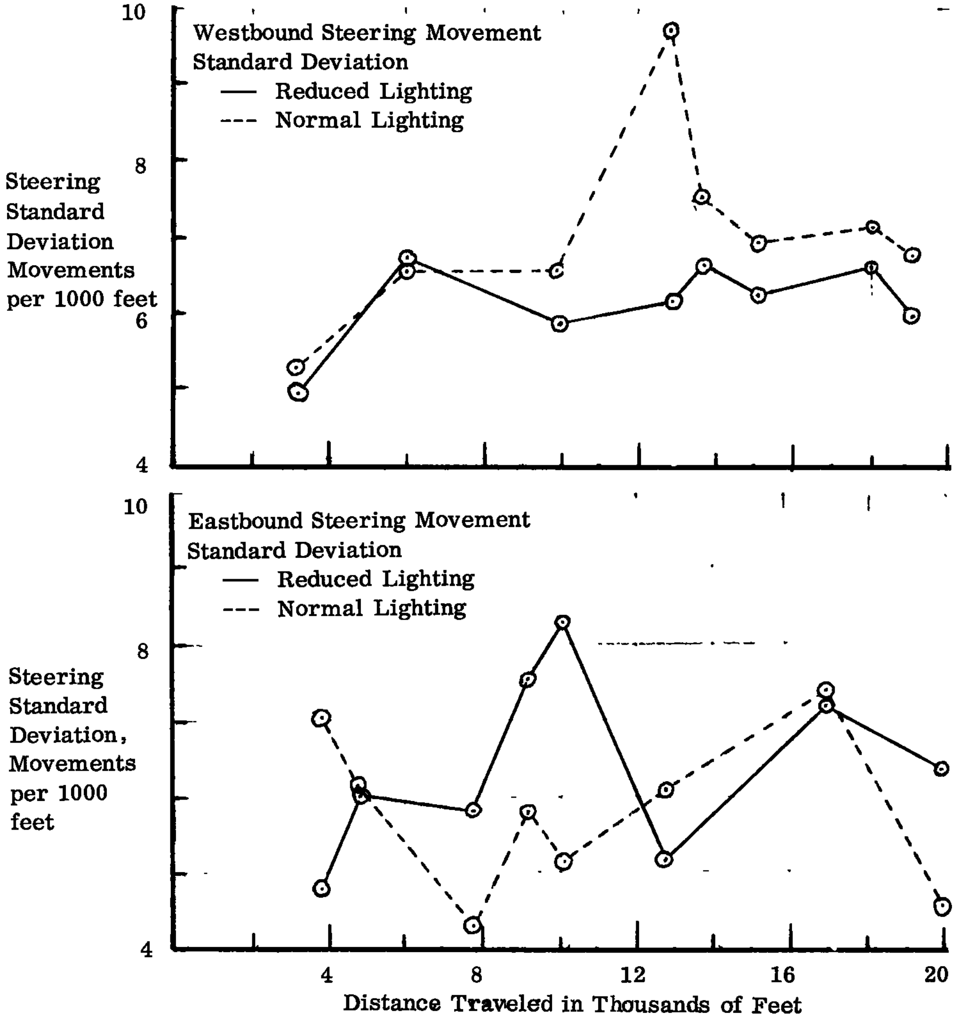

Figure 32. Standard deviation of steering movements per 1,000 ft on Connecticut Turnpike test runs.

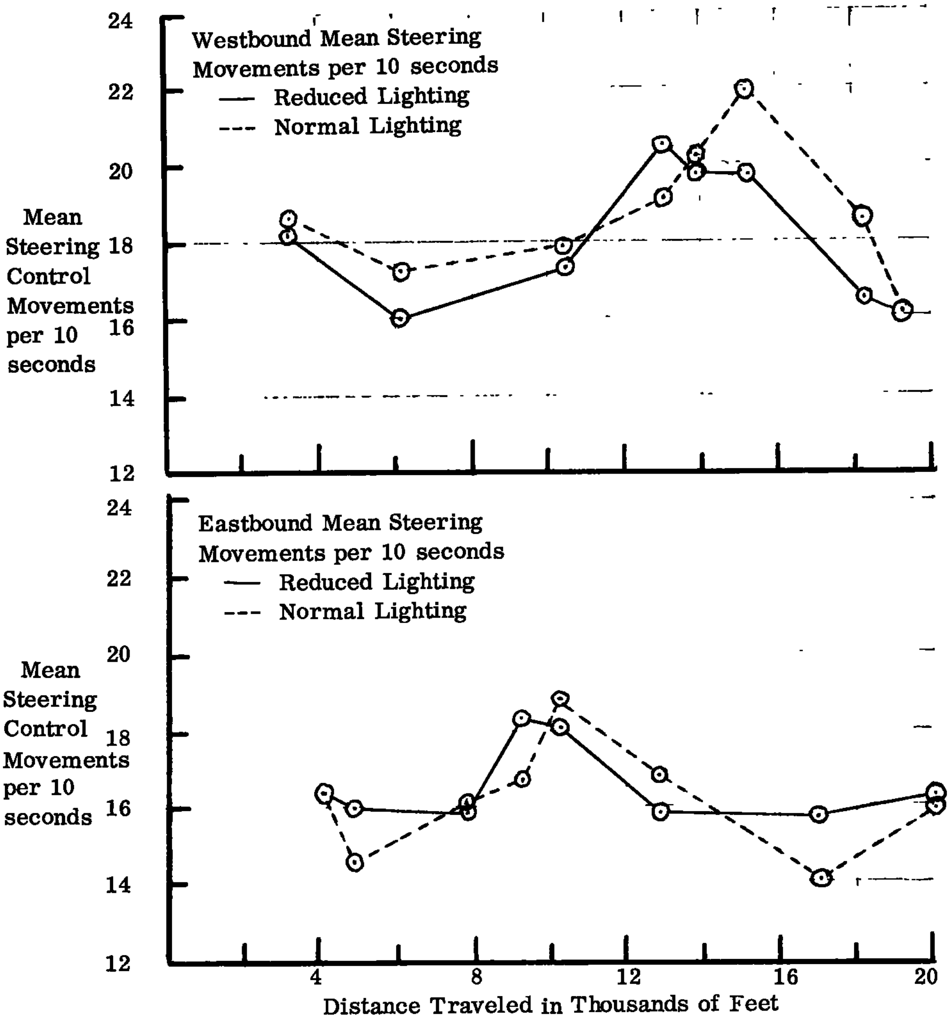

Figure 33. Mean steering control movements per 10 sec on Connecticut Turnpike test runs.

that gas pedal control movements were reduced with the reduced lighting level for each of the 16 sampling zones. The effects of vertical curvature on gas pedal activity is also evident, particularly at the eastern end of the test site where sampling zones alternate positive and negative 3 percent grades. One-way analyses of variance for each lighting condition and driving direction showed sampling zones to be significantly different at the 0.001 level in terms of gas pedal activity. This result emphasizes the need to explicitly consider geometry in studies of this kind.

Gas pedal behavior by individual subjects was studied in terms of pooled data from zones with 3 percent upgrades and zones with 3 percent downgrades (numerical results are presented graphically in Appendix I). It was found that nine of the ten subjects displayed greater pedal activity on upgrades than on downgrades, and these differences were far greater under normal lighting than under the dimmed condition. When slopes were examined individually, the dimmed lighting produced reduced pedal activity on 3 percent upgrades by nine of the ten drivers, with mixed results on the downgrades.

TABLE 31

SUMMARY OF BRIDGEPORT NIGHTTIME GAS PEDAL DATA FOR ALL SUBJECTS AND ZONES

ITEM	VALUE
Mean gas pedal activity:	
All trials	16.41[a]
Normal lighting	17.93[a]
Reduced lighting	14.90[a]
Standard deviation:	
All trials	5.24[a]
Normal lighting	5.75[a]
Reduced lighting	4.70[a]
Correlation coefficients, all trials:	
Gas pedal activity—lighting level	0.260
Gas pedal activity—highway grade	0.253
Gas pedal activity—subject age	0.178
Gas pedal activity—replication No.	0.118
Gas pedal activity—adj. traffic vol.	0.072
Gas pedal activity—oncoming traf. vol.	0.035
Gas pedal activity—horiz. curvature	0.023

[a] Gas pedal control movements per 1,000 ft of highway.

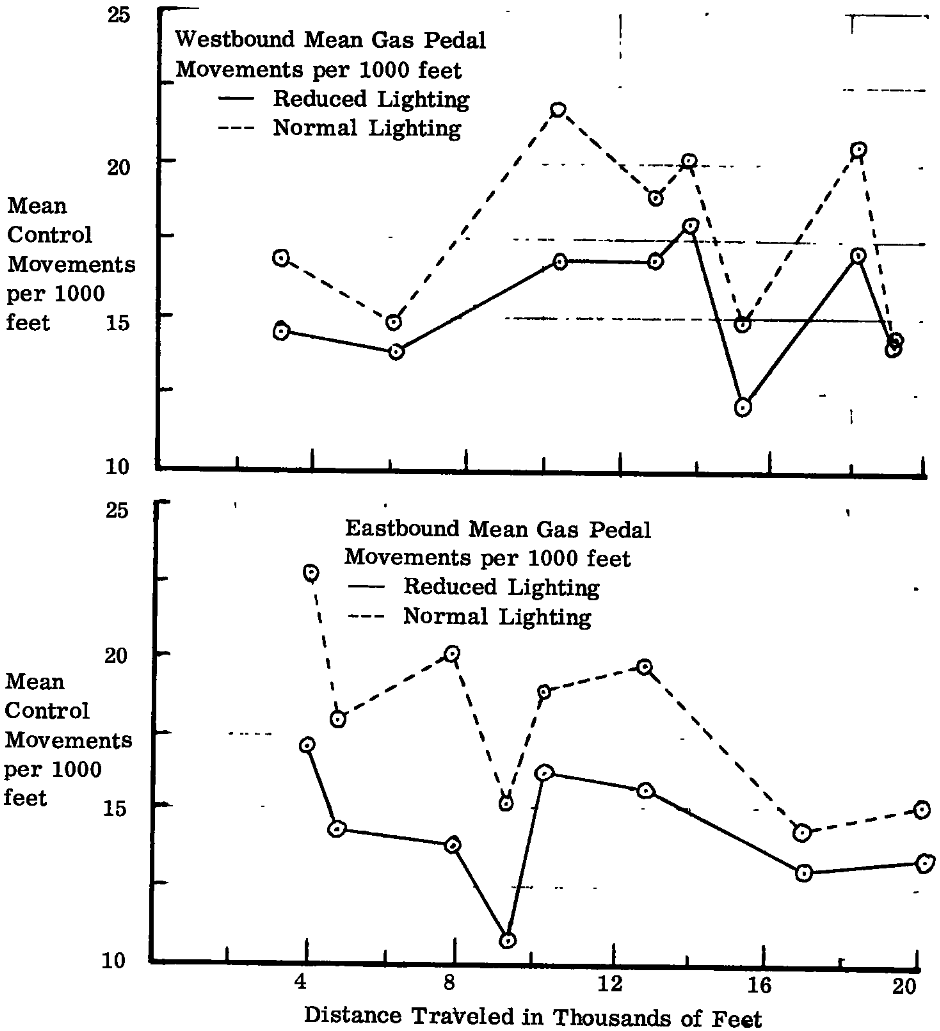

Figure 34. Mean gas pedal movements per 1,000 ft on Connecticut Turnpike test runs.

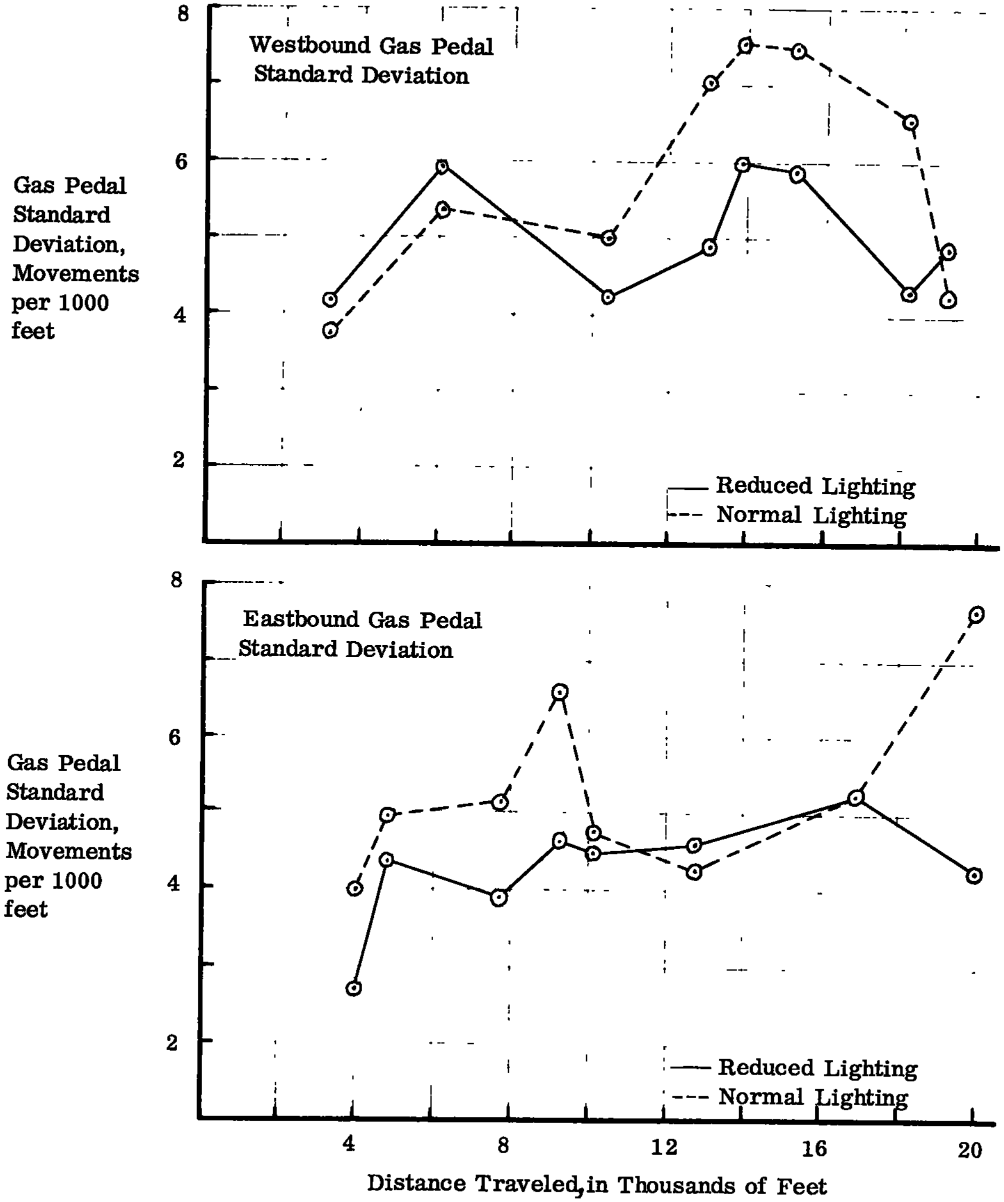

Figure 35. Standard deviation of gas pedal movements per 1,000 ft on Connecticut Turnpike test runs.

TABLE 32

GAS PEDAL ACTIVITY MEANS AND STANDARD DEVIATIONS BY ZONES, WITH α-LEVELS OF SIGNIFICANT DIFFERENCES DUE TO LIGHTING

		GAS PEDAL MOVEMENTS (NO./1,000 FT)					
		MEAN			STANDARD DEVIATION		
ZONE	GRADE	REDUCED	NORMAL	α	REDUCED	NORMAL	α
		(*a*) WESTBOUND					
1	−0.5	14.50	16.87	NS	4.19	3.72	NS
2	1.0	13.83	14.89	NS	5.85	5.31	NS
3	0.9	16.79	21.91	0.001	4.20	4.99	NS
4	−0.5[a]	16.95	18.91	NS	4.83	7.02	0.050
5	3.0[a]	18.15	20.18	NS	5.95	7.49	NS
6	−3.0	12.08	14.84	NS	5.86	7.42	NS
7	3.0	17.15	20.61	0.025	4.25	6.48	0.050
8	−3.0	14.36	14.04	NS	4.80	4.16	NS
		(*b*) EASTBOUND					
11	3.0	17.13	22.76	0.005	2.69	3.96	0.100
12	−3.0	14.33	17.89	0.050	4.36	4.93	NS
13	3.0	13.81	20.21	0.001	3.90	5.20	0.100
14	−3.0[b]	10.72	15.33	0.010	4.62	6.62	0.050
15	0.5[b]	16.29	18.90	0.050	4.49	4.74	NS
16	−0.9	15.75	19.82	0.005	4.60	4.31	NS
17	−1.0	13.16	14.45	NS	5.18	5.64	NS
18	0.5	13.45	15.24	NS	4.30	7.66	0.010

[a] Combined with a left curve of 3° per 100 ft.
[b] Combined with a right curve of 3° per 100 ft

Table 32 gives means and standard deviations of gas pedal activity in each of the sampling zones for the two lighting levels, together with significance levels for differences between lighting conditions. As noted earlier, the rate of an accelerator movement is lower for the reduced lighting level in each of the sampling zones. Statistically, gas pedal activity under the dimmed lights is significantly less in 8 of the 16 sampling zones.

Sample standard deviations computed for each sampling zone and lighting condition also are given in Table 32. Significant differences from lighting levels were found in 6 of the 16 sampling zones. In general, variability tended to be reduced at the lower lighting level, as shown in Figure 35, which also illustrates the interzone pattern similarity that occurred between the two weeks of testing.

Summary

Subjects driving in Connecticut tests displayed gas pedal responses to the two lighting levels in a number of ways. The general response was a reduction in pedal activity when lighting levels were reduced. This was particularly true on upgrades, where the differences in pedal movement rates due to grades were also reduced by dimmed luminaires.

Statistically, it may be concluded that gas pedal activity was significantly reduced by reduced lighting; numerical reduction occurred in every sampling zone, with one-half being statistically significant. Variability in pedal activity also showed a decrease with reduced lighting in some zones, although results were not as marked as was the case with the sample means.

CHAPTER SIX

NIGHTTIME ENCOUNTERS WITH ONCOMING VEHICLES

Although each year the system of wide-median expressways grows more complete and complex, drivers will be required for the forseeable future to use two-lane and four-lane nondivided highways. These introduce to the driving task many inputs for which the expressway driver has little concern, such as the encounter of vehicles not separated by a dividing section. On modern expressways, drivers need and receive little information concerning oncoming traffic. On nondivided highways, however, drivers must be concerned with oncoming traffic, especially in regard to the relative lateral displacement of the two vehicles.

Driving at night eliminates many of the visual cues the driver would normally use to make judgments about this lateral displacement. The glare from the headlights of an oncoming vehicle obscures additional visual cues, leaving the driver with a greatly reduced amount of information with which to make decisions about the control of his vehicle. Ottander (*14*) points out that the glare from an approaching car at night may, if one takes into account all of the known factors, give rise to two negative effects on the driver's ability to detect objects on the road. One is the reduction of the contrast ratio between the light from the object and the light from the road on the retinas of the driver. The other effect is that the approaching light temporarily changes the adaptation level of the eyes, thus causing decreased light sensitivity.

These, of course, are visual responses. Of more direct interest with regard to safety considerations is the consequence of glare upon a driver's performance in controlling his vehicle. Initial concern has been directed toward experiments to identify the forms of response (if any exists) to oncoming headlight glare in terms of control activity. It is useful to begin by briefly noting the concepts of encounters and driving response as employed in this study.

The notion of an *encounter* arises from needs relating to identification and measurement of driver control response to glare from oncoming headlamps. At present there do not appear to be reasonable grounds upon which such a response may be assigned, partially or wholly, to headlight glare. In the absence of information on the significance or nonsignificance of effects from the various components of the imposed experimental conditions or environment, one must attribute any response detected to the total experimental condition—the nighttime encounter. Accordingly, during analysis and interpretation of the experimental findings driver response to encounters is spoken of herein with the understanding that a significant part of the encounter is indeed headlight glare.

The notion of driver *response* is limited herein to changes in driver control activity (steering and brake pedal) that may occur during an encounter. Certain numerical measures of control activity are proposed and employed to present some empirical evidence of the existence and nature of driver response to encounters in terms of control activity.

DATA COLLECTION PROCEDURE

Data on response to encounters would be most effectively gathered on actual roads in normal traffic as the encounters occur. Geometry and other factors should be controlled by testing on straight, flat roads of uniform width long enough to allow transient control dither to ebb before responses are recorded. Such a test site should also have a moderate amount of nighttime traffic, and yet be free of exogenous glare sources such as neon signs, farm lights, and traffic signals.

An extensive search aided by the valuable assistance of The Ohio Department of Highways yielded two test sites which, although not completely satisfying the requirements outlined, furnished adequate locations for early data gathering activities. U. S. Route 33 westward from Dublin, Ohio, provided a two-lane, high-speed, nonilluminated rural location for testing. A second site, near Euclid, Ohio, included lighted and unlighted sections, although studies here were handicapped by nonuniform pavement and a 35-mph speed limit.

During the experiments subjects were instructed to drive as they normally would, although avoiding car-following situations. Speeds were elected, and the subjects tended to drive at speeds close to the posted limits. The instrumented vehicle was equipped for these studies with an infrared detector to provide oscillograph records of the passage of oncoming headlights. Artificial or staged encounters were not used during the experiments. Encounters were recorded as they normally occurred on the highway, with the experimenter noting meetings with multiple vehicles, trucks, and bright or defective headlights.

Figure 36 shows a sample of actual driving activity as recorded with this equipment. The experimenter's memo in the upper left-hand corner signals the appearance of headlights on the horizon; the actual passage of the oncoming vehicle is recorded by the infrared detector. The traces shown represent slightly less than one-half mile of highway at 60 mph. The vertical lines show the 6-sec period before the encounter and the 4-sec period after.

The traces in Figure 36 are typical of thousands of feet of similar traces from other studies. They include the property that changes in slope in the gas pedal and steering traces appear to be discrete, and the second derivative may be considered as vanishing or as a series of spikes. One way to attach numbers to such traces is to count the changes within some arbitrarily chosen time or distance interval, as was done in the Connecticut Turnpike study. Another

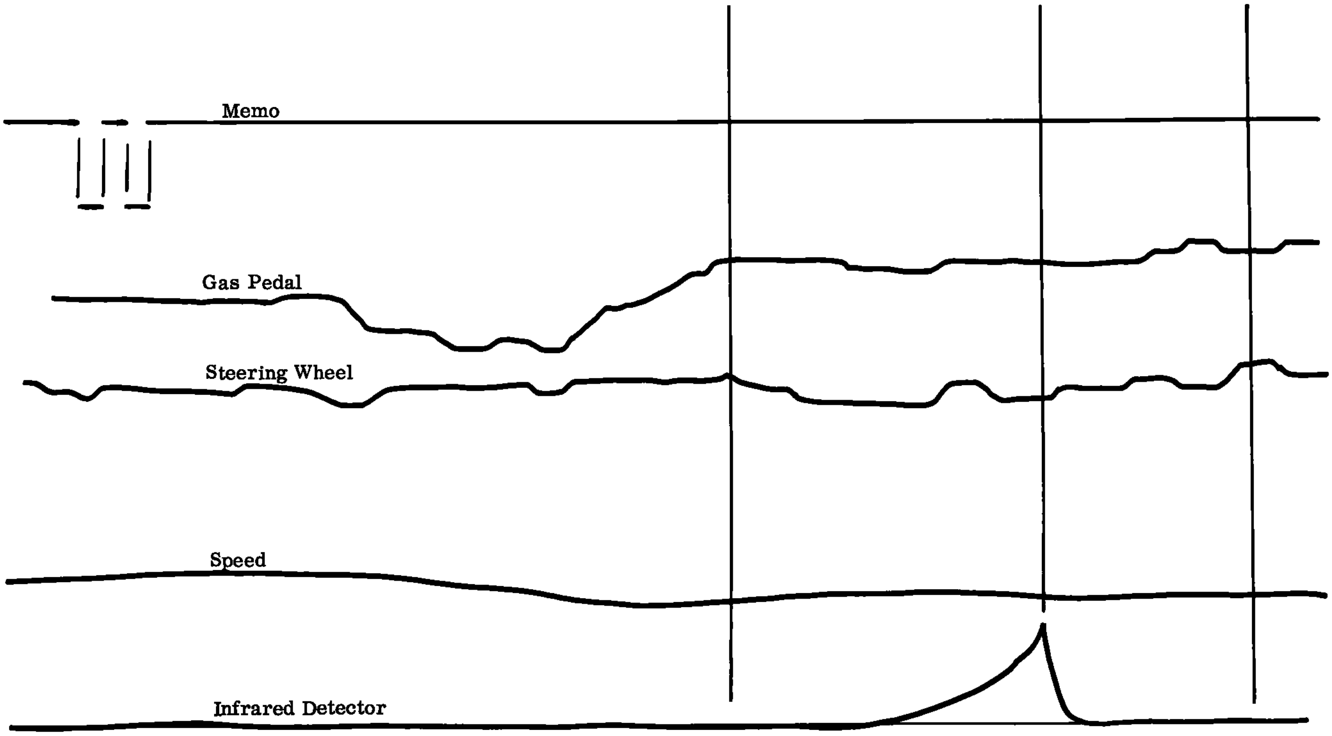

Figure 36. Driver control movements as recorded by oscillograph recorder.

approach is to note the fractions of time that the control is in motion; i.e., with nonzero slope. Both of these measures were used to quantify the data discussed in the following.

NIGHTTIME RESPONSES

Figure 37 shows an aggregate of encounter responses for six subjects and 80 encounters. The data were collected on US 33 under nighttime driving conditions. The measure used is mean control movements (changes in the slope of the recording trace) per 3-sec interval, as recorded for seven consecutive intervals prior to the encounter and three intervals after the encounter. Steady-state control activity means are also shown for comparison. The steady-state driving condition occurs on the open road when no oncoming vehicles are visible.

Figure 37 suggests a number of interesting hypotheses. Steering wheel response to the encounter begins more than 9 sec before the encounter, whereas changes in gas pedal activity appear to occur only within 3 sec of the passage of the oncoming vehicle. It should also be noted that steering wheel activity decreases immediately after the encounter while gas pedal movements increase. This behavior was also noted individually for each of the six subjects who participated in the experiment.

Determining the statistical significance of these data could be accomplished by testing the hypothesis that control activity is the same during encounters as in the steady-state open-road driving condition. Efforts to perform conventional statistical hypothesis tests of this sort are precluded by the shape of the steady-state frequency distribution, which could not be fit or approximated by standard probability density functions.

Accordingly, the chi-square goodness of fit test was used to test whether the sample of data under encounter conditions could be considered a random sample from the steady-state distribution. To reject this hypothesis is to infer that drivers *do respond* to encounters in terms of their control activity.

The sample data from each of the successive 3-sec intervals before and after an encounter were tested against the steady-state distribution. Figure 38 shows a plot of the chi-squared statistics computed for each of the 3-sec periods near the encounter. The horizontal lines bound the critical regions associated with significance levels of 0.05 and 0.10. In this manner Figure 38 serves as a graphical test for the hypothesis that near-encounter activity does not differ from open-road control activity. Rejection of this hypothesis near the encounter is clear from the figure, which indicates the following:

1. The distribution of gas pedal activity differs significantly ($\alpha=0.10$) from steady-state during the 3-sec interval immediately prior to the passage of the oncoming vehicle. Significant responses do not appear to be present at other times.

2. The distribution of steering wheel control movements does not differ from steady-state during the period prior to the encounter. After the oncoming vehicle has passed, however, the distribution changes markedly (significant at less than 0.05) for at least 6 sec after the encounter.

Based on these data it is concluded that encounter

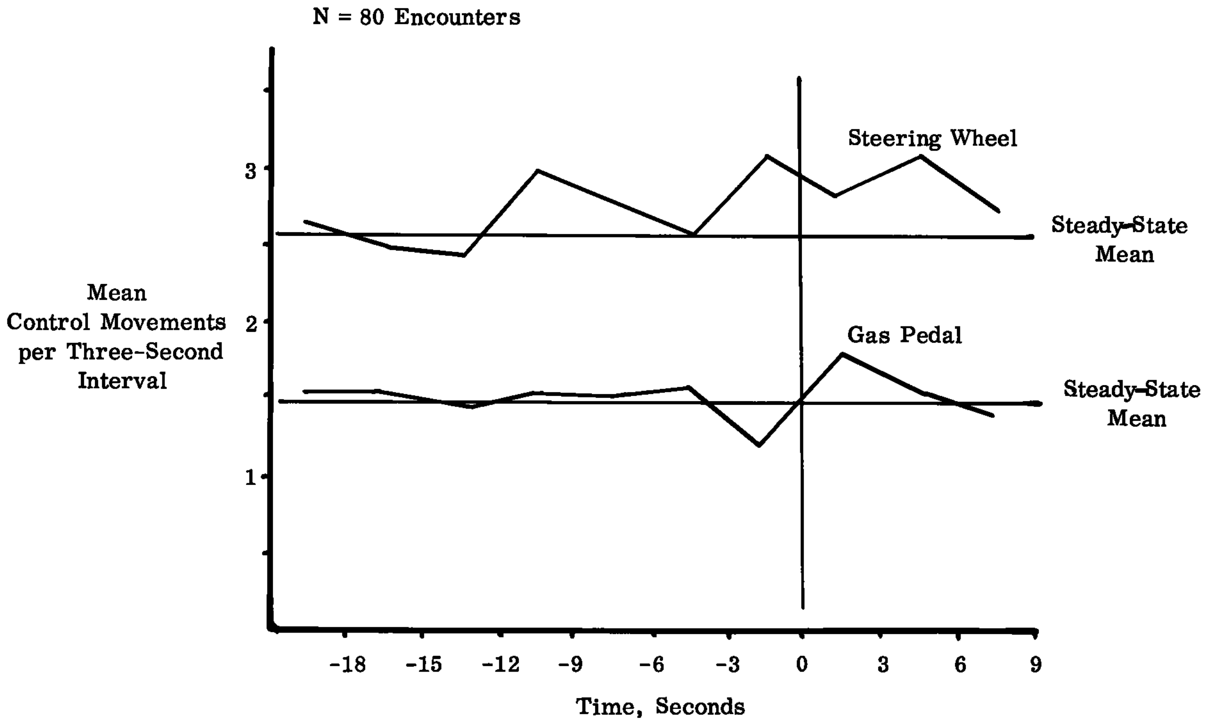

Figure 37. Mean control activity levels during nighttime encounters (6 subjects, 80 encounters).

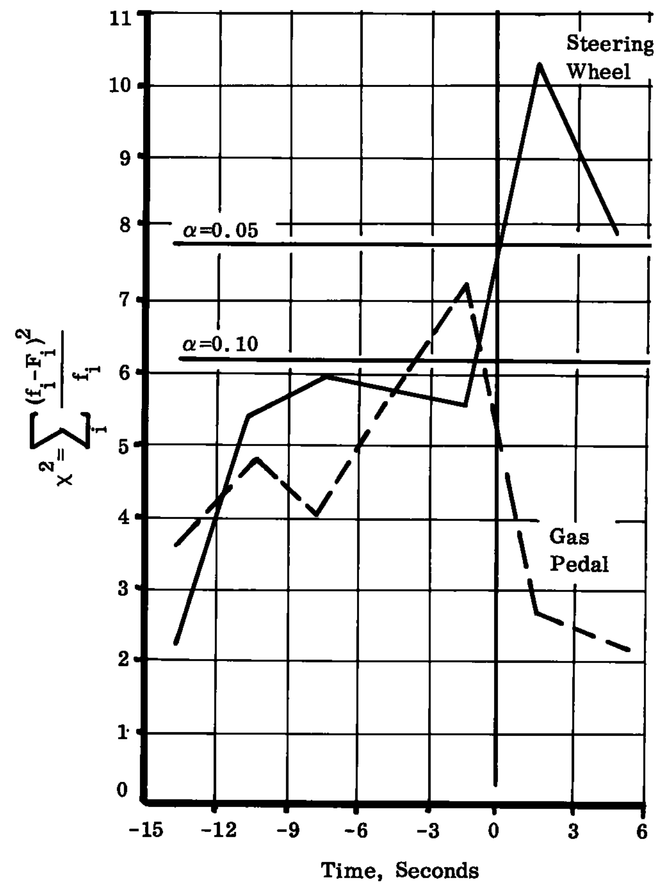

Figure 38. Chi-square goodness of fit test comparing control activities during encounters against open-road distributions.

response manifested in driver control movements does exist, occurring in the gas pedal immediately before the encounter and the steering wheel immediately after. It is emphasized no statistical assertion has been made about the nature of the response. The chi-square procedure tests only differences in distribution; accordingly, the significant difference detected might be reflected in mean, variance, or any of many distribution properties. Behavior of sample means was shown in Figure 37, but additional data would be required before specific conclusions could be made.

These results must also be interpreted in terms of certain other properties of the experimental data. Subject-to-subject differences are substantial. Table 33 gives steady-state sample means for six subjects' gas pedal and steering wheel activity. These differences may be exemplified by comparing the relative quiescence of subject 2 with the suggested hyperactivity of subject 3. The possibility that steering and the gas pedal may be active or inactive together for a given subject is negated by the data for subject 4.

The data also indicated a nonindependence of data from successive 3-sec intervals under the steady-state conditions. Autocorrelations of the order of 0.45 were obtained for both the gas pedal and steering wheel traces with a one-interval time lag. This suggests that the basic or natural frequency (if it exists) of driver change in control activity is smaller than that associated with a 3-sec interval.

ENCOUNTER RESPONSE AND ILLUMINATION LEVELS

Further testing on US 33 was undertaken to explore for possible day-night differences in control response to encounters. Four additional subjects were tested, with control performance recorded for the following.

1. Steady-state, when no oncoming vehicles are in view.
2. The 6-sec period before the encounter.
3. The 4-sec period following the encounter.

Driving performance was in this case reported in terms of the percentage of time the gas pedal or steering wheel was in motion. Table 34, summarizing the data from this study, suggests a slight decrease in steering activity during the periods immediately before and after the passage of an oncoming vehicle. Day-night differences for the steering measure are not evident. Data recorded on gas pedal activity during the experiment showed a decrease in pedal activity at night under open-road (dark horizons) conditions with a marked increase in activity immediately after an oncoming vehicle has passed.

Similar tests on the lighted and unlighted sections of the Euclid test site used four test subjects in the 40 to 60 age group. Response was defined as the algebraic difference between steady-state and encounter control activity levels under a given set of roadway properties. Although dependent on estimates of steady-state activity parameters, this linear model permits both the steady-state and the near-encounter activity level to differ under varied environments with a significant change in response. Data from the Euclid tests were reduced in terms of the linear model, and analysis of variance on the resulting data yielded the following:

1. No pure effect was found in response level due to the day-night condition. The over-all magnitude of control activity varied between darkness and daylight, but the response measure (the previously discussed linear combination) did not differ significantly.
2. Strong and significant effects on response from roadway differences were noted.
3. Significant interactions between the day-night and roadway conditions were also present.

The data did not permit statements regarding possible relations between the significant interaction effect and the roadway differences; i.e., it was not possible to determine if the effect may be attributed to the lighting or if other differences in the roadways may be significant contributors.

TABLE 33

MEAN STEADY-STATE ACTIVITY LEVELS, IN MOVEMENTS PER THREE-SECOND INTERVALS[a]

SUBJECT	GAS PEDAL	STEERING WHEEL	SAMPLE SIZE[b]
1	1.71	1.60	64
2	0.42	1.36	52
3	3.42	3.40	70
4	0.45	3.23	73
5	0.55	2.14	28
6	1.53	3.60	30

[a] U.S. Route 33; two-lane, rural, non-illuminated. [b] Number of intervals

SUMMARY

The studies of nighttime driving response to encounters with oncoming vehicles reported in the preceding sections were completed on a small scale and must be considered exploratory. Although the data consistently yielded evidence of encounter response near the moment of passage of the oncoming vehicle, the nature of the response varied widely. This is not surprising for a modest investigation undertaken in an environment fairly teeming with potentially influential variables. Pooling of data from different test subjects was also dictated by cost considerations, where cost is measured in terms of useful data points per unit of driving time. Data attrition in encounter studies is large, because attention was initially centered on one of the simplest (and most infrequent) encounters—the single-vehicle encounter (no trucks) preceded and followed by clear horizons.

Nevertheless, these limited studies do indicate that driver control responses to the passage of an oncoming vehicle exist, and can be noted in both the gas pedal and steering behavior although the response differs greatly among drivers.

TABLE 34

DAY AND NIGHTTIME CONTROL ACTIVITIES BEFORE AND AFTER ENCOUNTERS[a]

MOVEMENT	ACTIVITY (%) TIME OF DAY	STEADY STATE[b]	6 SEC BEFORE[c]	4 SEC AFTER[d]	SAMPLE SIZE (ENCOUNTERS)
Steering wheel	Day	52.1	45.6	47.5	10
	Night	50.8	46.8	48.3	15
Gas pedal	Day	25.7	23.5	28.0	10
	Night	18.9	22.2	33.5	15

[a] On US 33; two-lane, rural, non-illuminated.
[b] No oncoming vehicles in view.
[c] 6-Sec period before encounter
[d] 4-Sec period after encounter.

PART III

VISUAL EVALUATION

ANDRIES J. BIRKHOFF AND H. RICHARD BLACKWELL
INSTITUTE FOR RESEARCH IN VISION
ENGINEERING EXPERIMENT STATION
THE OHIO STATE UNIVERSITY

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PART I Operating Characteristics of Freeways

PART II Driving Performance

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PART III

VISUAL EVALUATION

SUMMARY

This part of the report summarizes the work done under NCHRP Project 5-2 investigating visual aspects of freeways under reduced lighting. The over-all study of operating characteristics of highways and illumination was a combined endeavor of four research groups. The Institute for Research in Vision, at The Ohio State University, had the task of evaluating visibility under two levels of fixed lighting. For this purpose, time and equipment were shared with the Systems Research Group of The Ohio State University. The Institute for Research in Vision built special photometers, which after being mounted on the Systems Research Group's test vehicle transformed this car into a mobile photometer which assessed the visual surround of this vehicle.

The luminances within a driver's visual environment on a highway can be thought of as originating from three sources. The two major sources are (a) the fixed lighting system and (b) the vehicular lighting system. A third group would include all lighting which was not purposely introduced (i.e., building lights, billboards, etc.).

After mapping the pertinent variations such as horizontal luminance, vertical illumination, and the disability glare fluxes entering the driver's eye, a visibility analysis was made. This analysis was executed by considering that a number of objects with known reflectances were transported along the highway, producing a number of dynamic variations in the relative visibility of different objects as they occupied different locations. It was found that at the higher illumination of 0.62 fc the relative visibility factor (RVF) improved by 32.4 percent as compared with an illumination of 0.22 fc. This effect is believed significant, but is less than one-half the improvement to be expected from the increase in illumination, due, no doubt, to the presence of a large fixed component of vehicular illumination under both conditions.

CHAPTER SEVEN

INTRODUCTION

The study reported in this part was undertaken as a portion of an over-all study of the effect of the quantity of fixed roadway lighting on the operating properties of a modern limited-access highway. Two levels of fixed roadway lighting were used, one representing an average horizontal illumination of about 0.6 fc, the other representing about 0.2 fc. The larger value was obtained by normal use of the fixed roadway equipment; the smaller was obtained by modifying the fixed roadway equipment to accommodate lamps of reduced wattage.

Extensive basic studies of human vision (*e.g.*, *15*) have identified the physical variables which have the most significant effects on the visibility of objects in the visual environment. Object size and distance have a primary effect, with object shape of secondary importance. Luminance contrast of an object has a primary effect, with chromatic contrast of secondary significance. Except at extremely low levels of general luminance, luminance contrast is of considerably more importance than the over-all level of luminance. The time available for observation has comparatively little effect on visibility, so long as the eye has at least ⅕ sec of observation time, the time of an ocular fixation. The visibility of an object depends significantly upon the spatial pattern of luminances in the visual field, with the presence of luminances considerably greater than the object of interest and its background reducing object visibility by means of the "disability glare" effect. Visual performance is also affected by the complex history of luminances to which a particular portion of the retina has been exposed, with a history of equilibrium conditions representing optimal visual performance.

The visual environment represented by a modern limited-access highway is obviously a very complex one, in which rapid changes occur in nearly all the factors affecting object visibility and visual performance. In the absence of any highway traffic, a simple change in the quantity of illumination provided by fixed lighting would have a predictable effect on object visibility. Object sizes and distances, object shapes, and times of observation would remain fixed. Inasmuch as luminance and chromatic contrasts are scalar quantities, they would be unaffected by the quantity of fixed lighting. Only the luminances of objects would change and these would be altered in direct proportion to the change in the level of illumination. Such an analysis has, of course, no resemblance to the actual situation and would be of no value. In point of fact, a large portion of the illumination of elements of the visual environment will be provided by vehicular lighting and this, of course, will be unaffected by the quantity of fixed highway lighting. Thus, the problem becomes one of analyzing the changes in luminous aspects of the roadway when the level of fixed lighting is altered but when vehicular lighting is unchanged.

The changes in the visual environment to be expected when the level of fixed lighting is changed are complex. The geometry of fixed lighting produces controlled distributions of luminous flux designed to illuminate the roadway surface as uniformly as possible while at the same time producing a minimum of high-luminance areas capable of reducing object visibility by the disability glare effect. Distributional control implies that the contrast of objects will depend in a complex manner on the placement of the object with respect to the source of fixed lighting, and the precise gonio-photometric reflectance properties of the object and the pavement background. Of course, the degree of loss in object visibility will depend on the distributional properties of each roadway luminaire, and on the locations of the object, the luminance, and the driver's eye. Vehicular lighting has a very different geometry, thus affecting object contrast and the disability glare effect in different ways. Whereas fixed lighting would be expected to produce repetitive visibility conditions in synchrony with occurrence of luminaires at regular spacings, vehicular lighting would be expected to produce random vsibility effects which would with large data samples prove unrelated to locations of evenly-spaced luminaires.

These evident complexities in a comparison of the visual environments produced by two levels of fixed lighting led to making a careful photometric survey of relevant luminous quantities in roadway lighted on separate occasions by the two different levels of fixed lighting. Then the physical data were used to analyze the circumstances of object visibility under each of the two roadway conditions.

The measurements were made in close collaboration with the Systems Research Group of The Ohio State University, utilizing the special test vehicle developed by this group. The reader is referred to the report of the Systems Research Group (Part II herein) for descriptions of the special measuring and recording equipment, and identification of the sections of highway used with appropriate descriptions of their physical properties. Further description of the highway may be found in the report of the Yale University Bureau of Highway Traffic (Part I herein).

CHAPTER EIGHT

EXPERIMENTAL PROCEDURES

DATA COLLECTION

In the collecting of data, the Institute for Research in Vision shared the facilities of the instrumented research vehicle of the Systems Research Group. This 1963 Chevrolet sedan equipped with a 50-channel oscillograph recorder produces continuous traces of signal inputs on 400-ft rolls of 12-in. photosensitive paper. For the purposes of the test runs, several photometric devices were installed.

Pavement Luminance

Figure 39 shows a roadway luminance photometer consisting simply of a tube with apertures and a photoconductive cell. The luminance photometer is directed downwards and forward of the vehicle at an angle of 8° from the horizontal. The area of roadway assessed consisted of an ellipse with a 7-in. minor and a 20-in. major axis. The point of inter-

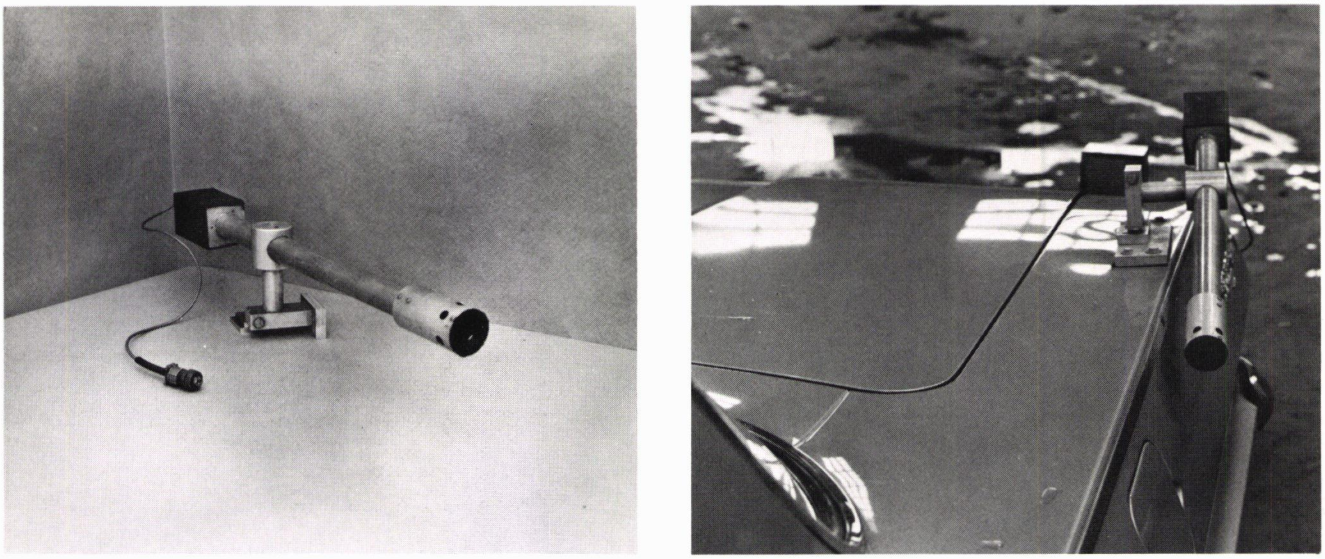

Figure 39. Pavement luminance meter (left) as mounted on instrumented vehicle (right).

section of the photometer line of sight with the road was 18-in. in front of the vehicle on perfectly level roadway.

Vertical Luminance

Figure 40 shows an integrating photometer used to measure vertical illumination. A diffusing hemisphere was mounted over a photoconductive cell. The unit responded to incident light in terms of Lambert's law to a precision of 0.5 percent over a range of 170°.

Glare

Figure 41 shows the photometers used to evaluate the flux coming to the driver's eye from different portions of the visual environment when proceeding along the roadway. The five flux photometers were used to respond to the flux coming from five regions of the visual field, as shown in Figure 42. The sizes and shapes of the solid angles of the glare flux photometers were arbitrarily decided on, taking in account the geometry of the highway system and its fixed lighting. The glare flux photometers approximately

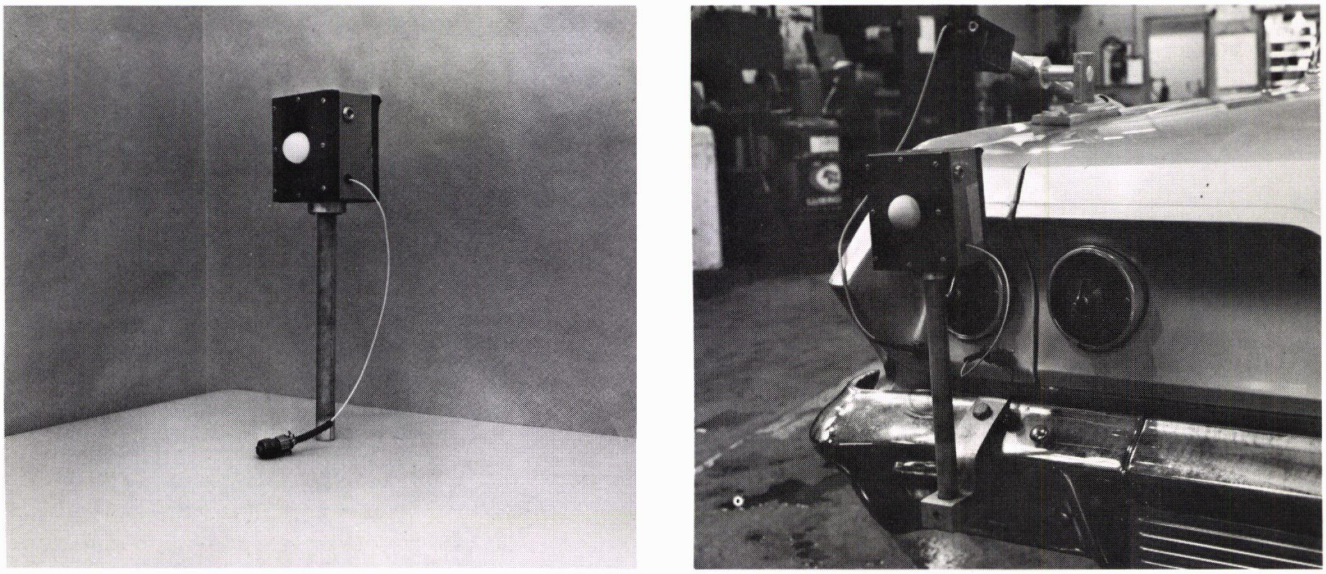

Figure 40. Cosine corrected illumination meter (left) as mounted on instrumented vehicle (right).

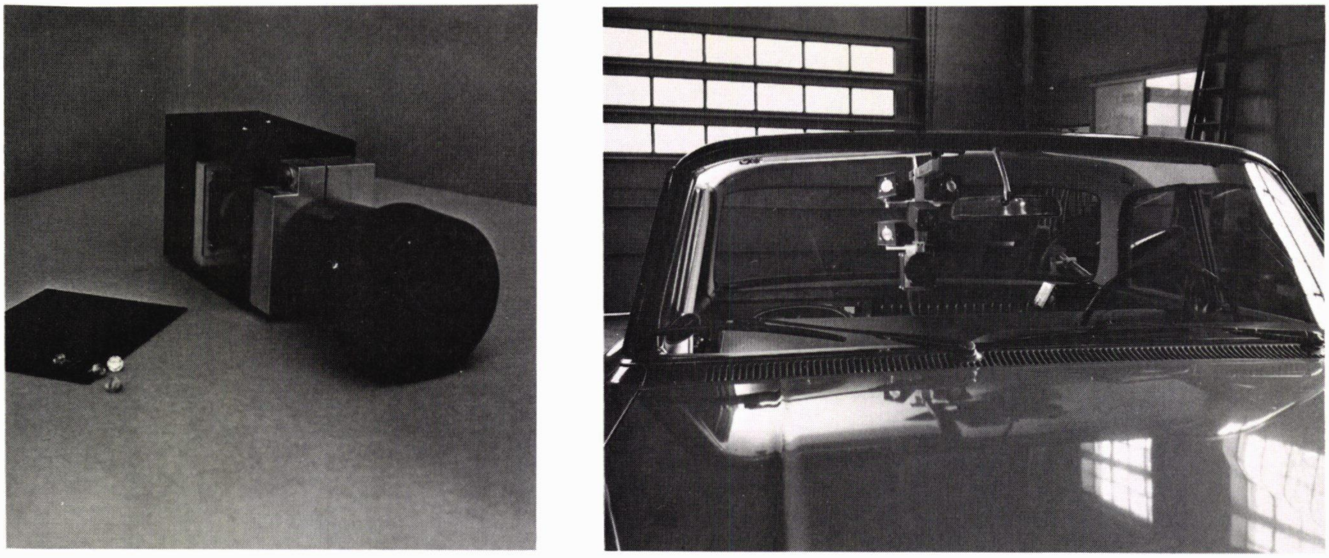

Figure 41. Glare photometer lens (left) and cluster mounted in instrumented vehicle (right).

differentiate the fluxes from the headlamps of oncoming vehicles; the flux from the fixed lighting at the left-hand side of the driver; the flux from the luminaire at the right-hand side of the driver; the light from billboards, tail-lights, houses, etc., at the right-hand side of the driver; and the flux from the highway ahead of the driver, including the hood and dashboard of the vehicle proper. There was also a photometer fitted with a "disability glare lens," produced in accordance with the procedure described by Fry, Pritchard and Blackwell (*16*). This lens accepts flux from the full forward hemisphere, but weights the flux in accordance with a weighting function of the angular separation between each ray and the direct line of sight of the photometer (Fig. 43). The weighting function is a radically-symmetrical function of the angle of separation, as follows:

$$B_{vi} = \frac{K E_i \cos \theta_i}{\theta_i \, (1.5 + \theta_i)} \tag{2}$$

in which

B_{vi} = the effective veiling luminance produced by a ray from θ_i;

E_i = the illumination of the ray measured normal to the direction of the ray; and

K = an arbitrary constant, which also takes account of the units in which B and E are specified.

As will be seen, the integrated value of B_{vi}, representing the effect of summing values of B_{vi} from the entire forward hemisphere, may be used to evaluate the total disability glare effect of a roadway environment.

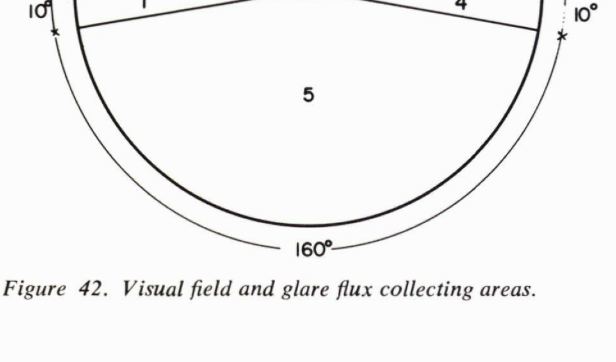

Figure 42. Visual field and glare flux collecting areas.

The five "glare flux" photometers and the integrating disability glare photometer consisted of objective lenses and photoconductive cells. The objective lenses of the glare flux photometers produced an image of the outside world on a thin translucent screen. This screen was one side of a white diffusing cavity, the luminance of which was measured by a photoconductive cell. Black opaque masks were placed in front of the white screen, cutting the receiving solid angle to the desired dimensions (Fig. 42). The over-all optical and photoelectric transfer function was checked by rotating the photometers individually on a photometer bench while imaging the filament of a tungsten ribbon lamp. In spite of the wide-angle acceptance, linearity over 40° remained within 5 percent; over 70° within 10 percent. The cluster of photometers was mounted to look into a diffuse illuminated hemisphere and the electronic networks adjusted for equal output and excursion of the galvanometers.

To maintain calibration in the field, a Pritchard photometer (Fig. 44) was calibrated in conjunction with a field transfer standard (Fig. 45). This portable device could be held in front of each of the glare flux photometers and the pavement luminance meter. Accurate lineup was facilitated by means of locating fit-pins and squares. During the field experiment this portable luminance transfer standard was checked regularly with the Pritchard photometer, both calibrations being based on N.B.S. standard lamps. Before each session the photometers were checked and adjusted. The illumination meter was checked by using the cosine correcting sphere as a target for the Pritchard photometer.

The calibration of the photometer equipped with the disability glare lens was achieved separately. A point source was used to illuminate the glare lens at each of 20 values of θ_l, and the response of the photometer recorded at each. Separate readings were taken at each of the four cardinal positions of the photometer as it was rotated about its own line of sight. Then the average values for the four positions were obtained, and the upper and lower of the four values obtained were considered as limits plus and minus the average value. The values of B_{ll} are plotted in Figure 43 with Eq. 2 put through the data to demonstrate the conformity between the actual and theoretical weighting functions. The agreement is considered quite satisfactory.

Because the disability glare photometer was calibrated in absolute units without the special lens, a calibration factor is required to convert recorded photometer readings into values of B_l. The average values of B_{vl} were used to compute a value of this calibration factor. Each of the 20 values of B_{ll} was given equal weight, except that the value for $\theta_l = 1°$ was discarded on the basis of the 3-σ rule for rejecting data points. (It is clear from inspection of Figure 43 that this value of B_{ll} departs considerably from the theoretical curve.) The average calibration factor was 0.220, meaning that B_l is given in foot-lamberts by multiplying the calibrated luminance in foot-lamberts by this value.

TEST SITE

Figure 25 shows a plan view of the test site on the Connecticut Turnpike near Bridgeport. The analysis described here was made on zones 1, 6, 13, and 18, which may be described as follows:

Sections 1 and 6 carry westbound traffic, whereas sections 13 and 18 carry eastbound traffic. Sections 1 and 18 are parallel and were chosen for analysis because of the open, or least built-up, roadway environment. Sections 1 and 18 are straight in both the horizontal and vertical sense.

Sections 6 and 13 are also parallel, but have approximately 3° vertical slope, which is downslope for the eastbound traffic and upslope for the westbound. The environment seemed quite comparable with that of sections 1 and 18.

The two conditions of fixed lighting may be described as follows:

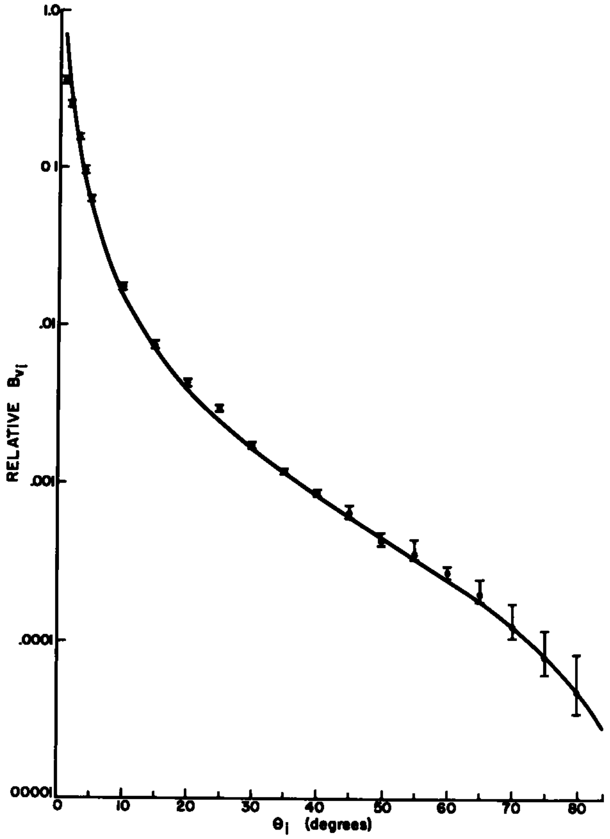

Figure 43. Glare lens calibration curve.

The lighting system comprised enclosed refractor-type luminaires on steel poles with outriggers. Mounting height was approximately 35 ft. Pole distance on one side was approximately 200 ft, the poles of the row on the other side being staggered between the nearside spacing.

The change from normal to reduced lighting was achieved by use of a specially made lamp in which the mercury arc was shortened with a resistor. It was expected that the geometry of the optical system would not be affected, but the lighting surveys as given in Table 35, as well as the rise times of the values of E (illumination in vertical plane) and B (pavement luminance) indicate otherwise.

The specified luminous output for the lamps as indicated by the Connecticut State Highway Department were 20,500 initial lumens for the normal lighting condition and 7,000 initial lumens for the reduced lighting condition. In both cases the arc was in the same quartz envelope. The reduced lamp, due in all probability to lower gas pressure, had a smaller diameter arc-stream, which produced a more sharply defined optical pattern on the roadway.

The lighting surveys in Table 35 as made by the Connecticut State Highway Department agreed well with the pooled photometric data as well as the spotchecks made by the Institute for Research in Vision during the experiments at the site.

In all, for photometric purposes, approximately 50 test

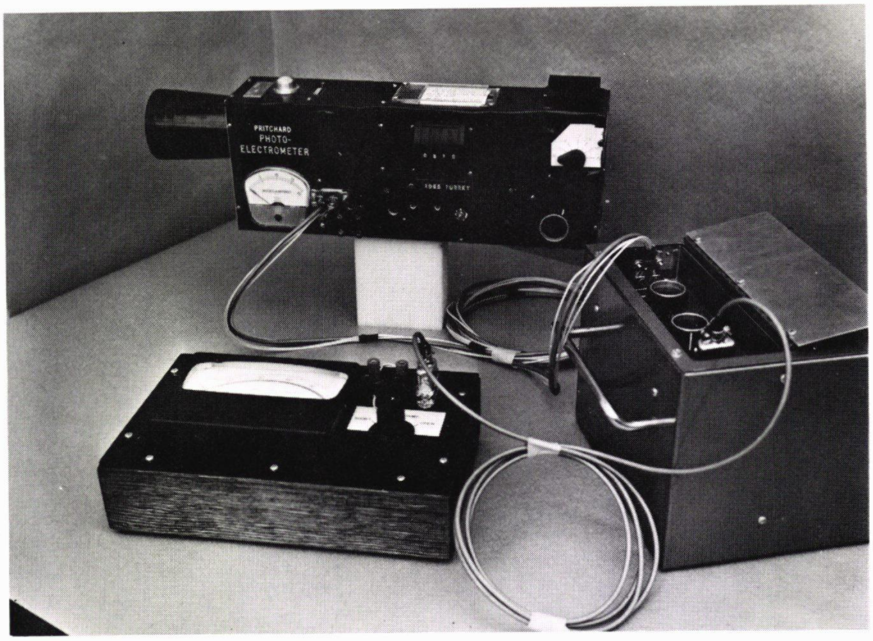

Figure 44. Pritchard photometer.

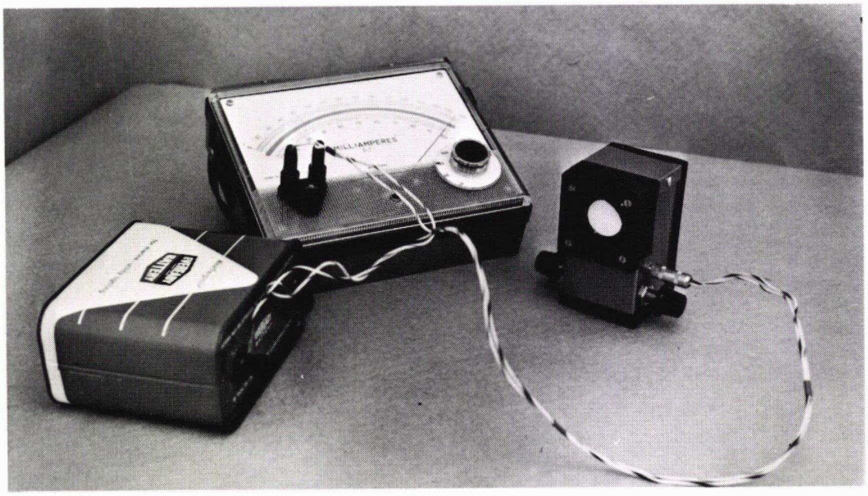

Figure 45. Field calibration array.

runs were made with normal illumination and 50 were made under conditions of reduced illumination.

DATA ANALYSIS

The principal photometric data of interest are the following:

$B =$ the average luminance (foot-lamberts) of the roadway as measured by the pavement luminance photometer;

$E =$ the average illumination (lumens/ft^2, or foot-candles) falling on a vertical surface as measured by the illumination photometer;

$B_v =$ the integrated veiling luminance (foot-lamberts) of the visual environment presented to the driver's eye as measured by the glare photometer fitted with the disability glare lens.

(After completing discussion of the main data analysis based on these three quantities, consideration is given to the secondary data analysis based on the flux measurements made with the five photometers which responded to portions of the visual environment.)

The first step in data analysis was the reading of the photometric quantities at periodic intervals from the oscillographic recorder. This was accomplished with a Benson-Lehrner reader. The results could be punched onto cards, with each card representing one moment in time during a test run, and hence one point in space along the roadway.

Before punching the data cards into code, it was necessary to establish the points in the oscillographic record which corresponded to the location of the highway luminaires. Considerable hand-probing of the data revealed that the cyclical variations in the values of *E* were more sensitive measures of the location of a roadway point with respect to the luminaires than the use of position on the record. Of course, variations in vehicle speed would influence the accuracy of position measures based on the elapsed oscillographic record. Thus it is perhaps not surprising that the location of a point in the record did not give a very reliable measure of location on the roadway. However, it was reassuring to discover that location along the roadway could be so accurately forecast from a study of variations in *E*.

Once the points on the record corresponding to the location of luminaires had been established, the points on the oscillograph record were coded with respect to the distance of the point along the roadway from a highway luminaire. Considering that the luminaires were separated by 200 ft, it seemed reasonable to select a total of six roadway locations each separated by 33 ft. The code which was adopted referred to distance measured from each luminaire. Thus, location 0 corresponded to the case in which the vehicle was just abreast of a luminaire, location 1 corresponded to the case in which the vehicle was 33 ft ahead of a luminaire, and so on.

Pooling data in terms of the distance of a roadway point from the nearest luminaire is obviously visually meaningful. As noted in Chapter Seven, vehicular lighting will be randomly located along the roadway, but the fixed highway luminaires contribute to the elements in the visual environment in a repetitive manner corresponding to their regular spacing. Pooling data with respect to luminaire location should tend to average out the effects of vehicular lighting, thus leaving the effects of fixed lighting combined in a sense with the effects of an average amount of vehicular lighting.

TABLE 35

RESULTS OF HORIZONTAL ILLUMINATION SURVEY

DIST. FROM LUMINAIRE (FT)	HORIZONTAL ILLUMINATION (FC) AT INDICATED DISTANCE [a]															
	REDUCED								NORMAL							
	SECTION 1, WESTBOUND				SECTION 18, EASTBOUND				SECTION 1, WESTBOUND				SECTION 18, EASTBOUND			
	0 FT	12 FT	24 FT	36 FT	0 FT	12 FT	24 FT	36 FT	0 FT	12 FT	24 FT	36 FT	0 FT	12 FT	24 FT	36 FT
0	0.62	0.85	0.77	0.42	—	—	—	—	1.60	2.05	1.80	1.00	0.15	0.15	0.15	0.26
5	—	—	—	—	0.06	0.07	0.11	0.14	—	—	—	—	—	—	—	—
10	0.40	0.69	0.62	0.35	0.06	0.07	0.11	0.14	1.05	1.80	1.70	0.92	0.15	0.15	0.18	0.26
20	0.29	0.48	0.41	0.25	0.07	0.08	0.08	0.12	0.70	1.15	1.08	0.69	0.12	0.18	0.20	0.26
30	0.25	0.40	0.32	0.21	0.06	0.09	0.10	0.12	0.68	1.00	0.80	0.60	0.12	0.20	0.28	0.28
40	0.19	0.30	0.24	0.15	0.09	0.10	0.10	0.10	0.50	0.65	0.67	0.42	0.17	0.27	0.30	0.25
50	0.12	0.20	0.18	0.13	0.10	0.10	0.12	0.10	0.28	0.42	0.41	0.33	0.21	0.40	0.39	0.38
60	0.10	0.14	0.10	0.12	0.10	0.19	0.18	0.12	0.14	0.30	0.31	0.29	0.42	0.60	0.61	0.50
70	0.08	0.12	0.10	0.10	0.16	0.25	0.21	0.15	0.12	0.18	0.23	0.25	0.65	0.90	0.85	0.61
80	0.08	0.10	0.07	0.09	0.22	0.39	0.30	0.19	0.09	0.15	0.22	0.25	0.90	1.25	1.25	0.75
90	0.08	0.09	0.09	0.09	0.31	0.45	0.41	0.22	0.09	0.15	0.19	0.22	0.95	1.85	1.75	1.00
100	0.07	0.10	0.10	0.10	0.38	0.65	0.62	0.34	0.10	0.15	0.19	0.22	1.55	2.50	2.10	1.15
110	0.08	0.09	0.10	0.10	0.55	0.91	0.68	0.38	0.09	0.18	0.20	0.23	1.55	2.60	2.12	1.10
120	0.09	0.10	0.11	0.10	0.57	0.93	0.68	0.38	0.09	0.16	0.18	0.22	1.08	1.85	1.92	1.00
130	0.10	0.12	0.13	0.11	0.42	0.70	0.61	0.33	0.12	0.20	0.20	0.21	1.02	1.33	1.40	0.70
140	0.12	0.16	0.17	0.13	0.34	0.60	0.39	0.22	0.12	0.25	0.28	0.24	0.81	0.97	1.08	0.59
150	0.13	0.21	0.20	0.15	0.25	0.50	0.28	0.21	0.20	0.35	0.44	0.30	0.59	0.70	0.58	0.42
160	0.20	0.30	0.29	0.20	0.18	0.35	0.20	0.17	0.32	0.55	0.58	0.39	0.35	0.55	0.43	0.30
170	0.23	0.42	0.41	0.29	0.12	0.25	0.15	0.12	0.45	0.90	0.78	0.49	0.30	0.33	0.31	0.27
180	0.35	0.58	0.54	0.35	0.10	0 12	0.11	0.11	0.65	1.10	1.00	0.60	0.22	0.28	0.21	0.25
190	0.41	0.80	0.82	0.49	0.07	0.07	0.08	0.10	0.85	1.55	1.40	0.85	0.20	0.17	0.18	0.25
200	0.60	1.00	0.90	0.52	0.05	0.05	0.08	0.09	1.40	2.15	1.65	1.05	0.12	0.15	0.16	0.20
205	0.61	1.05	0.86	0.53	—	—	—	—	—	—	—	—	—	—	—	—
210	—	—	—	—	0.05	0.08	0.18	0.10	—	—	—	—	—	—	—	—
Mean	*0.24*	*0.38*	*0.34*	*0.23*	*0.20*	*0.32*	*0.26*	*0.18*	*0.41*	*0.70*	*0.65*	*0.44*	*0.53*	*0.79*	*0.75*	*0.49*

[a] Distance from outside edge of pavement (each measurement at edge of respective lane).

As Blackwell (*17, 18, 19*) has shown, the visibility of objects in a roadway environment may be evaluated in terms of photometric quantities in the following manner. If the effects of disability glare are omitted, only values of B, the roadway luminance, and C, the physical contrast of an object in the roadway environment, are required. Blackwell (*20*) has shown the usefulness of defining contrast as follows:

$$C = \frac{B_o - B}{B} \qquad (3)$$

in which

B_o = average luminance of the object; and

B = average luminance of the roadway background of the object.

Although the sign of C as given in Eq. 3 may be usefully neglected, it will be convenient to remember that values less than zero refer to objects darker than their backgrounds, whereas values greater than zero refer to objects brighter than their backgrounds.

Because the current photometric measurements were made by sweeping photometers through the environment, there are no "objects" whose contrast could be measured. Instead, artificial vertical objects of varying luminous reflectance may be created by calculations. By definition,

$$C_\rho = E\rho - B/B \qquad (4)$$

in which

E = the vertical illumination as measured; and

ρ = the luminous reflectance of an artificial vertical object.

Thus, values of C for artificial vertical objects of selected reflectances may be computed and the visibility of these objects in terms of paired values of C and B for selected points along the roadway may be studied.

The analysis which includes the effect of disability glare is only somewhat more complex. As shown earlier by Blackwell (*17*) the visibility of objects in the presence of disability glare may be evaluated in terms of the quantities B_e and C'. That is,

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

$$C' = C\,B/B_e \qquad (6)$$

Eqs. 5 and 6 make it clear that disability glare, which operates by the physical addition of stray light scattered within the eye, affects both the luminance to which the eye is adapted and the physical contrast of the object. Thus, pairs of values of C' and B_e must be evaluated at various locations along the roadway if full account is to be taken of the effects of disability glare.

Evaluation of the pairs of values of B and C, and B_e and C', may be made in terms of basic data describing the relative importance of these quantities to the degree of visibility of an object. The basic data of Blackwell as reported in the *IES Lighting Handbook* (*2*) have been used (Fig. 46) to show the method of analysis. Here one has the trade-off between luminance and contrast for equal visibility. The curve shown represents a degree of visibility which the IES has selected as a suitable criterion level to be supplied by lighting. It represents an accuracy level of 99 percent per single ocular fixation of 1/5 sec for an object subtending an angle of 4 min, considered representative of visual details in environment. It also represents what is called a "field factor" of 6.67. This means that the value of C at a given value of B is 6.67 times the value required for bare detection of presence under the ideal conditions of the experimental laboratory.

The technique of visibility analysis used here was described earlier (*18, 19*). It involves determining the value of the relative visibility factor (RVF). In the present case

$$\mathrm{RVF} = C/\overline{C} \qquad (7)$$

in which

C = the physical contrast without allowance for disability glare; and

$\overline{C}$ = the contrast required for the criterion of visibility built into Figure 46, taken at B.

Similarly,

$$\mathrm{RVF}' = C'/\overline{C} \qquad (8)$$

in which

C' = the physical contrast after allowance for disability glare; and

$\overline{C}$ = the contrast required for the criterion built into Figure 46, taken at B_e.

Values of RVF equal to unity signify that the roadway environment provided precisely the level of visibility considered essential by the IES. Values of RVF less than unity signify that the roadway environment fails to provide the criterion level of visibility.

Throughout this study it has seemed desirable to present separately the analyses in which the effects of disability glare are included and those in which these effects are omitted. In this way, the reader may evaluate the role played by the disability glare effect.

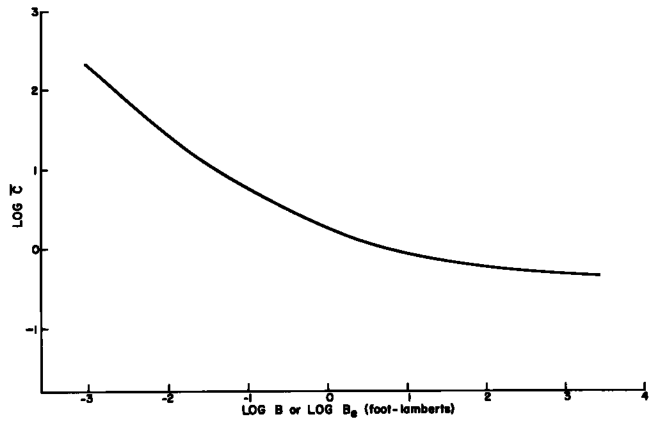

Figure 46. Standard visual performance curve; disc of 4-min angle, ⅕-sec fixation, 99% accuracy; field factor = 6.67.

The secondary analysis of the fluxes coming from different portions of the visual field proceeded in the following way. The flux values recorded by each of the five photometers were expressed in terms intended to represent their percentage contribution to the value of B_v. An approximate weighting coefficient was computed for each of the five photometers, representing an approximate value of the B_v weighting function for the portions of the visual field involved. Each photometer reading was weighted by the appropriate coefficient, and the weighted value for each photometer expressed as a percentage of the total of the five weighted values. Then the averages of these percentage values were obtained for each of the two illumination levels, for each of the four roadway sections. These data will be useful in analyzing the significance of different portions of the visual field in producing disability glare.

CHAPTER NINE

RESULTS

VISIBILITY ANALYSIS

The visibility analysis requires tables of values of E, B, B_v, B_c, C, C', RVF, and RVF′. These data are presented in Tables 36, 37, 38, and 39. Each table presents C and RVF data for vertical objects assumed to have luminous reflectances of 10, 30, 50, and 70 percent and data are segregated by location with respect to luminaires. The six values for different locations have also been analyzed in terms of the arithmetic means and standard deviations, S.

The RVF and RVF′ data are also presented in Figures 47 through 62. These graphs present surveys of disability conditions, in which objects of four different reflections are considered for each of six locations with respect to position of the highway luminaires. The spread of the curves in a given graph reveals the variability in visibility among different objects as they appear in different roadway locations. The center of gravity of the curves represents a single index of the visibility conditions presented in a given roadway section for one or the other illumination condition. Separate graphs are used to present the values of RVF and RVF′.

Inspection of the graphs demonstrates clearly that visibility conditions were improved by the use of the normal illumination conditions. The graphs also show a significant reduction in visibility resulting from the disability glare effect.

A numerical measure of the visibility conditions provided by each of the two illumination conditions can be obtained by averaging the values of mean RVF and RVF′ for objects of the four contrasts. These data are presented in Table 40, which also gives averages of the results for the four roadway sections. It is seen that use of the normal illumination level produced an average increase of 40.8 percent in RVF, the visibility index which omits the effect of disability glare, and produced an average increase of 32 percent in RVF′, the visibility index which includes the effect of disability glare.

Because concern is with the level of visibility provided the driver from moment to moment, it is of interest to assess the variability in the visibility measure as well as the averages. It is only meaningful to describe the standard deviations, S, in terms of the means from which the deviations are measured. Variability may be described best by expressing the value of S as a percentage of its mean. Average values of this variability ratio for all reflectances and both directions of travel are as follows:

	VARIABILITY RATIO (%)	
VISIBILITY INDEX	NORMAL ILLUMINATION	REDUCED ILLUMINATION
RVF	13.1	13.8
RVF′	12.2	14.3

It may also be of interest to compare visibility indices for eastbound and westbound traffic, because eastbound traffic was generally heavier. The data for the averages of the two illumination levels are as follows:

	VALUE	
VISIBILITY INDEX	WESTBOUND	EASTBOUND
RVF	0.374	0.333
RVF′	0.284	0.242

ANALYSIS OF ORIGIN OF DISABILITY GLARE

The data summarizing the percentage contributions to the disability glare effect from the five portions of the visual environment are as follows:

GLARE ZONE	FLUX CONTRIBUTION
1	0.081
2	0.213
3	0.213
4	0.081
5	0.340

TABLE 36

EXPERIMENTAL VALUES, SECTION 1, WESTBOUND

LOCATION RELATIVE TO LUMINAIRES	E	B	B_r	B_e	C FOR $\rho =$				C' FOR $\rho =$				RVF FOR $\rho =$				RVF′ FOR $\rho =$			
					10%	30%	50%	70%	10%	30%	50%	70%	10%	30%	50%	70%	10%	30%	50%	70%
(*a*) NORMAL ILLUMINATION																				
0	0.256	1.202	0.595	1.799	0.970	0.928	0.886	0.843	0.650	0.621	0.593	0.564	0.554	0.533	0.509	0.484	0.439	0.420	0.401	0.381
1	0.313	1.102	0.648	1.750	0.963	0.907	0.850	0.793	0.607	0.572	0.536	0.500	0.529	0.498	0.467	0.436	0.404	0.382	0.357	0.333
2	0.451	1.039	0.624	1.666	0.948	0.862	0.775	0.689	0.594	0.540	0.485	0.431	0.509	0.463	0.416	0.370	0.388	0.353	0.317	0.282
3	0.653	1.016	0.579	1.595	0.928	0.800	0.673	0.545	0.592	0.511	0.429	0.348	0.493	0.425	0.358	0.290	0.382	0.330	0.277	0.225
4	0.941	1.051	0.551	1.601	0.903	0.726	0.549	0.372	0.593	0.477	0.360	0.244	0.485	0.390	0.295	0.200	0.382	0.308	0.232	0.157
5	0.818	1.097	0.539	1.638	0.916	0.764	0.612	0.460	0.614	0.512	0.411	0.309	0.503	0.420	0.336	0.253	0.396	0.330	0.265	0.199
Mean	*0.572*	*1.084*	*0.589*	*1.675*	*0.938*	*0.831*	*0.724*	*0.617*	*0.608*	*0.539*	*0.469*	*0.399*	*0.512*	*0.494*	*0.397*	*0.339*	*0.398*	*0.354*	*0.308*	*0.263*
S	0.245	0.118	0.0497	0.212	0.024	0.023	0.170	0.154	0.020	0.047	0.078	0.110	0.023	0.063	0.075	0.100	0.020	0.037	0.057	0.077
(*b*) REDUCED ILLUMINATION																				
0	0.421	0.778	0.513	1.291	0.927	0.815	0.703	0.591	0.564	0.492	0.420	0.348	0.444	0.390	0.336	0.283	0.332	0.289	0.247	0.205
1	0.282	0.728	0.533	1.261	0.945	0.867	0.789	0.711	0.552	0.508	0.464	0.420	0.440	0.403	0.367	0.331	0.321	0.295	0.270	0.244
2	0.428	0.637	0.501	1.174	0.920	0.793	0.667	0.540	0.536	0.464	0.393	0.321	0.426	0.367	0.309	0.250	0.303	0.262	0.222	0.181
3	0.643	0.650	0.447	1.097	0.887	0.694	0.502	0.309	0.533	0.419	0.306	0.192	0.411	0.321	0.232	0.143	0.293	0.230	0.168	0.105
4	0.769	0.689	0.450	1.138	0.870	0.644	0.417	0.190	0.531	0.394	0.257	0.120	0.405	0.300	0.194	0.0884	0.295	0.219	0.143	0.0667
5	0.771	0.745	0.444	1.189	0.878	0.667	0.455	0.244	0.553	0.418	0.282	0.147	0.408	0.310	0.212	0.113	0.314	0.238	0.160	0.0835
Mean	*0.552*	*0.710*	*0.481*	*1.192*	*0.904*	*0.747*	*0.589*	*0.431*	*0.545*	*0.449*	*0.354*	*0.258*	*0.422*	*0.348*	*0.275*	*0.201*	*0.310*	*0.256*	*0.202*	*0.148*
S	0.186	0.0575	0.0489	0	0.028	0.083	0.137	0.193	0.012	0.042	0.076	0.111	0.015	0.042	0.065	0.091	0.033	0.028	0.047	0.066

TABLE 37

EXPERIMENTAL VALUES, SECTION 6, WESTBOUND

LOCATION RELATIVE TO LUMINAIRES	E	B	B_r	B_e	C FOR $\rho =$				C' FOR $\rho =$				RVF FOR $\rho =$				RVF′ FOR $\rho =$			
					10%	30%	50%	70%	10%	30%	50%	70%	10%	30%	50%	70%	10%	30%	50%	70%
(*a*) NORMAL ILLUMINATION																				
0	0.407	1.047	0.485	1.533	0.952	0.873	0.794	0.715	0.952	0.873	0.794	0.715	0.491	0.449	0.409	0.368	0.411	0.378	0.344	0.309
1	0.473	0.995	0.495	1.491	0.944	0.848	0.753	0.657	0.944	0.848	0.753	0.657	0.502	0.451	0.401	0.349	0.393	0.354	0.314	0.274
2	0.556	0.951	0.461	1.414	0.934	0.818	0.702	0.586	0.934	0.818	0.702	0.586	0.484	0.424	0.364	0.303	0.386	0.338	0.290	0.242
3	0.659	0.933	0.443	1.376	0.922	0.781	0.641	0.501	0.922	0.781	0.641	0.501	0.478	0.401	0.329	0.257	0.377	0.319	0.262	0.205
4	0.829	0.967	0.439	1.406	0.907	0.737	0.567	0.398	0.907	0.737	0.567	0.398	0.470	0.382	0.294	0.206	0.382	0.310	0.239	0.167
5	0.707	1.020	0.460	1.480	0.923	0.784	0.646	0.508	0.923	0.784	0.646	0.508	0.478	0.406	0.334	0.263	0.397	0.337	0.278	0.218
Mean	*0.605*	*0.976*	*0.454*	*1.450*	*0.930*	*0.807*	*0.684*	*0.561*	*0.930*	*0.807*	*0.684*	*0.561*	*0.484*	*0.419*	*0.355*	*0.291*	*0.391*	*0.339*	*0.288*	*0.236*
S	0.141	0.187	0.0948	0.366	0.015	0.042	0.075	0.105	0.009	0.028	0.048	0.070	0.010	0.062	0.041	0.056	0.014	0.022	0.033	0.045
(*b*) REDUCED ILLUMINATION																				
0	0.160	0.644	0.323	0.967	0.957	0.908	0.858	0.809	0.634	0.602	0.569	0.536	0.412	0.391	0.370	0.349	0.332	0.315	0.298	0.281
1	0.190	0.622	0.328	0.950	0.952	0.892	0.833	0.773	0.621	0.582	0.543	0.504	0.409	0.383	0.358	0.332	0.320	0.300	0.280	0.260
2	0.225	0.619	0.322	0.941	0.946	0.875	0.804	0.733	0.621	0.573	0.526	0.480	0.403	0.374	0.344	0.313	0.318	0.294	0.270	0.246
3	0.256	0.635	0.319	0.953	0.942	0.862	0.783	0.703	0.625	0.572	0.519	0.466	0.406	0.372	0.338	0.303	0.324	0.296	0.270	0.241
4	0.313	0.646	0.312	0.957	0.934	0.838	0.743	0.647	0.628	0.564	0.499	0.435	0.406	0.362	0.323	0.281	0.329	0.295	0.261	0.228
5	0.293	0.619	0.363	0.982	0.935	0.843	0.750	0.657	0.594	0.535	0.476	0.417	0.396	0.357	0.318	0.278	0.313	0.282	0.250	0.219
Mean	*0.240*	*0.631*	*0.328*	*0.958*	*0.944*	*0.870*	*0.795*	*0.720*	*0.620*	*0.571*	*0.522*	*0.473*	*0.405*	*0.374*	*0.342*	*0.309*	*0.323*	*0.297*	*0.272*	*0.246*
S	0.0529	0	0.0316	0.0495	0.027	0.025	0.042	0.058	0.013	0.020	0.030	0.040	0.005	0.011	0.022	0.022	0.006	0.010	0.015	0.020

TABLE 38

EXPERIMENTAL VALUES, SECTION 13, EASTBOUND

LOCATION RELATIVE TO LUMINAIRES	E	B	B_t	B_e	C FOR $\rho =$ 10%	30%	50%	70%	C' FOR $\rho =$ 10%	30%	50%	70%	RVF FOR $\rho =$ 10%	30%	50%	70%	RVF' FOR $\rho =$ 10%	30%	50%	70%
(*a*) NORMAL ILLUMINATION																				
0	0.265	0.948	0.726	1.673	0.964	0.908	0.852	0.796	0.543	0.512	0.481	0.450	0.494	0.465	0.437	0.408	0.355	0.334	0.314	0.294
1	0.317	0.885	0.709	1.595	0.956	0.886	0.815	0.745	0.530	0.491	0.452	0.413	0.531	0.492	0.452	0.413	0.342	0.317	0.292	0.266
2	0.516	0.876	0.692	1.567	0.934	0.818	0.702	0.587	0.521	0.455	0.389	0.323	0.519	0.454	0.390	0.326	0.332	0.290	0.248	0.206
3	0.731	0.870	0.685	1.557	0.908	0.740	0.573	0.405	0.507	0.411	0.316	0.220	0.507	0.413	0.320	0.226	0.323	0.262	0.201	0.148
4	0.769	0.925	0.691	1.617	0.909	0.742	0.576	0.410	0.519	0.423	0.327	0.231	0.494	0.403	0.313	0.223	0.334	0.273	0.211	0.149
5	0.527	0.976	0.694	1.671	0.938	0.829	0.721	0.613	0.545	0.482	0.419	0.356	0.501	0.443	0.385	0.328	0.355	0.314	0.274	0.233
Mean	*0.521*	*0.913*	*0.700*	*1.613*	*0.935*	*0.820*	*0.706*	*0.593*	*0.528*	*0.462*	*0.397*	*0.332*	*0.508*	*0.445*	*0.383*	*0.321*	*0.340*	*0.298*	*0.257*	*0.215*
S	0.176	0.370	0.0312	0.20	0.021	0.064	0.029	0.120	0.013	0.036	0.061	0.086	0.013	0.030	0.053	0.075	0.012	0.025	0.040	0.060
(*b*) REDUCED ILLUMINATION																				
0	0.312	0.578	0.405	0.983	0.946	0.837	0.730	0.623	0.557	0.493	0.429	0.367	0.389	0.344	0.300	0.256	0.291	0.258	0.225	0.192
1	0.361	0.512	0.429	0.941	0.913	0.789	0.646	0.506	0.496	0.429	0.351	0.275	0.354	0.306	0.250	0.180	0.254	0.220	0.184	0.141
2	0.513	0.455	0.448	0.903	0.888	0.662	0.435	0.211	0.447	0.334	0.219	0.106	0.330	0.246	0.162	0.0784	0.226	0.169	0.111	0.0535
3	0.543	0.452	0.436	0.888	0.881	0.639	0.400	0.159	0.448	0.326	0.204	0.081	0.324	0.235	0.147	0.0585	0.224	0.163	0.102	0.0405
4	0.554	0.452	0.431	0.857	0.887	0.658	0.431	0.202	0.502	0.373	0.244	0.114	0.333	0.247	0.162	0.0759	0.248	0.184	0.121	0.0564
5	0.580	0.486	0.309	0.843	0.891	0.674	0.457	0.240	0.566	0.428	0.290	0.153	0.353	0.267	0.181	0.0952	0.277	0.210	0.142	0.0750
Mean	*0.477*	*0.488*	*0.410*	*0.902*	*0.910*	*0.710*	*0.516*	*0.324*	*0.503*	*0.397*	*0.290*	*0.183*	*0.347*	*0.274*	*0.200*	*0.124*	*0.253*	*0.201*	*0.148*	*0.093*
S	0.101	0.0142	0.320	0.0142	0.022	0.075	0.125	0.176	0.047	0.059	0.078	0.107	0.054	0.039	0.056	0.071	0.025	0.033	0.044	0.055

TABLE 39

EXPERIMENTAL VALUES, SECTION 18, EASTBOUND

LOCATION RELATIVE TO LUMINAIRES	E	B	B_t	B_e	C FOR $\rho =$ 10%	30%	50%	70%	C' FOR $\rho =$ 10%	30%	50%	70%	RVF FOR $\rho =$ 10%	30%	50%	70%	RVF' FOR $\rho =$ 10%	30%	50%	70%
(*a*) NORMAL ILLUMINATION																				
0	0.247	1.121	0.719	1.841	0.962	0.919	0.876	0.833	0.587	0.561	0.534	0.508	0.534	0.510	0.487	0.463	0.402	0.384	0.365	0.348
1	0.301	1.028	0.761	1.789	0.955	0.897	0.840	0.782	0.549	0.516	0.483	0.450	0.511	0.479	0.449	0.418	0.371	0.348	0.326	0.304
2	0.417	0.993	0.730	1.723	0.942	0.860	0.777	0.694	0.544	0.496	0.448	0.400	0.501	0.457	0.413	0.369	0.360	0.328	0.297	0.265
3	0.615	0.971	0.682	1.652	0.922	0.798	0.674	0.550	0.542	0.468	0.395	0.321	0.483	0.418	0.353	0.288	0.354	0.306	0.258	0.210
4	0.863	0.976	0.663	1.641	0.897	0.724	0.550	0.377	0.534	0.431	0.327	0.223	0.469	0.379	0.288	0.198	0.347	0.280	0.212	0.145
5	0.327	1.085	0.671	1.757	0.906	0.750	0.594	0.438	0.560	0.465	0.370	0.275	0.492	0.407	0.323	0.238	0.373	0.310	0.246	0.183
Mean	*0.545*	*1.029*	*0.704*	*1.734*	*0.931*	*0.825*	*0.718*	*0.612*	*0.553*	*0.490*	*0.426*	*0.363*	*0.498*	*0.442*	*0.386*	*0.329*	*0.368*	*0.326*	*0.284*	*0.242*
S	0.231	0.0312	0.0312	0	0.024	0.73	0.121	0.054	0.017	0.042	0.070	0.099	0.021	0.080	0.070	0.095	0.018	0.020	0.050	0.070
(*b*) REDUCED ILLUMINATION																				
0	0.364	0.639	0.381	1.021	0.926	0.809	0.693	0.577	0.579	0.508	0.437	0.366	0.403	0.352	0.301	0.251	0.309	0.272	0.234	0.196
1	0.388	0.591	0.390	0.982	0.917	0.783	0.649	0.516	0.551	0.473	0.394	0.315	0.384	0.328	0.271	0.216	0.288	0.248	0.206	0.165
2	0.432	0.575	0.379	0.953	0.906	0.751	0.596	0.440	0.544	0.454	0.363	0.271	0.374	0.310	0.246	0.182	0.282	0.235	0.183	0.140
3	0.507	0.561	0.366	0.927	0.893	0.712	0.530	0.349	0.539	0.431	0.323	0.214	0.369	0.294	0.219	0.144	0.276	0.221	0.166	0.110
4	0.591	0.557	0.368	0.925	0.876	0.661	0.445	0.230	0.527	0.400	0.273	0.146	0.358	0.270	0.182	0.0939	0.270	0.205	0.140	0.0749
5	0.619	0.554	0.381	0.935	0.872	0.649	0.426	0.203	0.516	0.386	0.255	0.124	0.356	0.265	0.174	0.0829	0.266	0.199	0.131	0.0639
Mean	*0.484*	*0.580*	*0.378*	*0.957*	*0.898*	*0.728*	*0.556*	*0.386*	*0.543*	*0.442*	*0.341*	*0.239*	*0.374*	*0.303*	*0.232*	*0.162*	*0.282*	*0.230*	*0.177*	*0.125*
S	0.0948	0.126	0.092	0.0316	0.020	0.059	0.098	0.120	0.020	0.042	0.064	0.086	0.016	0.031	0.046	0.061	0.014	0.025	0.036	0.052

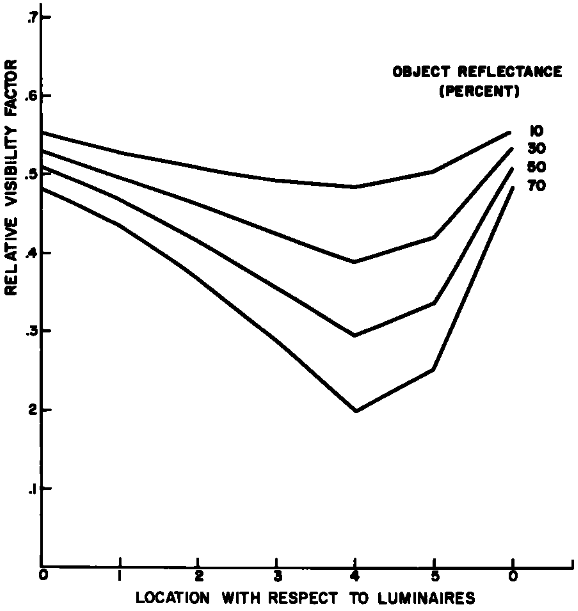

Figure 47. Visibility analysis, section 1, glare effect omitted, normal illumination.

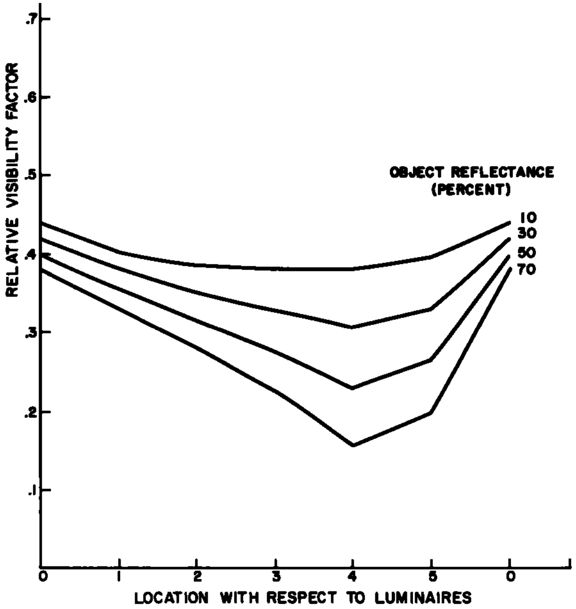

Figure 48. Visibility analysis, section 1, glare effect included, normal illumination.

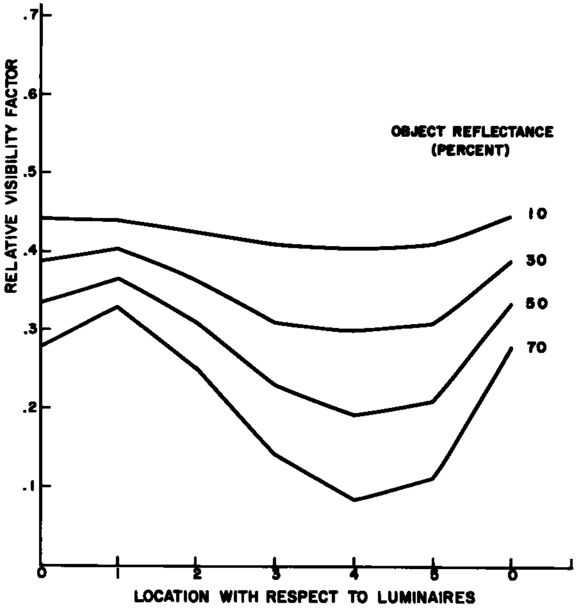

Figure 49. Visibility analysis, section 1, glare effect omitted, reduced illumination.

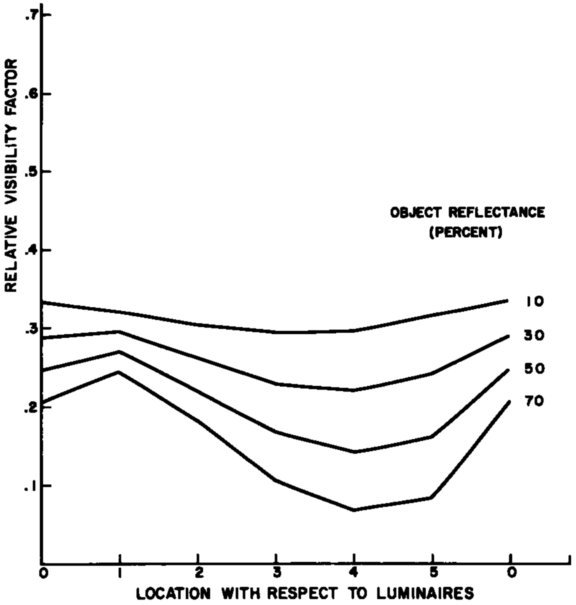

Figure 50. Visibility analysis, section 1, glare effect included, reduced illumination.

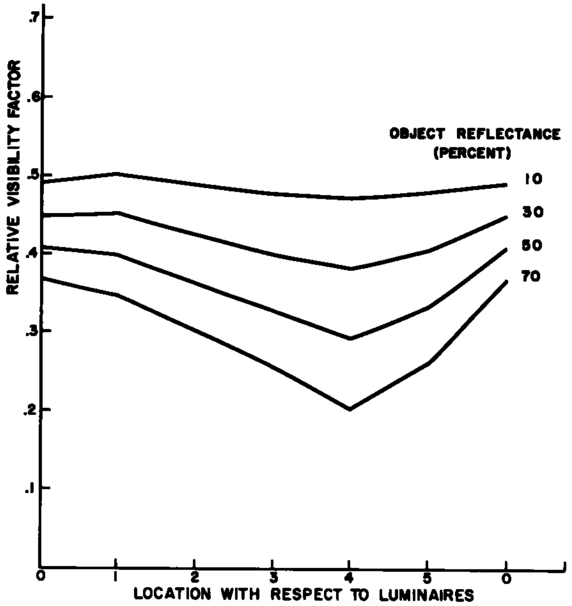

Figure 51. Visibility analysis, section 6, glare effect omitted, normal illumination.

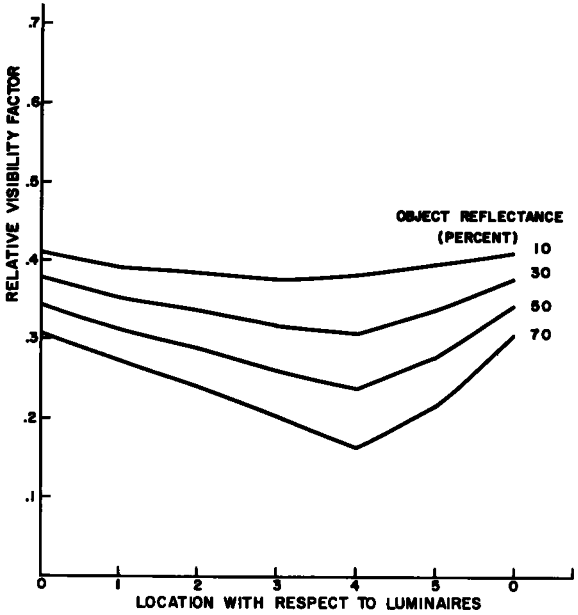

Figure 52. Visibility analysis, section 6, glare effect included, normal illumination.

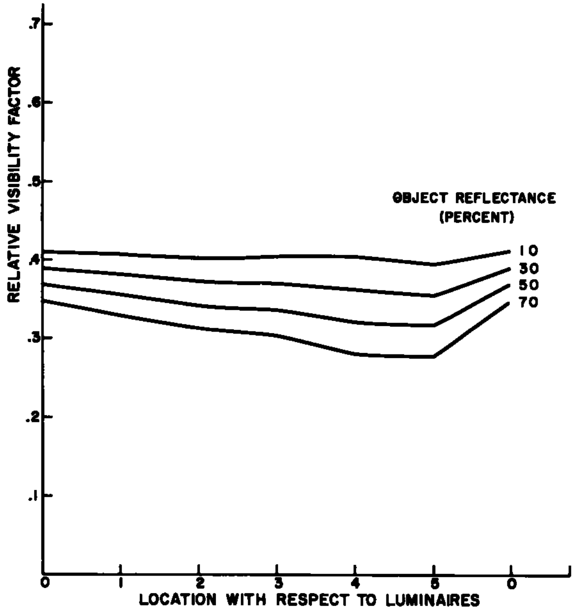

Figure 53. Visibility analysis, section 6, glare effect omitted, reduced illumination.

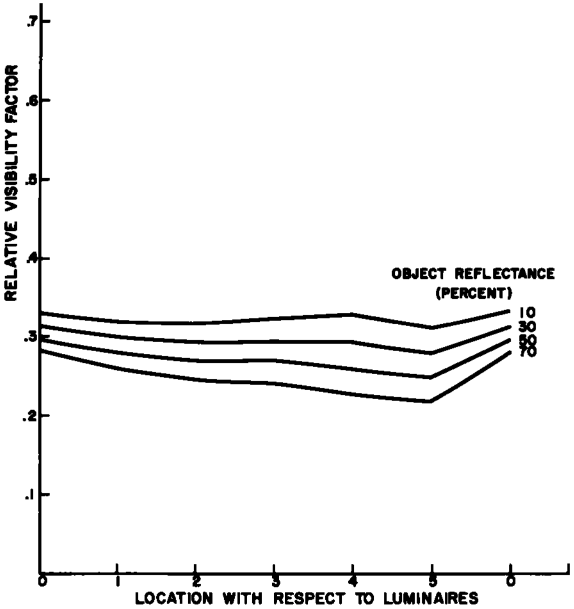

Figure 54. Visibility analysis, section 6, glare effect included, reduced illumination.

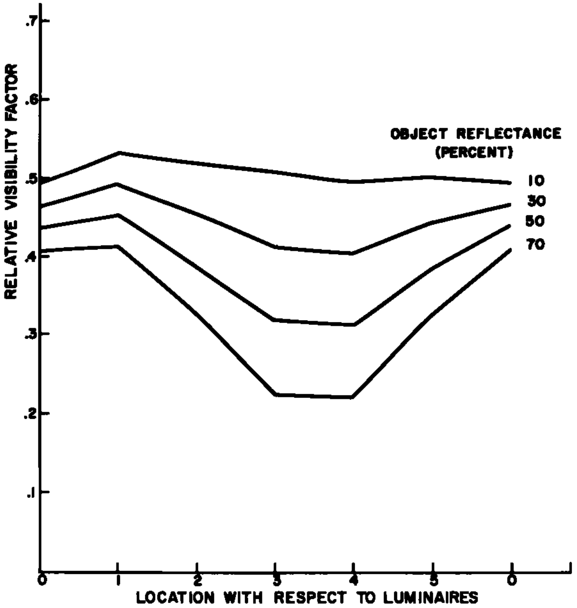

Figure 55. Visibility analysis, section 13, glare effect omitted, normal illumination.

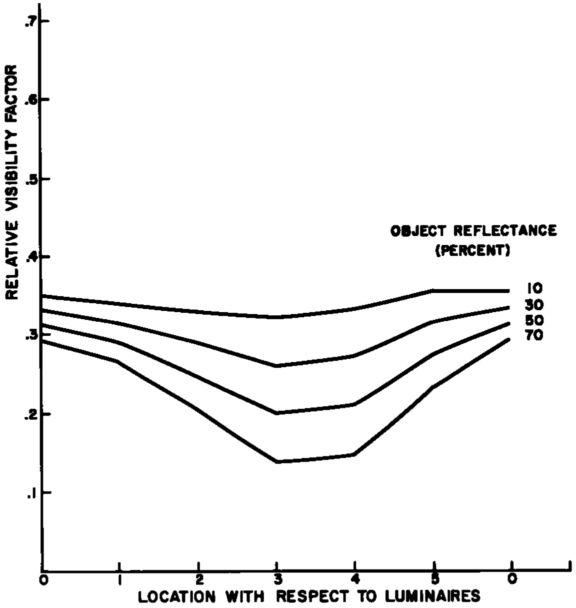

Figure 56. Visibility analysis, section 13, glare effect included, normal illumination.

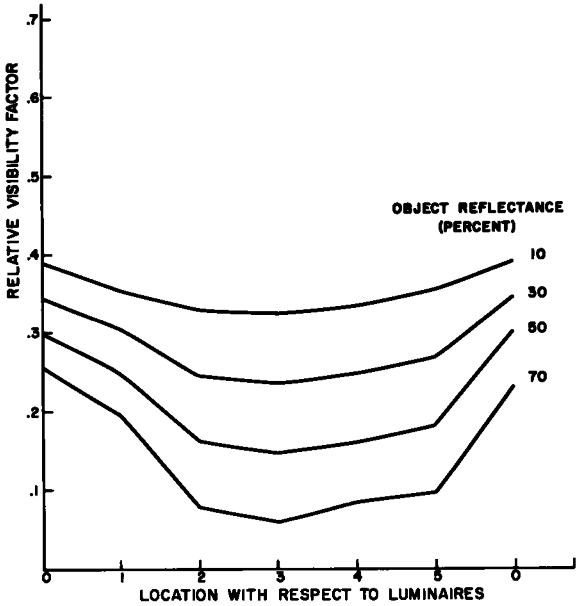

Figure 57. Visibility analysis, section 13, glare effect omitted, reduced illumination.

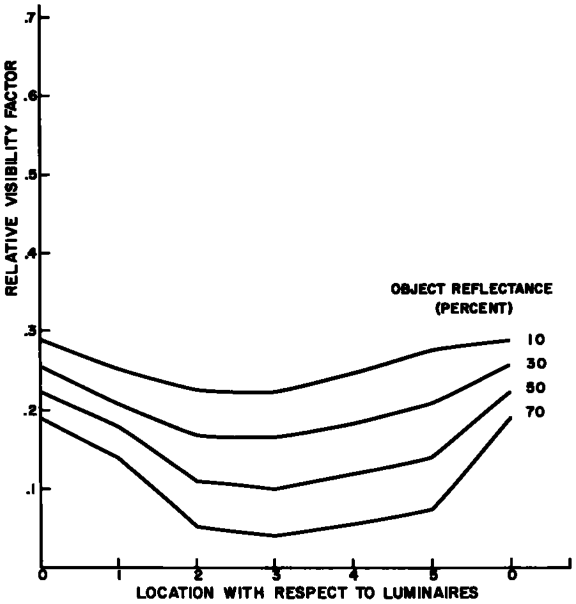

Figure 58. Visibility analysis, section 13, glare effect included, reduced illumination.

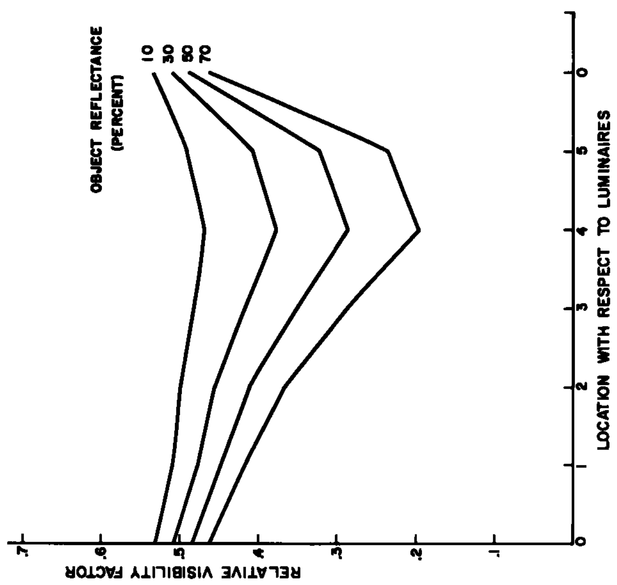

Figure 59. Visibility analysis, section 18, glare effect omitted, normal illumination.

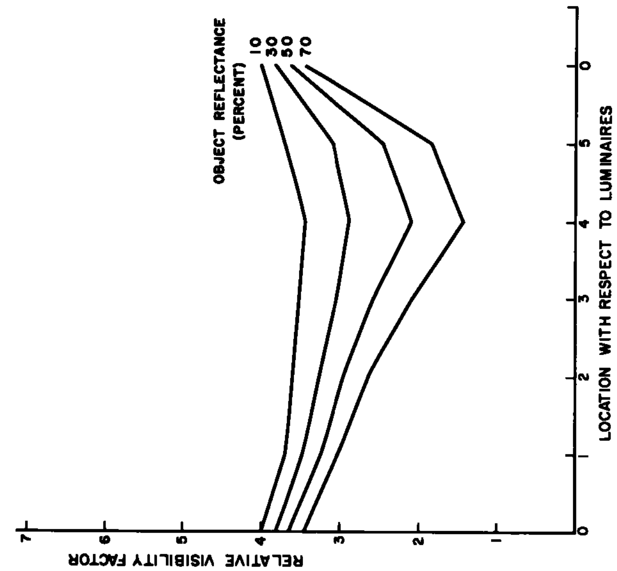

Figure 60. Visibility analysis, section 18, glare effect included, normal illumination.

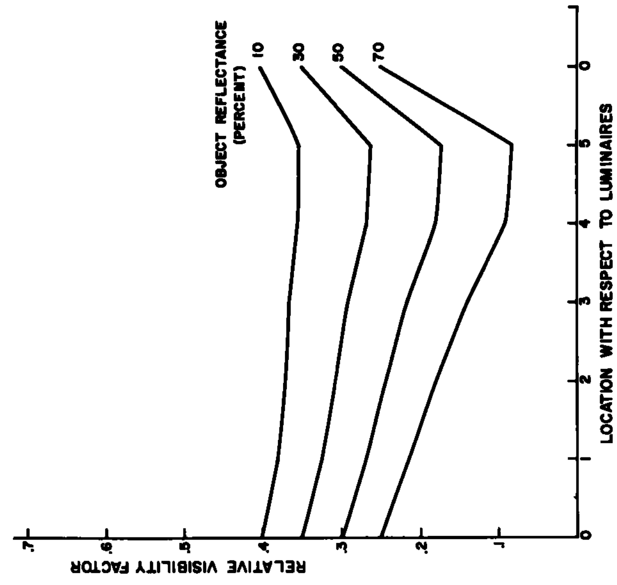

Figure 61. Visibility analysis, section 18, glare effect omitted, reduced illumination.

TABLE 40

COMPARISON OF RELATIVE VISIBILITY FACTORS

			RELATIVE VISIBILITY FACTOR		
ILLUMINATION [a]	GLARE EFFECT [b]	OBJECT REFLECTION (%)	WEST-BOUND	EAST-BOUND	GRAND MEAN
R	O	1	0.414	0.361	
		30	0.361	0.289	
		50	0.309	0.216	
		70	0.255	0.143	
		Mean	*0.335*	*0.252*	*0.294*
N	O	10	0.498	0.503	
		30	0.457	0.444	
		50	0.376	0.385	
		70	0.315	0.325	
		Mean	*0.412*	*0.414*	*0.413*
R	I	10	0.317	0.268	
		30	0.277	0.276	
		50	0.239	0.163	
		70	0.210	0.109	
		Mean	*0.261*	*0.192*	*0.226*
N	I	10	0.374	0.354	
		30	0.329	0.312	
		50	0.284	0.271	
		70	0.239	0.229	
		Mean	*0.306*	*0.292*	*0.299*

[a] R = reduced, N = normal. [b] O = omitted, I = included.

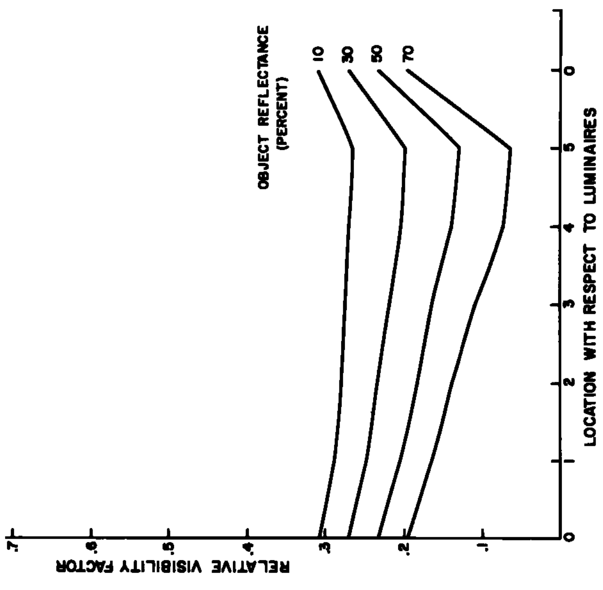

Figure 62. Visibility analysis, section 18, glare effect included, reduced illumination.

CHAPTER TEN

DISCUSSION

The key data are the grand mean values of RVF and RVF′, which characterize the degree to which a variety of objects will be visible in a variety of locations under each lighting condition. These values, given in Table 40, show that visibility was greater under the higher level of illumination by 32.4 percent with the disability glare effect included and 40.8 percent with the disability glare effect omitted.

One may well wonder how to interpret such differences. One method is to describe how much roadway illumination would be required to increase object visibility by these amounts in the simple case where there was no vehicular lighting. These quantities may be evaluated by reference to Figure 46, assuming that objects have an average reflectance of 50 percent. Using 0.22 fc of illumination as a base, one may say that the actual physical increase in illumination to 0.62 fc increased object visibility as much as a hypothetical increase to 0.36 fc, using the visibility data in which the disability glare effect was included. Using the visibility data in which the disability glare effect is excluded, the increase in visibility brought about by an actual increase to 0.62 fc had the effect to be expected from an increase from 0.22 to 0.42 fc.

This point may be illustrated in another way. The visibility improvement to be expected from a simple increase in illumination from 0.22 to 0.62 fc may be computed from Figure 46 as 78.9 percent. With the glare effect included the increase was only 32.4 percent. Thus, in the real roadway situation, the increase is illumination from 0.22 to 0.62 fc provided only 41.1 percent of the improvement in object visibility which may have been expected in some abstract sense.

These data reveal that the visibility improvements actually brought about by nearly tripling the illumination level were not nearly as great as would be expected on the basis of a simplified visual analysis. The primary reason, no doubt, is that vehicular headlights produced a substantial portion of the total illumination and these were presumably the same for the two lighting installations. This analysis suggests that the over-all effect of increasing fixed highway illumination on the operating characteristics of highways will depend on traffic volume, with the effects being least when traffic volume is high. Other aspects of the analysis suggest that the higher level of illumination slightly reduced the percentage variability of visibility from location to location and object to object in the highway environment.

In a global sense, the visibility improvements found due to the increase in illumination from 0.22 to 0.62 fc are relatively small compared to the change in visibility which occurs from night to day, but quite large compared to the improvements provided by substantial changes in the much higher levels of illumination used in interior environments. It may be argued that increases in visibility provided by increases in general illumination merely increase the number of visual tasks which can be adequately performed. If the tasks are relatively easy, they can be performed at very low levels of illumination, and the rather modest change from 0.22 to 0.62 fc would not have much effect on their performance. However, if the tasks were more difficult, this change in illumination could be expected to have a sizable effect on performance. Difficult visual tasks may not be required often in freeway driving, but when they are required they may be crucial to safety. Measuring general traffic flow or driving behavior will, of course, tend to mask this potentially important effect of illumination on visibility, because critical visual tasks may occur infrequently.

The present study reveals that visibility was better at 0.62 than at 0.22 fc, although perhaps by a smaller amount than might have been expected. Other portions of the present study do not reveal the expected improvements in driver performance and traffic flow which were expected from the use of the higher illumination level.

PART IV

DRIVER APPREHENSION

KENNETH PERCHONOK AND PAUL M. HURST
INSTITUTE FOR RESEARCH
STATE COLLEGE, PENNSYLVANIA

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PART I Operating Characteristics of Freeways

PART II Driving Performance

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PART IV

DRIVER APPREHENSION

SUMMARY

Questionnaires were handed out to drivers on the Connecticut Turnpike to study the effects of differential roadway lighting on driver apprehension and dissatisfaction. The roadway illuminations corresponded to 0.6 and 0.2 fc. The questionnaires were given to drivers at a toll station preceeding the 5-mile test site by 2 miles; they were returned using self-addressed, postage-paid envelopes. Drivers were instructed to answer the questionnaire when they finished driving. The returns were sorted on the date and the exit used by the driver in order to help insure utilization of data for which drivers still retained knowledge of their attitudes in the test site.

The questionnaire contained four sections. The first was concerned with personal information determining where the driver left the Turnpike, his driving experience, his familiarity with the road, and the date on which he filled out the questionnaire.

The second section, the DCS (Driver Comfort Scale), was a check list containing 21 items referring to feelings of apprehension, safety, etc. Scaling procedures were applied in order to assign weights to driver responses and, hence, scores to each driver.

The third section, a checklist, contained statements of potential visual difficulties for drivers. The number of statements checked constituted an NTD (Nighttime Driving) score which was taken as a measure of driver dissatisfaction.

The last section of the questionnaire simply provided space in which drivers were encouraged to write comments.

A total of 615 returns were analyzed. None of these drivers indicated awareness of the illumination change. Inasmuch as the lighting was changed only in the test site, subjective differences in intensity must have been slight.

The results indicated that apprehension and dissatisfaction were higher for the higher, rather than lower, illumination levels. DCS scores showed apprehension to be greater (1) when the higher roadway lighting was in effect, (2) when there was more light from the moon, and (3) during the day as opposed to night. NTD scores were higher: (1) when the higher roadway lighting was in effect; and (2) when there was more light from the moon. Most of these effects were not statistically significant at conventional levels; however, reduced illumination was not detrimental.

Other results include: (1) Reflected headlights of following vehicles were by far the most frequent source of complaint. (2) As weather caused reduced visibility and wet or snow covered roads, apprehension increased. (3) Vehicle volumes had essentially no effects on driver apprehension and dissatisfaction.

CHAPTER ELEVEN

INTRODUCTION AND RESEARCH APPROACH

A casual survey of automobile drivers could be expected to yield a variety of stated attitudes about the effects of roadway lighting conditions. Many drivers would undoubtedly exhibit some apprehension about driving at night on an unlighted road; others might prefer to drive in such situations. Between the two extremes of unlighted nighttime driving and daytime driving exists a continuum of lighting conditions which vary due to the effects of street lights, headlights, moon light, etc.

The general aim of this research was to ascertain the existence of systematic relationships between roadway lighting and driver apprehension. This investigaton was aimed not at driver attitudes about lighting conditions, but rather at the effect of these conditions on driver attitude. That is, prime interest was not placed upon drivers' opinions of what constitutes good or bad lighting, but rather upon the effects of differential lighting on drivers' general apprehension levels.

Two areas were investigated. In the first, drivers were queried directly about feelings of "apprehension," "safety," "confidence," "relaxation," etc. The second area of study related to visual problems experienced by people driving at night.

RESEARCH APPROACH

The instrument utilized to measure driver attitudes was a questionnaire. Copies were handed out to drivers in a pilot study, and later in seven separate data collections. They were given to drivers at a toll station preceding the test site; drivers were asked to fill out the questionnaire immediately after completing their trip. The test site was a section of the Connecticut Turnpike approximately 5 miles long on which the illumination provided by roadway lights was either at its normal level or lower. The normal level was 0.6 fc, whereas the lower level was 0.2 fc. The change was made by replacing the mercury-vapor lamps.

Data Collection

Each westbound driver was asked to take a questionnaire as he stopped to pay his toll at the Stratford toll station on the Connecticut Turnpike. If he accepted the questionnaire (which almost all did), he was asked to fill it out immediately after completing his trip; return-addressed, postage-paid envelopes were provided.

The toll station preceded the 5-mile test site by approximately 2 miles. The test site, on which the illumination was varied, was a high-volume, 6- to 8-lane road which provides short-range transportation within and between medium sized cities, as well as longer-range transportation between upper New England and New York City. Entrances and exits in the area average approximately two of each per mile.

Data were collected both day and night, with the majority at night. Each of the seven data collections was spread over three consecutive days, which always ran from Monday to Wednesday. Within each collection, there were three handout sessions per day with starting times held constant over the three days. The schedule of data collections is given in Table 41. (Modifications were made in lane definition and speed control during the term of the project; this is noted in Table 41.) The first nighttime session of each day was initiated well after apparent sunset. Times were chosen so as to include high volumes and to include drivers with high, as well as low, familiarity with the road.

The dates for the collection of data were selected to permit the comparisons given in Table 42. This pattern allowed for the study of the effects of *changing* illumination as well as *changed* illumination while obviating the potentially confounding influence of the change in speed markers and lane separators.

At the time of each handout session, two other types of information were obtained. Weather and road conditions were noted—the former with respect to cloudiness and precipitation, and the latter in terms of wet, dry, and snow cover. Also, vehicle volumes during the time questionnaires were actually being given to drivers. Due to the presence of entry ramps and exits, these volumes were not equal to test site volumes; however, they were used as indicators of test site volumes.

The Questionnaire

A copy of the questionnaire in its final form is shown in Appendix K. The first page of the questionnaire, the "Personal Information Section," was used to determine (1) where the vehicle left the Turnpike, (2) the subject's driving experience measured as his approximate annual mileage, (3) the subject's familiarity with the test site measured by the approximate frequency with which he drives on it, and (4) the date on which he answered the questionnaire. (Provisions were made to detect individuals returning more than one questionnaire. However, the frequency was so low that this information was essentially ignored.)

Because interest was in measuring apprehension as influenced by the lighting level, steps were taken to reduce contamination due to expression of relatively permanent opinions about highway lighting (e.g., "Everyone knows higher illumination reduces accident frequency.") Instead of analyzing all returns, cutoff points were established and questionnaires were disregarded if they were filled out more than one day after receipt or if they were

TABLE 41

DATA COLLECTION SCHEDULE

DATE	TIME (PM)	ILLUM. LEVEL	ROAD CHANGE
Dec. 16-18, 1963	5:30, 7:30, 9:00	Normal	No
Feb. 17-19, 1964	6:00, 7:30, 9:00	Low	No
Aug. 17-19, 1964	1:30, 8:30, 9:30	Low	Yes
Nov. 16-18, 1964	5:30, 7:30, 9:00	Low	Yes
Dec. 14-16, 1964	5:30, 7:30, 9:00	Normal	Yes
Feb. 15-17, 1965	6:00, 7:30, 9:00	Normal	Yes
Aug. 9-11, 1965	1:30, 8:30, 9:30	Normal	Yes

TABLE 42

PLANNED COMPARISONS

DATA COLLECTIONS	TREATMENT
Dec. 1963 vs Feb. 1964	Effect of reducing illumination
Aug. 1964 vs Aug. 1965	Effect of low vs normal illumination
Nov. 1964 vs Dec. 1964	Effect of increasing illumination
Nov. 1964 vs Feb. 1965	Effect of low vs normal illumination
Dec. 1964 vs Feb. 1965	Transitory effect of increasing illumination

filled out by drivers who remained on the Turnpike more than approximately 5 miles beyond the end of the test site. The questionnaire contained no written reference to the illumination change. (An early form of the questionnaire did not require that the date be entered; at that time, the postmark was compared to the cutoff date.)

The second section of the questionnaire, the "Driver Comfort Scale," or "DCS," consisted of 21 statements which subjects were instructed to check to indicate those with which they agreed. Originally 80 items were written which described possible feelings along a dimension ranging from apprehension to security. These items were submitted to each of 20 psychologists, who were instructed to locate each item on the apprehensive-secure dimension. Twenty-five of the 80 items were retained because they met two basic requirements: (1) the consistency of judges' ratings was such as to indicate minimum misunderstanding and ambiguity of the item, and (2) the range from extreme apprehension to extreme security was fairly uniformly covered.

In November 1963 a pilot study was run in which 1,500 questionnaires containing these 25 items were submitted to drivers on the Connecticut Turnpike. A subsequent analysis led to the rejection of four more items due to their failure to sufficiently discriminate between high- and low-apprehension drivers. In other words, these four items seemed to measure something different than the other 21 items. The remaining 21 items thereafter constituted the Driver Comfort Scale section of the questionnaire.

The third section of the questionnaire, labeled "Nighttime Driving." and hereafter referred to as "NTD," was a check list consisting of 15 items. The first 14 items each specified potential difficulties associated with vision in nighttime driving. The last item, "none of the above," simply offered an indication as to whether a blank page was overlooked or intentionally unmarked. This section was included to provide a measurement of dissatisfaction with visual conditions and to provide knowledge of the sources of such dissatisfaction.

Finally, space was allowed for drivers to respond in an unrestricted manner about any problems associated with their drive.

DCS Scaling Procedures

In order to maximize the information obtained from the DCS, weights were assigned to each possible response. Basically, the intention was to assign weights so that if response A indicated more apprehension than did response B, then weight A should have the more negative weight. Once the weights were determined, a subject's score was given by the arithmetic mean of the weights associated with his responses. This class of scoring technique yields far more discrimination of apprehension levels than merely counting response frequencies.

The specific technique for determining weights is given by Guttman (*21*) and Mosteller (*22*). In this approach each of the 21 items was considered to have two response categories corresponding to "agree" or "disagree." Weights were then assigned to each of the 42 categories so that viewing all subjects simultaneously, "categories checked by a person have weights as much alike as possible and as different as possible from weights assigned to categories not checked by that person." (*22*). In other words, if one considers the categories, each placed according to its weight on a measuring stick, those categories checked by each individual should hopefully be close to each other. The effect is to maximize the difference in scores from person to person. The degree to which this can be achieved is dependent strictly on the data and can be measured in terms of the correlation ratio, η, between subjects and the weights of the categories they checked. Appendix L contains an outline of the technique of assigning weights to categories and scores to subjects.

If a situation is considered in which categories refer solely to different degrees of the same characteristic and subjects are able to judge quite accurately the amount of the characteristic they possess, the resulting data might look like Table 43, which displays four subjects and two items. Scaling these data according to the techniques used in this research yields the scalogram given in Table 44, in which weights have been assigned to response categories, scores computed for subjects, and both categories and subjects have been ordered in terms of weights and scores, respectively. The correlation ratio for these data is 0.82.

Under less desirable circumstances, with a less than perfect test and subjects who cannot accurately place themselves with respect to the characteristic being mea-

TABLE 43

CHART OF HYPOTHETICAL DATA SHOWING CATEGORIES CHECKED BY SUBJECTS IN A TWO-ITEM TEST

SUBJECT DESIGNATION	RESPONSE TO CATEGORY A	B	C	D
A	X		X	
B	X		X	
C	X			X
D		X	X	

TABLE 44

SCALOGRAM FOR HYPOTHETICAL DATA IN TABLE 43

SUBJECT		CATEGORY WEIGHT/RESPONSE CATEGORY			
SCORE	DESIGNATION	−3/B	−2/C	1/A	3/D
−2	D	X	X		
0	A		X	X	
0	B		X	X	
2	C			X	X

sured, a scalogram such as that in Table 45 might result. Here, $\eta = 0.71$.

A noticeable characteristic of scalograms is the tendency for the X's to fall into a cluster in the shape of a parallelogram extending diagonally across the page. This is simply a restatement of the intent of the scaling procedure. It should be noticed that the data in Table 44 fall into a tighter cluster than those in Table 45, and that this is reflected in the respective values of the correlation ratios.

The nature of this scaling procedure is such that the numbers assigned weights and scores will be positive and negative; however, this does not mean that a negative score implies apprehension, nor does a positive score necessarily indicate lack of apprehension. The resultant weights or scores for the data on which the scale is based can be transformed by any linear translation without changing their meaning. Thus differences between, rather than absolute values of, weights and scores carry the provided information.

TABLE 45

SCALOGRAM FOR LESS SCALABLE DATA

SUBJECT SCORE	CATEGORY WEIGHT −4	−2	2	4
−3	X	X		
−1	X		X	
1		X		X
3			X	X

CHAPTER TWELVE

RESEARCH RESULTS

From a subjective point of view, the two levels of illumination utilized in the study were barely, if at all, discernible. The most notable information obtained in the last, or "Comments," portion of the questionnaire was the failure of a single reference by drivers to the change in illumination. Inasmuch as the lower illumination level occurred only in the test site, as contrasted with areas of the road immediately preceding and following it, and because drivers' comments ranged from expressions of appreciation for the overhead lights to discussions of roadside washrooms, there seems to be a strong indication that drivers did not realize that a different illumination level was in effect. Therefore, many of the analyses discussed herein relate to the attempted measurement of effects reflecting events of which drivers were not consciously aware.

DRIVER COMFORT SCALE

Item Analysis

Table 46 gives the distribution of the returned questionnaires.

The weights for the driver comfort scale (DCS) were determined using the 615 nighttime returns. A scalogram giving the responses for every 20th subject is given in Table 47. The diagonal spread of the data points shows that it was possible to assign weights and scores so that the characteristic measured by the DCS could be distinguished from person to person. For this set of subjects $\eta = 0.54$, or $\eta^2 = 0.29$. This means that 29 percent of the variance in all responses is accounted for by differences in

TABLE 46

BREAKDOWN OF QUESTIONNAIRE RETURNS

DATA COLLECTION	ACCEPTABLE RETURNS				
	NIGHTTIME, NO PRECIP., DRY ROAD	TOTAL NIGHTTIME	TOTAL DAYTIME	TOTAL	ALL RETURNS
Dec. '63	49	72		72	512
Feb. '64	46	66		66	544
Aug. '64	50	63	46	109	542
Nov. '64	113	157		157	527
Dec. '64	121	121		121	422
Feb. '65	112	112		112	400
Aug. '65	22	24	28	52	377
Total	513	615			3,324

that characteristic measured by the DCS; viz., apprehension. Table 48 gives the item categories and their resultant weights. Each item appears twice—when it appears marked "APP," the weight is that given for an apprehensive response; "SEC" indicates the weight if the secure response is chosen.

TABLE 47

A PORTION OF THE SCALOGRAM RESULTING FROM QUESTIONNAIRE RETURNS

	SUBJECT SCORE	HIGH APPREHENSION LOW
HIGH	−14.2	XXXXXXXXXXXXXXXXXXXXX
	−11.0	XXXX XXXXXXXXX XXXXXXX X
	−8.6	XX X XXX X XXX XXXXXX XX XX X
	−6.9	X XXX XXXXXXXXXXXXX XXX X
	−6.0	XXXX XXX XXX X XX XX XXX X X X
	−5.1	XXX X XXXXXXXXX XX XX XX XX
	−4.1	X XX XXXXXXXXXXXXX XX XX X
	−3.6	XXXXXXXX XXXXXX XXXX X X X
	−2.6	X XXXX XX XXX XXXXXXXX X XX
	−2.2	X XX X XXXXX XXX X XX X XXXX X
	−1.6	XXX XX X XXXXXXXXXXXX X X X
	−1 0	XX XXX X X XXX XXXX XXXX X XX
	−0.4	X X X X X X X X X XXXXXX X XX XX X
APPREHENSION	0.1	X X X X XXXXXXXXXXX XXXXX X
	0.5	X X XXXXXXXXXXXXXXX XXXX
	0.9	XXXXXXXXXXXXXX XX XXXX X
	1.3	X X X XXXXXXXXXXXXXX X XXX
	1.6	X XX X XXXXXXXXX XX XXXXX X
	1.9	X X X XXXXXXXXXXXXXXXXXX
	2.3	XXX XXXXXXXXX XXXXXXXX X
	2.7	X X XX XXX XXX XXXXXXXXX XX
	3.1	X X X X XXXXXXX X XXXXXXXX X
	3.4	XX X X XXXXXXX XX XXXXX XXX
	3.7	X X XXXXXXXXXXXXXXXXXX X
	4.0	X X XXXXXXXXXX XXXXXXXXX
	4.6	X X XXXXXXXXXXXXX XX XXXX
	4.8	XXXXXXXXXXXXXXXXXX XXX
	5.0	X X XX XXXXXXXXXXXX XXXXX
	5.6	XXXXXXXXXXXXXXXXXXXXX
LOW	5.8	X XX XXXXXXXXXXXXXXXXXX
	6.4	XXXXXXXXXXXXXXXXXXXXX

TABLE 48

DCS CATEGORIES RANKED BY WEIGHT

RANK	WEIGHT	RE-SPONSE	ITEM CATEGORY
1	−34.08	APP	I thought the drive was extremely hazardous.
2	−25.82	APP	I wish I could have felt more safe on my trip.
3	−23.09	APP	Actually, the driving was not a simple task.
4	−19.80	APP	I felt slightly apprehensive.
5	−19.39	APP	I felt uneasy about passing other vehicles or being passed by them.
6	−18.00	APP	I drove in accordance with my usual driving habits.
7	−16.78	APP	I would not like to drive on this road at night more frequently than is necessary.
8	−15.71	APP	The drive required almost my full concentration to insure against accidents.
9	−15.46	APP	For the most part, I felt no great demands on my driving ability.
10	−14.52	APP	I tried to be more careful than usual.
11	−11.65	APP	I didn't feel that the drive was particularly stressful.
12	−10.60	APP	I was extremely careful.
13	−10.24	APP	I felt completely relaxed.
14	−9.72	APP	Most of my driving involved rather automatic responses.
15	−9.38	APP	At no time did I feel unsafe.
16	−8.70	APP	I thought some other drivers were discourteous in their driving.
17	−8.27	APP	I was always confident that I was safe.
18	−7.78	APP	At times other drivers seemed quite thoughtless.
19	−7.65	APP	I found I had ample time to think about things not related to driving.
20	−6.94	APP	The thought that I might have an accident never entered my mind.
21	−5.65	APP	I felt the drive was completely free from hazards.
22	1.52	SEC	I drove in accordance with my usual driving habits.
23	1.87	SEC	I thought the drive was extremely hazardous.
24	3.92	SEC	I was extremely careful.
25	4.27	SEC	I felt slightly apprehensive.
26	4.32	SEC	I felt uneasy about passing other vehicles or being passed by them.
27	4.54	SEC	I wish I could have felt more safe on my trip.
28	4.59	SEC	Actually, the driving was not a simple task.
29	4.78	SEC	I thought some other drivers were discourteous in their driving.
30	5.08	SEC	I would not like to drive on this road at night more than is necessary.
31	5.24	SEC	I tried to be more carful than usual.
32	5.33	SEC	At times other drivers seemed quite thoughtless.
33	5.93	SEC	Most of my driving involved rather automatic responses.
34	6.05	SEC	The drive required almost my full concentration to insure against accidents.
35	7.13	SEC	For the most part, I felt no great demands on my driving ability.
36	7.66	SEC	I didn't feel that the drive was particularly stressful.
37	8.63	SEC	I found I had ample time to think about things not related to driving.
38	9.93	SEC	The thought that I might have an accident never entered my mind.
39	10.44	SEC	At no time did I feel unsafe.
40	10.86	SEC	I was always confident that I was safe.
41	10.97	SEC	I felt completely relaxed.
42	12.45	SEC	I felt the drive was completely free from hazards.

Figure 63 shows the distribution of the DCS scores, based on all acceptable nighttime scores. It appears to be truncated on the right (or skewed to the left), with the cutoff occurring at the highest possible score. This indicates that the questionnaire would probably have been more sensitive had categories corresponding to more highly secure responses been available. It was judged, based on work by Norton (*23*) and Scheffe (*24*), that the shape of this distribution should not preclude the use of statistics requiring normal distributions.

Roadway Lighting

All analyses and values reported in this section were based on data collected when the road was clear and dry and there was no precipitation. In this way, confounding effects of weather were held to a minimum.

Figure 64 shows the effect of illumination on DCS mean scores for particular illumination conditions. The abscissa refers to data collections arranged in order from lighting recently returned to normal, to normal, to low, to recently reduced to the lower level. Thus, any systematic effects of illumination level on apprehension should be observable. Inspection of the plotted information failed to yield such systematic effects. There appeared to be no support for the hypotheses that increasing illumination, or that higher illumination, resulted in more secure driver responses.

To statistically test illumination effects, three analyses of variance were performed in accordance with the comparisons described in Table 42. The results are given in Table 49.

Recalling that a higher (more positive) DCS score corresponds to less apprehension or more security, the following can be seen: (1) In the first analysis, although reducing the illumination yielded more apprehension, the difference was so insignificant as to yield an *F*-ratio smaller than 1. (2) In the second analysis, again the analysis of variance showed the difference between means

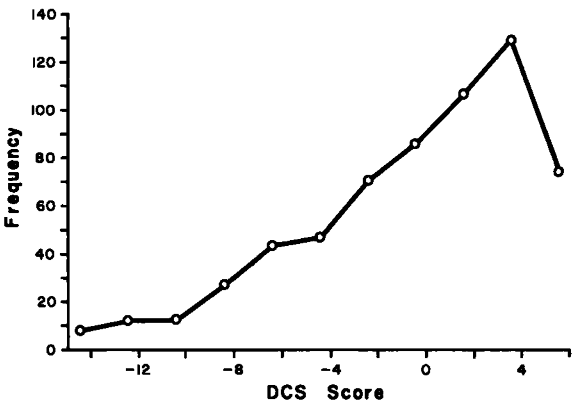

Figure 63. Distribution of DCS acceptable nighttime scores.

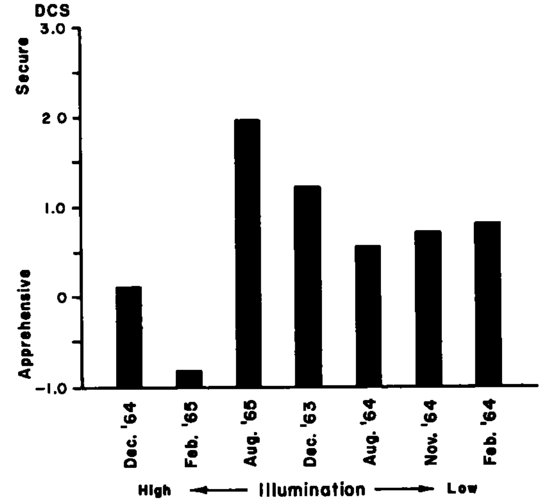

Figure 64. Effect of illumination on DCS mean scores for particular illumination conditions.

to be insignificant; once again the difference was in the direction of more secure responses for the higher illumination condition. (3) In the third analysis, the lowest illumination condition produced the least apprehension; the value of the *F*-ratio corresponds approximately to the 6 percent level of significance. By combining the results of these statistical analyses with the curve of Figure 64, it can safely be concluded that no increase in apprehension for lower illumination was found.

Because the results just given may well have been influenced by other factors, a multiple linear regression analysis was performed in order to remove some of these effects; viz., driver familiarity with the road, driver experience, and vehicle volume at the time of the data collections. This analysis yielded expected values of DCS means under the hypothetical condition that there were no linear effects on DCS scores of familiarity, experience, and volume; thus, "purer" estimates of light effects were obtained. The results are given in Figure 65. Although this curve

TABLE 49

ILLUMINATION EFFECTS: THREE COMPARISONS

DATA COLLECTION	ILLUMINATION CONDITION	SAMPLE SIZE	MEAN DCS SCORE	RELATIVE APPREHENSION *	
Dec. '63	Normal	49	1.217	Low	
Feb. '64	Low, recently reduced	46	0.808	High	
			Diff. between means:		0.409
			Standard error:		0.773
			Student *t*:		0.529
			p (for two-tailed test):		>0.50
Aug. '64	Low	50	0.556	High	
Aug. '65	Normal	22	1.981	Low	
			Diff. between means:		1.425
			Standard error:		1.218
			Student *t*:		1.169
			p (for two-tailed test):		0.24
Nov. '64	Low	113	0.712	Low	
Dec. '64	Normal, recently increased	121	0.114	—	
Feb. '64	Normal	112	—0.808	High	
			Between groups means square:		65.942
			Within groups mean square:		22.405
			F ratio:		2.943
			p (for two-tailed test):		0.06

* Relative apprehension refers to a comparison within analyses; it is provided simply as an aid in interpreting differences in DCS means.

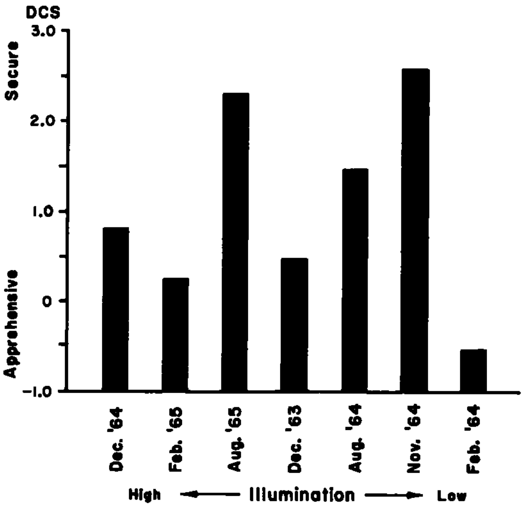

Figure 65. Expected values of DCS means with no linear effects by familiarity, experience, and volume.

differs from the uncorrected curve in Figure 64, here again an obvious relationship between illumination and apprehension fails to exist.

Next, an analysis of variance was performed which compared the raw mean for all normal illumination data collections versus that for those data collections in which the low illumination level was in effect. The results are given in Table 50. Although the conventional significance levels were not achieved, it is important to note that the higher DCS mean, indicating less apprehension, occurred under the low illumination condition.

Finally, an analysis of variance was performed on the acceptable nighttime clear-weather data for all data collections simultaneously. The analysis of variance is given in Table 51. Although this analysis shows a significant difference between DCS means for the seven data collections, it must be borne in mind that the logic of the analysis permits factors other than illumination to have affected driver apprehension. The experimental design was such that this was indeed true of all three analyses reported in the foregoing. In summary, it would appear that there were real differences in apprehension among the data collections, but that these differences could not be attributed with assurance to changes in illumination.

Day vs Night

To study the more basic premise that there is likely to be more apprehension while driving at night than during the daytime, data were collected for daytime as well as nighttime drivers in August 1964 and August 1965. A two-way analysis of variance was performed to study the day-night effect; because disproportionate cell frequencies were encountered, as might be expected, an analysis described by Scheffe (*24*), which allowed for this, was utilized. The results are given in Table 52.

Although significance is not achieved at the 0.05 level, it is important to note two things. (1) The direction of change in apprehension is such as to suggest potentially higher apprehension during the day. This conceivably could result, however, from differing driver populations. In this regard, it should be recognized that due to the late summer sunset the "daytime" group was made up of a wide cross-section consisting of both short-trip shoppers as well as commuters in addition to other types. (2) The difference in means was greater for the August 1964-August 1965 comparison than for the day-night comparison. These data, therefore, suggest greater change in apprehension due to unknown factors than to day-night effects.

Effects of Moon Brightness

An important factor in the determination of nighttime illumination is the brightness of the moon. The contributon of this factor to driver apprehension levels was investigated.

The effective illumination due to the moon was computed from information giving moonrise and moonset in Greenwich (*25*), the moon phase (*26*), and its declinations at the times of its rise and set. First, the intensity of the moonlight falling on a plane outside the earth's atmosphere perpendicular to the line of sight was determined as a function of the moon phase (*27*). This intensity was reduced to account for estimated atmospheric extinction. Next, the intensity was reduced by a factor of the sine of the elevation angle to yield the intensity normal to the earth's surface. This last factor and extinction required the use of the elevation angle, which was computed using the geographic coordinates of the test site and the moon cordinates (*28*) as determined from Greenwich rise and set times and the declination at those times. Having determined a number proportional to the estimated intensity, logarithms were computed to determine subjective brightness in accordance with Fechner's Law (*29*). A more complete discussion of these computations is given in Appendix M.

The estimated brightness was computed once for each questionnaire handout session for a time corresponding to 15 min after the session began. This was done only for those sessions taking place in conditions judged to be clearer than partly cloudy; there were 39 such periods. These handout sessions were placed in class intervals according to the values of the computed brightness. When the moon was new, had set, or had not yet risen, the corresponding sessions were placed in the first interval. There were nine equal-sized intervals of brightness following the first.

To test the effect of illumination due to the moon, a Kruskal-Wallis nonparametric one-way analysis of variance (*30*) was performed. The null hypothesis under test was that DCS scores would not be different (by a linear transformation) among the various moon brightness conditions. The test statistic has, under the null hypothesis, a chi-square distribution with degrees of freedom equal to the number of experimental groups minus one. The resultant value of the test statistic in this test was 15.162, which corresponds to a significance level of 0.9.

If a meaningful relationship existed between DCS and moon brightness, one would expect the relationship to be monotonic and thus to contain a linear component. In order to judge the degree to which linearity exists, a Pearson product-moment correlation coefficient was computed between the moon brightness index and the mean DCS score for respective handout sessions. Unweighted DCS means were used so as to ignore the number of drivers during the session. (This procedure was used for all the correlations to follow except those involving driver characteristics.) The value of the coefficient was −0.203. Although these data are in accord with the earlier findings in that increased moon illumination tended to correlate with increased apprehension, the relationship was a weak one.

Vehicle Volume

Vehicle volume at the time of the various data collections might well be expected to affect driver apprehension. First, the increased proximity of other vehicles might be of concern for drivers. Second, increased volumes at nighttime will yield the higher illumination corresponding to more headlights.

To test the effect of volume on DCS scores, clear-weather nighttime drivers were categorized according to the volume at the time of their respective handout sessions. They are grouped in intervals corresponding to thousands of vehicles per hour. A Kruskal-Wallis oneway nonparametric analysis of variance was applied to the data and the resulting statistic, whose value was 29.800, indicated significance at the 0.01 level. To study the nature of the relationship a product-moment correlation coefficient was computed between session volumes and mean DCS scores; its value was −0.044. Whether or not a "true" or significant linear relationship exists between apprehension and traffic volume, the estimated strength of such a relationship is extremely small. This strength of relationship is given by the square of the correlation coefficient, which equals 0.007. This means that if a straight line were used to predict apprehension from traffic volume the prediction would be 0.7 percent better than random guessing. It is suggested therefore, that although apprehension levels were different from one volume level to the next, these differences might well be best atributable to some variable other than traffic volume.

TABLE 50

ILLUMINATION EFFECTS: ALL DATA COMBINED

ILLUMINATION LEVEL	SAMPLE SIZE	MEAN DCS SCORE	RELATIVE APPREHENSION
Low	209	0.696	Low
Normal	304	0.087	High

Diff. between means: 0.609
Standard error: 0.414
Student *t*: 1.473
p (for two-tailed test): 0.14

TABLE 51

ONE-WAY ANALYSIS OF VARIANCE FOR THE EFFECT OF DATA COLLECTIONS UPON DCS SCORES

SOURCE	SUM OF SQUARES	DEGREE OF FREEDOM	MEAN SQUARE
Between	278.782	6	46.464
Within	10,592.090	506	20.933
Total	10,870.872	512	

$F = 2.22$, therefore $p < 0.05$.

Effects of Weather

The final environmental condition to be studied was that of weather. Weather conditions were separated into nine groups—clear, partly cloudy, cloudy, lightning but no pre-

TABLE 52

EFFECT OF DAY VERSUS NIGHT

SOURCE	SAMPLE SIZE	MEAN DCS [a]	DIFFERENCE	RELATIVE INDICATED APPREHENSION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	p
Day Night	74 72	−0.030 1.269	1.299	High Low	54.918	1	54.918	2.667	.11
Aug. 1964 (low) Aug. 1965 (norm.)	96 50	−0.123 1.361	1.484	High Low	71.613	1	71.613	3.479	.07
Within cells	—	—	—	—	2,923.950	142	20.591	—	—

[a] Due to disproportionality of cell frequencies, unweighted cell means are prescribed.

cipitation, snow flurries with dry road, wet road with no precipitation, light rain, snow on the road with acceptable visibility, and snow on the road with poor visibility.

Again a Kruskal-Wallace analysis was performed to see if different weather conditions were accompanied by differential apprehension levels. The data tested were all those collected at night. The scores obtained in each handout session were assigned to an appropriate weather group. The resulting test statistic had a value of 27.1922, which with eight degrees of freedom corresponded to better than a 0.001 level of significance.

Numbers from 1 to 9 were assigned to the weather conditions in the order previously given, and these numbers were correlated with DCS session means. The value of the correlation coefficient was -0.537. The negative correlation indicates that as weather conditions became worse in sense of the ordering given, DCS means grew more negative, indicating increased driver apprehension. The value of the coefficient implies that 29 percent $(= -0.537^2)$ of the variance in DCS means was associated with change in weather. Figure 66 shows the relationship between apprehension and weather. It can be seen that the relationship is strongest as driving becomes hazardous.

It should be pointed out that the ordering of the weather conditions was done before the analysis was performed. Clearly the correlation coefficient could have been inflated by using the optimum ordering as indicated by the data. The resultant value would have been obviously biased because it would have capitalized on random effects.

Driver Characteristics

Finally, the effect of two driver characteristics on DCS scores was studied; the driver traits were (1) driving experience measured as stated mileage per year, and (2) familiarity with the test site, measured as stated frequency with which it had been driven. For each of these variables a product-moment correlation coefficient was computed. The data utilized were gathered from all nighttime drivers—615 in all. The correlation of DCS scores with driver experience was 0.068; with driver familiarity it was 0.006. The latter value essentally indicates no linear dependence between apprehension and familiarity. The former coefficient suggests that as driving experience increases so does driver security; this statement has a 0.1 level of significance associated with it.

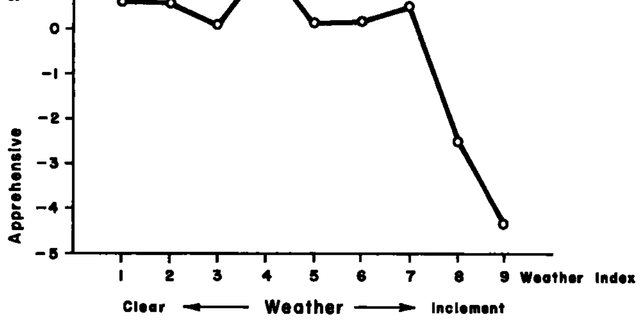

Figure 66. Relationship between apprehension and weather.

Discussion

Although the effects of roadway illumination, moon brightness, or daytime versus nighttime driving were not found to be significant, they all shared a common factor: the observed means tended to indicate greater apprehension under the higher illumination conditions.

Many difficulties in providing a sensitive measure of changes in apprehension were anticipated. First of all, because it was impracticable to make a large number of changes in illumination, infrequent changes were utilized thus making it virtually impossible to separate illumination effects from those due to other uncontrollable changes in roadway environment. Thus, significant differences were found between clear weather data collections although these differences could not be traced to illumination effects or to the influence of any other known factor.

Another problem related to the difficulties is the measurement of apprehension. Although the results of the scaling procedures indicated that the driver comfort scale indeed measured apprehension, the major problem was to measure apprehension not as a personality characteristic, but rather as a temporary, induced state. Here it was required that the subjects be able to recognize their feelings with respect to the DCS items, that they be able to recall these feelings when they answered the questionnaire, and that they do so in a cooperative manner. That apprehension, as measured by the DCS, decreased as weather improved demonstrates that these latter problems did not preclude the efficacy of the utilized procedures.

The sensitivity of the utilized procedures can be examined from another point of view. In order that the effects of decreasing illumination on driver apprehension were to be judged meaningful, one could have required that the resultant increase in apprehension be of some specified size. In this example, say it is required that apprehension increase by only one-tenth of a standard deviation in order to conclude that decreased illumination adversely affects driver apprehension. Using the results for the test of normal versus low illumination (for all data combined) gives a standard deviation of DCS scores of 21.18, based on within-groups sums of squares; the required difference between true means is, therefore, -2.118, assuming the negative direction to refer to increased apprehension. If this were actually the case, then with the procedures of this research, and specifically the analysis previously referenced, the probability of detecting this difference at the 0.05 level of significance would have been greater than 0.995. (The computations yielding this result are given in Appendix N.) It can be concluded from this that had there been a true increase in apprehension of only one-tenth of a standard deviation due to reduced illumination, the procedures of this research would have been extremely likely to detect it; hence, the existence of illumination effects of that size or larger was very unlikely.

NIGHTTIME DRIVING SECTION

Item Analysis

The NTD items, statements of potential sources of visual difficulties, were first studied in terms of the frequency with which drivers indicated they had such difficulties. Table 53 lists the items in order of the frequency with which they were checked. It is immediately apparent that the headlights of other vehicles were very prominent as a stated source of visual disturbances. Significantly, the reflected lights of following vehicles were the source of complaint far more frequently than were lights from oncoming vehicles. The latter source shares approximately equal frequency of complaint with difficulties in seeing the outlines of lanes and the edge of the road.

The least frequently checked item was "glare from street lights." This result is certainly pertinent to any concern that street lights can cause substantial discomfort; they probably can, but only at levels considerably higher than those used on the Connecticut Turnpike.

The NTD section of the questionnaire was scored by simply summing the number of checks or "complaints" indicated by each subject. Scores, therefore, ranged from 0 to 14, with higher scores corresponding to greater dissatisfaction. A frequency distribution of all 615 scores is shown in Figure 67. The mean score was 1.37.

Inasmuch as the scores were obviously non-normal, normal statistics were precluded and nonparametrics were used.

Roadway Lighting

Figure 68 shows the NTD score means for each of the data collections. These means are based on the scores of the 513 drivers passing through the test area at night in clear weather. The data collections indicated on the horizontal axis are grouped with those having normal illumination at the left, and those having low illumination at the right.

TABLE 53

NTD ITEMS RANKED BY FREQUENCY OF RESPONSE

RANK	RESPONSE FREQUENCY	ITEM
1	171	Distraction due to glare in rear view mirror from headlights behind you.
2	156	Temporary blinding due to glare in rear view mirror from headlights behind you.
3	106	Distraction due to headlights of vehicles traveling in the opposite direction.
4	90	Difficulty in seeing the outlines of the lanes.
5	54	Difficulty in seeing the edge of the road.
6	47	Temporary blinding due to headlights of vehicles traveling in the opposite direction.
7	39	Difficulty in judging velocities of other vehicles.
8	38	Confusion due to presence of too many lights.
9	34	Eyes became tired or strained.
10	26	Difficulty in telling if a light was on a car, on a truck, on a sign, etc.
11.5	25	Inability to see far enough.
11.5	25	Difficulty in reading signs.
13	19	Difficulty in judging distance.
14	12	Glare from street lights.

Casual study of Figure 68 shows little difference in NTD means for normal versus low illumination; perhaps

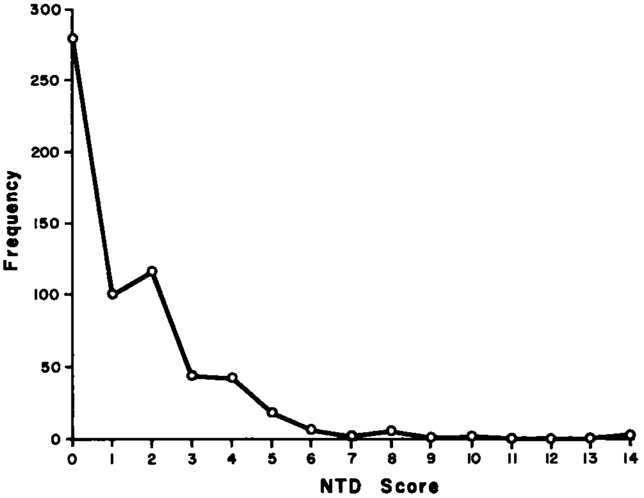

Figure 67. Frequency distribution of NTD scores.

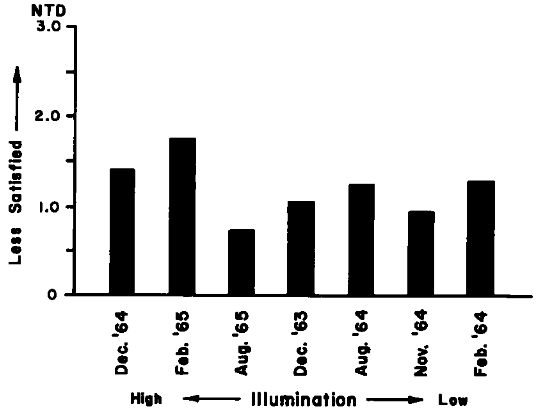

Figure 68. NTD score means for each data collection condition.

TABLE 54

EFFECTS ON NTD SCORES OF NORMAL VERSUS LOW ILLUMINATION LEVEL

ILLUMINATION	SAMPLE SIZE	MEAN NTD SCORE	DIFF.	RELATIVE INDICATED DISSATIS.
Normal	304	1.434	0.329	High
Low	209	1.105		Low
		Value of Mann-Whitney U:		28,249
		Corresponding z score corrected for ties:		2.273
		p (for two-tailed test):		.024

scores appear slightly higher for the normal illumination condition. A Kruskal-Wallis test for differences in NTD scores among all seven data collections yielded a test statistic value of 13.44. With six degrees of freedom the differences were significant at approximately the 0.04 level. To determine if the significance was attributable to effects operating between illumination conditions, as opposed to within illumination conditions, a Mann-Whitney U test was performed. The results of this test and comparative means are given in Table 54.

Once again, the unexpected occurred; relative dissatisfaction, as measured by the number of complaints checked in the NTD portion of the questionnaire, was significantly higher under normal illumination than under the reduced illumination level.

Effects of Moon Brightness

Following the procedure outlined for studying moon brightness effects on DCS scores, a Kruskal-Wallis nonparametric analysis of variance was performed to detect differential brightness level effects on NTD scores. This analysis was performed using the 460 subjects who passed through the test area at night under clear skies. The resultant value was 9.143, which with nine degrees of freedom corresponds to a significance level greater than 0.3. In addition, a product-moment correlation coefficient was computed; its value was 0.161, which indicates a weak tendency toward increased dissatisfaction with increased moon illumination.

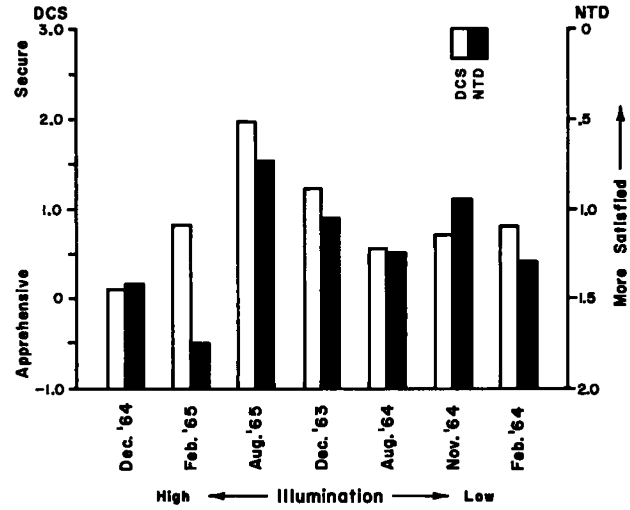

Figure 69. Relationship between NTD (Fig. 68) and DCS (Fig. 64).

Volume Effects

Proceeding as was previously done with DCS scores, the effect of vehicle volume on NTD scores was studied via a Kruskal-Wallis analysis. The value of the test statistic, 21.071, with 13 degrees of freedom, was significant at approximately the 0.07 level. The value of the correlation between NTD and volumes was less, in magnitude, than 0.012, thus mediating against any linear, or monotonic, relationship between these variables.

Weather Effects

As in the investigation of the effects of weather on DCS scores, another Kruskal-Wallis analysis was performed to study the relationship between weather and NTD scores. The data from all nighttime returns was used, yielding a sample size of 615. The test statistic equalled 8.797, which at eight degrees of freedom corresponded to a significance level greater than 0.5. Thus, no difference between NTD scores as a function of weather conditions is indicated, and no further analyses were performed.

Driver Characteristics

The correlation between NTD and driver experience was 0.051; between NTD and driver familiarity with the road, 0.028. The values are such as to suggest the absence of an important monotonic relationship between driver dissatisfaction and driver experience or familiarity.

Discussion

NTD scores, which can be considered to be measures of driver dissatisfaction, were significantly higher under the higher illumination conditions. Furthermore, there was a weak tendency for dissatisfaction to increase as the light from the moon grew brighter. Thus, dissatisfaction, like apprehension, was greater under conditions in which illumination was higher.

DCS VERSUS NTD

Although the DCS was intended to measure generalized feelings of apprehension and the NTD score was to reflect more overt dissatisfaction with specific conditions, one would expect the two attitudes to have much in common. That is, a driver who was aware of numerous difficulties in his environment might well feel apprehension toward that environment. This contention is supported somewhat by earlier results showing the tendency for illumination changes to produce similar results with respect to both apprehension and dissatisfaction. To measure this expected joint relationship, a product-moment correlation coefficient was computed; its value was − 0.333. This correlation, computed over individuals, confirmed the fact that increased apprehension (decreased DCS score) is likely to be accompanied by increased dissatisfaction (increased NTD score). On the other hand, the coefficient was not so high as to indicate that both measures related exclusively to the same attitudes.

The relationship between NTD and DCS is shown in Figure 69, which is based on Figures 64 and 68. In this case, a linear transformation was performed on the NTD scale so as to reverse the algebraic sign and make its range commensurate with the range of the DCS scores. This figure clearly exhibits the tendency of the two sets of scores to covary. The correlation coefficient for these seven data points was − 0.887, the increase in magnitude over the previously given value being attributable to the reduced contribution of individual differences to the latter relationship.

CHAPTER THIRTEEN

CONCLUSIONS

It was thought, prior to an examination of the data, that decreased illumination might well lead to an increase in driver apprehension and dissatisfaction. However, because this was based entirely on intuitive grounds, two-tailed tests were performed throughout this research.

Although significant differences in DCS scores were found among data collections, there was no indication that decreased illumination resulted in increased apprehension. Indeed, a direct comparison of DCS means between the normal and low illumination levels indicated that if differences were to be found in future research, the hypothesis of no difference between means is likely to be rejected in favor of decreased illumination yielding less apprehension. With regard to NTD scores as a measure of driver dissatisfaction, significantly less dissatisfaction was observed under the lower illumination condition. It was also shown that although the difference in DCS means for daytime drivers as compared to nighttime drivers could be judged significant only at the 0.11 level, this difference again tended to favor greater apprehension in the higher illumination (daytime) condition.

Among the various potential correlations between the two attitude scales and moon brightness, traffic volume, weather conditions, driver familiarity with the road, and driver experience, only that relating DCS to weather conditions reached important magnitudes. Driver experience was significantly, though weakly, correlated with apprehension. In both cases, the correlation was in the expected direction: (1) As weather conditions degenerated, apprehension increased; and (2) drivers with greater experience exhibited less apprehension. It is interesting to notice that the correlations between vehicle volume and apprehension and between volume and dissatisfaction were extremely small. Finally, a relatively strong relation was found in which apprehension and dissatisfaction seemed to vary together.

Integrating these results, one can conclude that the measurement techniques utilized in this study provided meaningful measures of driver attitudes, and that these measures show no support for the premise that reduced illumination will, in general, increase apprehension. Rather, the data indicate that under the described conditions of observation reduced illumination is more likely to yield a reduction in apprehension and dissatisfaction. In this regard, it should be noted that it would be very difficult to measure the value or worth of a change in driver apprehension. Thus, economically speaking, if a choice were to be made between the two levels of illumination, the less expensive level is suggested; if this corresponds to the lower illumination lamps, a rise in driver apprehension would be unexpected, a reduction would not be unexpected.

This has implications for future research. Clearly, there is no basis for generalizing these conclusions to other illumination ranges; furthermore, it seems apparent that there is likely to be a lower limit to the amount of light below which apprehension would rise quite rapidly. It is in the region of this lower value that future research might be most profitable.

PART V

REFERENCES
AND
APPENDICES

CONTENTS

PART I Operating Characteristics of Freeways

PART II Driving Performance

PART III Visual Evaluation

PART IV Driver Apprehension

PART V References and Appendices

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APPENDIX A

MOTOR VEHICLE ACCIDENT DATA

Two particular sources of information were required to make an analysis of accidents: (a) accurate accident reporting, and (b) accurate information about the amount of travel (vehicle-miles). Accident information for this project was furnished by the Connecticut State Highway Department and was based on individual accident reports as recorded by the Department of Motor Vehicles. In these records, accident location was coded to the nearest 0.01 mile and the time of day to the nearest hour. Information on age and sex of driver, vehicle type, and pavement condition was available but was not used in the analysis because there was no data on the number of vehicle-miles driven by or under these different categories.

Estimates of the vehicle-miles of travel on the Turnpike were furnished by the Connecticut Highway Department. There are four barrier toll gates within the limits of the Turnpike portions used for accident analysis. During 1960, accurate volume counts at each of the four toll stations were made by hour of the day, day of the week, and month of the year. (Detailed hourly volume records were not kept at the four toll stations after 1960.)

The Highway Department also furnished annual average daily traffic (AADT) volume estimates for each segment of the Turnpike for each year from 1961 to 1965. These estimates of AADT volumes were based on annual, 24-hr machine counts made at each intersecting ramp. Detailed information for day of the week and month of the year (but not hour of the day) was available for each of the four toll locations. The AADT estimates of ramp volumes were accumulatively added to or subtracted from the toll gate volumes to give the estimates of volume along each of the segments of the Connecticut Turnpike.

These AADT volume estimates were then adjusted to give the volume estimates categorized as daylight, dusk, or dark. The following methods were used to estimate the approximate volumes:

1. The 1960 volume factors, showing each hour as a percentage of the monthly average daily traffic, were applied to the monthly volume factors for subsequent years (1961-1965). These volume factors were obtained for each of the four toll locations and applied to the contiguous segments of highway. Because there is a consistent pattern of monthly factors from year to year, it was assumed that 1960 hourly factors might be "borrowed" for the subsequent years. The monthly average daily traffic, as a percentage of the annual daily traffic, for each year from 1960 through 1965 is given in Table A-1.

2. An almanac was consulted to obtain the time of sunrise, sunset, and dusk so that it was possible to calculate the hours of daylight, dusk, and darkness for each day of the year, to the nearest hour. (Accident data were coded to the nearest hour of occurrence.)

3. From the dates and months of the year it was possible to calculate the volume of travel during daylight, dusk, and night hours for each day, for each segment of the Turnpike. The product of volume and segment length resulted in vehicle-miles.

4. The days of the year were divided into six approximately equal time intervals, the dates separating time intervals coinciding with dates of change in lighting intensity, hours of sunrise or sunset, traditional vacation time, etc. The six intervals selected were as follows:

(a) Jan. 18 to March 21	63 days
(b) Mar. 22 to May 21	61 days
(c) May 22 to July 10	50 days
(d) July 11 to Sept. 11	63 days
(e) Sept. 12 to Nov. 23	73 days
(f) Nov. 24 to Jan. 17	55 days

5. The numbers of Annual Average Daily Traffic units far day, night, or dusk during the six time intervals were calculated by accumulating the hours of daylight, dusk, or darkness for all of the days in each time interval. Table A-2 gives the 1960 results for the Greenwich toll station, located near the west end of the Turnpike. As would be anticipated, the total number of "average" days of travel in the summer interval (78) exceeds the number of calendar days of travel (63) for the interval July 11 to Sept. 11. The opposite effect is evident in the winter months; there are only 49 days of "average" travel during the 63 calendar days from Jan. 18 to Mar. 21. Except for dusk there is considerable variation in the percentage of travel during the different natural light conditions. The percentage of travel for dusk ranges from only 10 to 13 percent. The percentage of daytime travel ranges from a low of 55 percent in the interval between Nov. 24 and Jan. 17 to a high of 76 percent for the period May 22 to July 10. More than one-third of the total travel during the Nov. 24-Jan. 17 interval is at night, whereas as little as 14 percent of all travel occurs at night in the May 22-July 10th period. For the year as a whole, 66 percent of all travel at the Greenwich toll station is during daylight, 11 percent is during dusk, and 22 percent is at night. Similar results were obtained for all four of the toll stations for all the years 1960 to 1965.

6. The vehicle-miles of travel for the different natural lighting conditions were then aggregated for the three geographical locations (west, test, and east) and for the three time periods (before, during, and after test lighting change).

7. The total number of reported accidents, for each segment and condition to be compared, was accumulated and then divided by the vehicle-miles to obtain accident rate per million vehicle-miles.

TABLE A-1

MONTHLY AVERAGE TRAFFIC AS A PERCENTAGE OF AADT 1960–1965

LOCATION	YEAR	AADT (VEH)	MONTHLY AVERAGE TRAFFIC (% OF AADT)											
			JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
Greenwich	1960	29,549	74.75	80.32	76.47	97.15	98.20	109.70	123.58	127.57	111.66	102.99	96.82	90.82
	1961	35,602	72.04	70.16	86.20	94.94	97.23	112.89	122.12	128.29	113.95	104.35	105.68	92.15
	1962	38,493	78.73	75.26	87.03	98.16	98.11	114.43	122.63	129.08	108.85	98.68	98.75	90.30
	1963	41,211	74.48	79.71	85.88	99.06	98.92	113.96	120.26	131.40	109.28	98.57	97.50	90.97
	1964	45,333	72.58	78.01	87.35	92.88	99.69	114.51	123.17	131.63	111.90	101.16	97.67	89.48
	1965	48,993	68.95	80.36	81.68	96.78	99.37	113.18	122.83	131.06	114.27	102.67	97.53	91.86
Norwalk	1960	26,194	75.29	82.07	78.88	96.25	99.11	109.40	125.07	128.52	112.61	101.67	103.68	87.46
	1961	29,759	71.71	73.51	86.19	94.63	96.24	111.99	123.65	128.33	113.13	104.06	104.41	92.15
	1962	32,149	78.40	76.50	87.16	97.45	96.94	113.54	122.94	129.69	110.00	98.85	99.31	89.23
	1963	34,781	75.15	81.03	86.27	98.27	97.22	112.41	122.01	130.98	109.36	99.28	97.58	90.44
	1964	37,895	74.18	79.93	86.66	92.57	98.66	113.12	123.92	132.14	112.83	101.41	97.41	87.19
	1965	40,853	69.79	81.13	82.49	95.60	98.18	110.87	125.26	130.96	115.06	102.89	97.40	90.38
Stratford	1960	24,063	75.45	82.82	79.38	95.38	98.26	107.31	121.75	125.67	114.23	103.32	105.29	91.33
	1961	27,444	73.21	76.91	88.25	94.83	96.37	111.48	119.85	124.72	112.17	103.96	104.92	93.35
	1962	29,710	78.40	77.57	86.96	97.98	96.52	110.67	118.38	127.28	110.87	100.44	101.38	93.54
	1963	32,709	76.33	82.76	87.10	100.87	97.29	110.74	117.26	127.64	107.98	101.34	98.28	92.44
	1964	35,437	75.45	81.44	88.27	93.56	98.31	110.47	119.83	128.50	111.97	103.06	99.08	90.11
	1965	38,752	71.54	83.01	83.94	96.61	98.50	108.87	121.09	127.56	113.46	103.21	99.22	92.26
West Haven	1960	16,695	74.39	80.84	78.45	94.66	97.78	111.19	128.73	132.36	114.51	99.69	100.18	87.22
	1961	18,512	70.82	75.26	86.47	92.66	94.67	111.99	125.80	131.56	113.33	103.76	101.70	91.95
	1962	20,149	76.96	76.11	85.91	94.79	94.89	111.12	123.19	134.76	112.28	100.60	98.32	91.07
	1963	21,704	76.75	81.33	86.88	96.99	96.45	111.81	122.89	133.74	108.61	99.53	95.54	98.50
	1964	23,340	74.32	79.85	86.36	93.16	97.24	109.74	124.26	137.02	112.52	100.67	96.43	88.49
	1965	25,432	70.63	80.68	83.05	93.89	96.81	108.93	125.17	131.37	113.98	103.39	97.81	93.00

TABLE A-2

NUMBER OF ANNUAL AVERAGE TRAFFIC DAYS BY NATURAL LIGHT CONDITIONS, GREENWICH TOLL STATION, 1960

PERIOD		NO. OF CALENDAR DAYS	ANNUAL AVERAGE TRAFFIC DAYS							
			DAY		NIGHT		DUSK		TOTAL	
NO.	DATES		(NO.)	(%)[a]	(NO.)	(%)[a]	(NO.)	(%)[a]	(NO.)	(%)[a]
1	1/18-3/21	63	29.13	59.44	13.55	27.65	6.32	12.90	49.00	100.0
2	3/22-5/21	61	40.75	70.97	9.83	17.13	6.83	11.90	57.41	100.0
3	5/22-7/10	50	41.78	75.84	7.74	14.05	5.57	10.11	55.09	100.0
4	7/11-9/11	63	56.32	72.41	12.79	16.44	8.67	11.15	77.78	100.0
5	9/12-11/23	73	47.52	61.14	20.88	26.87	9.31	11.98	77.71	100.0
6	11/24-1/17	55	26.63	55.09	16.45	34.03	5.26	10.88	48.34	100.0
All		365	242.13	66.27	81.24	22.24	41.96	11.49	365.33	100.0

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[a] Percentage of total days during period.

APPENDIX B

DEVELOPMENT OF CAMERA MEASUREMENTS

The use of time-lapse photographs for the measurement of speeds and placement has been reported by several investigators (*3, 4, 5, 6*). Common to all of the methods noted is the use of a perspective grid, which is introduced when the plane of the film is not parallel to the plane of the roadway.

Grid points on the ground are carefully located and marked so as to be identifiable on the film as well as on the ground. From the known points it is possible to construct a perspective grid of the study area. As each frame is analyzed it is necessary to position the perspective grid so that the projected images of the known coordinate points are superimposed over the same points of the perspective grid. The longitudinal and transverse position of the vehicle (usually one of the tires) can then be visually interpolated using the perspective grid as a guide.

Figure B-1 shows a simple perspective view of a tangent segment of roadway superimposed on a rectangular coordinate system. The convergence of both the longitudinal and transverse joints of the pavement plane (generally the same directions for which vehicle measurements are required) makes accurate visual interpolation difficult. Forbes and Fairman (*5*) overcame this, in part, by mounting the projected image at a horizontal angle approximating the angle between the pavement and the plane of the film in the camera. Nevertheless, this did not eliminate the need to carefully align the perspective grid with known points on each film image.

A simpler means of reading for the viewer would be the determination of the rectangular coordinates of any point in the plane of the pavement. These readings could then be converted to the equivalent perspective grid location. Rectangular coordinate systems can be easily read by mechanical means, and a computer can be used to perform the computational steps required to convert the rectangular coordinates to a perspective coordinate system of the projected roadway plane.

In the technique developed for this study the rectangular coordinates of a point on the film were mechanically determined and automatically punched onto data processing cards. The data cards were then analyzed on an electronic computer locating each vehicle on the roadway plane. A detailed outline of the method follows.

RELATIONSHIP BETWEEN FILM PLANE AND ROADWAY PLANE

Consider the relationship between a roadway plane and a film plane as shown in Figure B-2. Each of the points 1 through 5 on the roadway plane has a corresponding image on the film plane. Each of the points in the roadway plane has the coordinates, XR, YR, and in the film plane the image of the same point has the coordinates XF, YF. The relationship between the two coordinate systems is (*7*)

$$\mathrm{XR}_i = \frac{A_1 + A_2\ \mathrm{XF}_i + A_3\ \mathrm{YF}_i}{A_4\ \mathrm{XF}_i + A_5\ \mathrm{YF}_i + 1} \qquad \text{(B-1}a\text{)}$$

$$\mathrm{YR}_i = \frac{A_6 + A_7\ \mathrm{XF}_i + A_8\ \mathrm{YF}_i}{A_1\ \mathrm{XF}_i + A_5\ \mathrm{YF}_i + 1} \qquad \text{(B-1}b\text{)}$$

in which

$\mathrm{XR}_i, \mathrm{YR}_i$ = the x and y coordinates of the i^{th} point in the roadway plane;

$\mathrm{XF}_i, \mathrm{YF}_i$ = the x and y coordinates of the image of the same point in the film plane; and

$A_1 \ldots A_8$ = coefficients which remain constant for the relationship between any pair of planes.

If the eight coefficients, A_{1-8}, are known, it is only necessary to determine the film coordinates (XF_i, YF_i) for any point and to solve for the roadway coordinates (XR, YR).

The determination of these eight coefficients is given by four pairs of equations of the type of Eqs. B-1a and B-1b. In other words, it is required that the roadway coordinates (XR, YR) and the associated film coordinates (XF, YF) of four points be known. Any number of roadway coordinates can then be determined from the film coordinates of the image of any point in the roadway plane. A further requirement is that no three of the roadway points lie on a straight line.

The solution for the eight coefficients is a relatively straightforward operation on an electronic computer and is quickly determined, as is the calculation of any other point in the roadway plane. As long as the camera (or the projector) remains fixed relative to the roadway plane the same coefficients can be used on successive frames. This assumption is implicit to graphical solutions of the photographic method. If the relationship between the film plane and the roadway plane should change (either the camera or the projector should be jarred) the film coordinates of the four known roadway coordinates can be reread and the eight coefficients recalculated.

Experimentation, in which the film coordinates of each of the four known roadway points was read on each frame, showed that there was no change in the coefficients between frames. This indicated that the camera mounting system and projector were stable, and that the film and ground planes remained fixed relative to each other. In practice, all four ground points were read at 50-frame intervals, primarily as a check on the continued accuracy of the data reduction system. (At a film speed of 90 frames per minute this corresponds to a check about every 33 sec of filming).

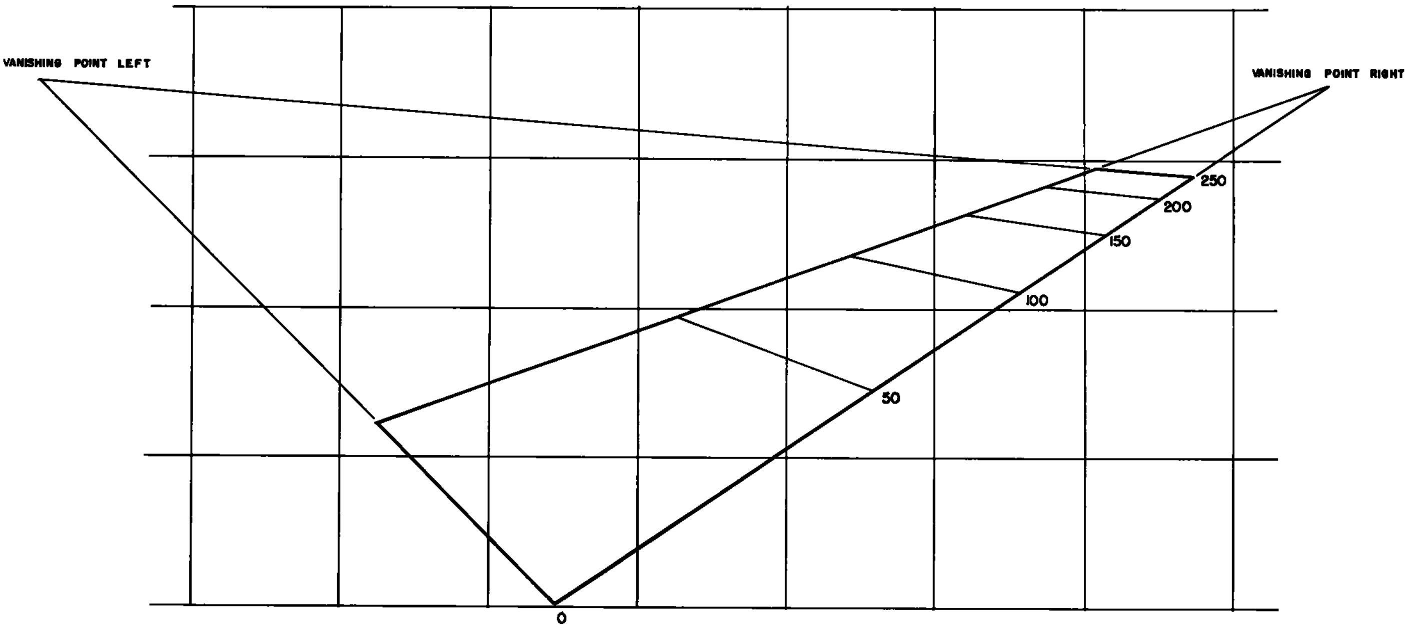

Figure B-1. Perspective of a tangent section of roadway superimposed on a rectangular grid.

CORRECTION FOR HEADLIGHT HEIGHT

In the foregoing discussion it is assumed that all points, including the four ground points, are located in the same plane (usually the pavement surface). It is difficult to detect the point at which a tire is in contact with the pavement, even in the daylight. A reading on the bumper of a vehicle or, at nighttime, on the headlights gives a more pronounced target. The disadvantage of reading a point other than the wheel contact point or of having reference points which are not in the same plane requires that corrections be applied to the location of a point on the film as calculated by Eqs. B-1. Therefore, it was necessary to modify the basic formula for the following reasons.

1. Observations were made at the level of the headlights and not the pavement. A correction was needed to adjust the apparent position of the headlights.

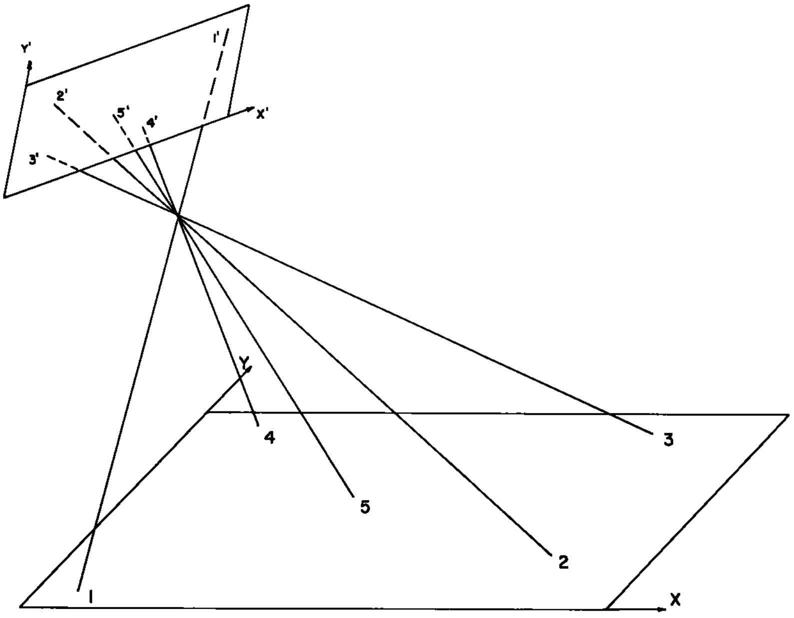

Figure B-2. Projection of points from roadway plane to film plane.

2. Pavement slope. Corrections for headlight height were based on the position of the camera as being at right angles to the pavement plane. It was therefore necessary to adjust the camera position in order to recognize the slope of the roadway.

3. Elevation of reference points. The reference points used to calculate the pavement grid were not at the same elevation as the roadway plane. Adjustments in location had to be made to overcome the discrepancy.

4. Corrections for warped surfaces. The surveyed reference points were not all in the same plane. Adjustments were made to recognize difference in elevation between roadway and analysis planes.

5. Development of the method assumed a rectangular coordinate system. It was possible to introduce corrections for circular curves, relating to the initial rectangular coordinate system.

Consider an elevation view (Fig. B-3) through the line of sight of the camera to a point B on the roadway plane. The camera was mounted at a height (MH) directly over the point O′ in the plane O′B′. The point B is in the plane at a distance O′B′ from the camera. The ray OB passes through a locus of points which are located some distance along the vector O′B′ and at an elevation ranging from O ft to MH as the point approaches the camera. The points B, C, and D would all be recorded at the same point on the film image in the camera at O, but the calculated position, based on the X,Y coordinates from the film, would give a correct position only for the point O′B′.

The correct distances O′D′ and O′C′ are a function of the height of the points D and C above the plane O′B′. Assume the height of point C is HH_c. From similar triangles it will be seen that

$$C'B'/O'B' = HH_c/MH \qquad \text{(B-2)}$$

so that

$$C'B' = O'B' \; (HH_c/MH) \qquad \text{(B-3)}$$

and

$$\begin{aligned} O'C' &= O'B' - C'B' = O'B' - O'B' \; (HH_c/MH) \\ &= O'B' \; [1 - (HH_c/MH)] \qquad \text{(B-4)} \end{aligned}$$

Similarily,

$$O'D' = O'B' \, [1 - (HH_d/MH)] \qquad \text{(B-5)}$$

in which O′B′ is the apparent location in the pavement plane. It will be seen that the correct position is based on three factors, as follows:

1. The mounting height of the camera above the plane (MH).

2. The height of the measured object, i, above the plane (HH_i).

3. The computed distance from the base of the camera to the apparent position of the point i in the plane.

In practice the mounting height can be measured directly by measuring the distance from the camera lens to the roadway. The headlight height (HH) was treated in three groupings: compact vehicles (HH = 2.00), passenger vehicles (HH = 2.25), and commercial vehicles (HH = 3.25).

The application of these corrections to a vehicle is shown in Figure B-4. Consider a rectangular plane coordinate system parallel to the roadway, where the origin is a point vertically beneath the camera. It is desired to locate the correct position (X_T,Y_T) of the headlight, T. Without a correction for headlight height (HH) the formula will give the apparent coordinates of A (X_A,Y_A). The correction to be applied to the Y-coordinate (in the pavement plane) is

$$T'A \cos \alpha \qquad \text{(B-6)}$$

in which α is the horizontal angle between the Y axis and the vector through T′. But

$$T'A = O'A \; (HH/MH) \qquad \text{(B-7)}$$

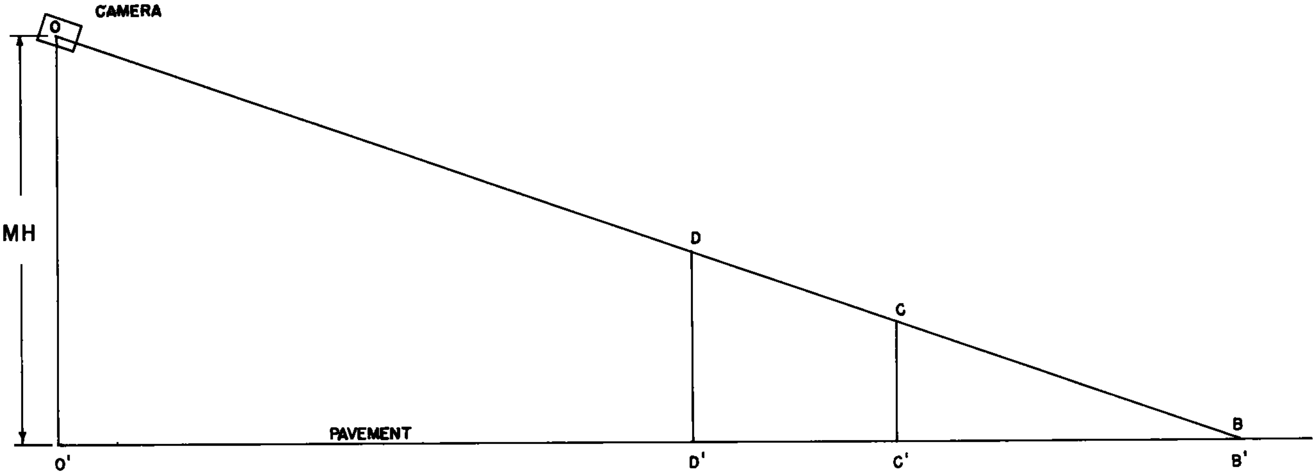

Figure B-3. Elevation illustrating how various points along a single ray all appear to be at the same point on the pavement.

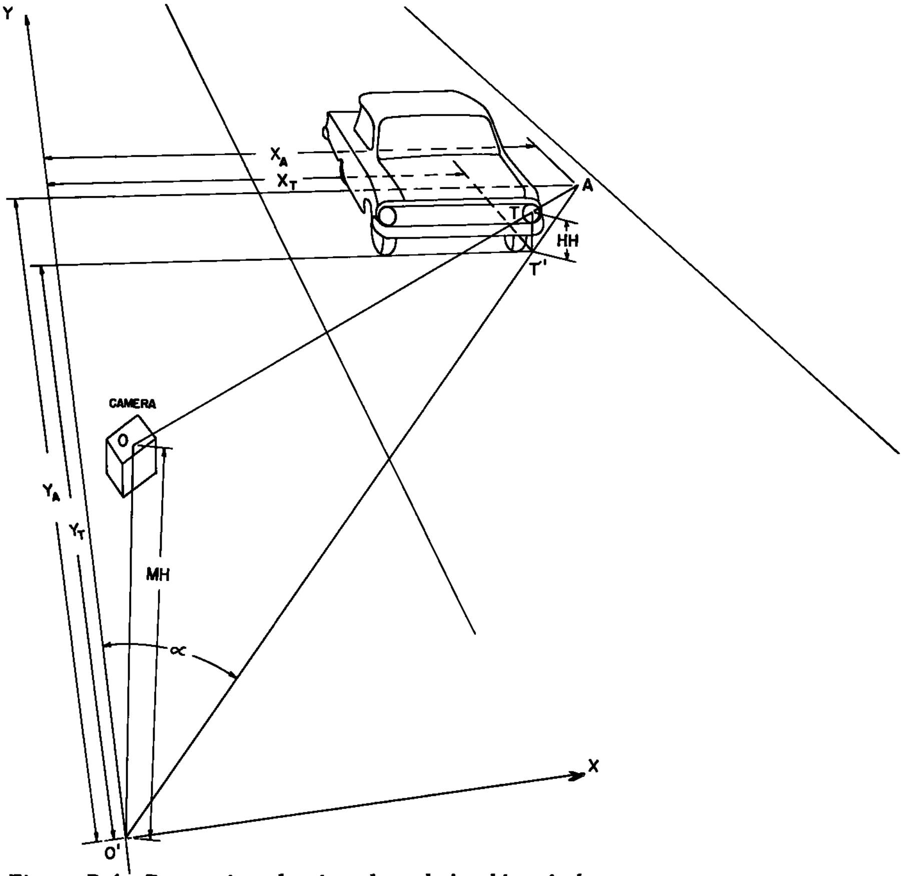

Figure B-4. Perspective showing the relationship of the apparent and true vehicle positions.

and

$$O'A = Y_A/\cos\alpha \tag{B-8}$$

Therefore, the correction becomes

$$Y = \cos\alpha\,[(Y_A/\cos\alpha)\ (\mathrm{HH/MH}])$$

$$= Y_A\ (\mathrm{HH/MH}) \tag{B-9}$$

The true location of the headlight is the apparent location less the correction and is given by

$$Y_T = Y_A - Y$$

$$= Y_A - [Y_A\ (\mathrm{HH/MH})]$$

$$= Y_A\,[1 - (\mathrm{HH/MH})] \tag{B-10}$$

Similarily,

$$X_T = X_A\,[1 - (\mathrm{HH/MH})] \tag{B-11}$$

Eqs. B-10 and B-11 form the basis of locating the true coordinates of a point in terms of headlight height and camera mounting height.

CORRECTION FOR PAVEMENT SLOPE

The relationships established in the foregoing are based on the assumption that the pavement is horizontal and that the camera is mounted at a right angle to the pavement. This is seldom the case, and it is therefore necessary to correct the camera position for the longitudinal and transverse slope of the pavement. The purpose of the correction is to adjust the mounting height of the camera and the location of the base of the camera. It will be recalled that the analytical solution for the apparent position of a point in the pavement plane is independent of pavement slope, mounting height, or headlight height. These corrections are required to obtain the proper factors needed to calculate the true position of the vehicle when measurements are made through the plane of the headlights.

Consider the relationship shown in Figure B-5 for the correction in longitudinal slope (grade):

Required: Correction mounting height MH'.

Correction in Y location of base (O' — O″).

Let: $\tan\theta =$ percent grade $(G)/100$, $\simeq \sin\theta$.

$\theta =$ arc tan (percent grade/100).

$Y_c = O'O''$

Then: $Y_c = \mathrm{MH}\ G/100$ (B-12)

$\mathrm{MH'} = \mathrm{MH}\cos\theta$ (B-13)

Example: Assume MH = 25 ft, $G = 5\%$, $Y_c = 25 \times 0.05$

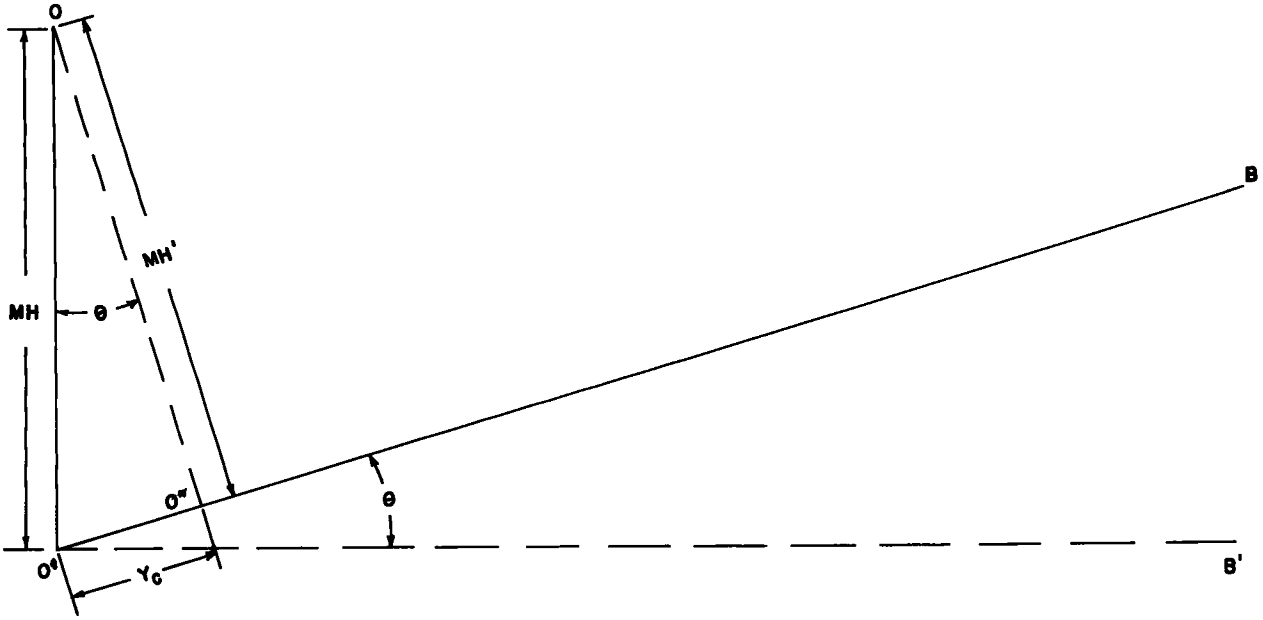

Figure B-5. Elevation illustrating grade corrections to camera position.

$= 1.25$ ft, $MH' = 25 \times 0.99875 = 24.97$ ft. Obviously, the change in MH is negligible for grades $< 5\%$).

Similarily, for cross slope

$$X_c = C \times \text{MH} \qquad \text{(B-14)}$$

in which C is the cross slope in ft/ft.

The correction is applied to the location of the pavement reference points [XR,YR] prior to calculating the parameters required to solve the equations for the apparent position of the vehicle.

As an example, assume the location and the elevations for a set of reference points located in the field (Fig. B-6), as follows:

	Location		
Object	*x*	*y*	Elevation
Camera	0	0	142.60
Ref. pt. 1	10	150	125.00
Ref. pt. 2	10	250	130.00
Ref. pt. 3	35	250	129.75
Ref. pt. 4	35	150	124.75

The grade of the reference plane $= (130.00 - 125.00)/100 = +5\%$.

$$\text{Cross slope} = \frac{129.75 - 130.00}{25}$$

$$= \frac{124.75 - 125.00}{25} = -0.01$$

(The sign of the grade and cross slope are determined from the location of the camera.)

The elevation of the plane at point O,O (projected through point 1) $= 125.00 + [0.01 \times 10] - [0.05 \times 150] = 117.60$

$\text{MH} = 142.60 - 117.60 = 25.00$ ft.

Correction in Y: $Y_c = 25.00 \times +0.05 = 1.25$ ft.

Correction in X: $X_c = 25.00 \times -0.01 = -0.25$ ft.

The corrections (with signs as calculated) are *subtracted* from the survey locations of the reference points so that the XR,YR values used to calculate the eight parameters are as follows:

Location	XR	YR
1	$10 + 0.25 = 10.25$	$150 - 1.25 = 148.75$
2	$10 + 0.25 = 10.25$	$250 - 1.25 = 248.75$
3	$25 + 0.25 = 35.25$	$250 - 1.25 = 248.75$
4	$35 + 0.25 = 35.25$	$150 - 1.25 = 148.75$

The base of the camera has therefore been moved 1.25 ft toward the reference points along the Y-axis and 0.25 ft away from the reference points along the X-axis in adjusting to the plane of the roadway.

CORRECTIONS FOR ELEVATION OF REFERENCE POINTS

The reference points used to locate the pavement coordinate do not always fall in the plane of the pavement. Therefore, it is necessary to make adjustments in order to bring the control points into the proper configuration. In the present study, done at night, the control points were flashlights, standing 4 in. high and placed either on the curb or on the shoulder of the roadway. For the most part the lights did not fall in the plane of the roadway and it was necessary to correct for the difference in elevation.

Assume in Figure B-7 that lights 3 and 4 are located 248.75 and 148.75 ft, respectively, from the camera after the camera location has been adjusted for the slope of the pavement. Light 3 is 3 in. below the pavement plane and

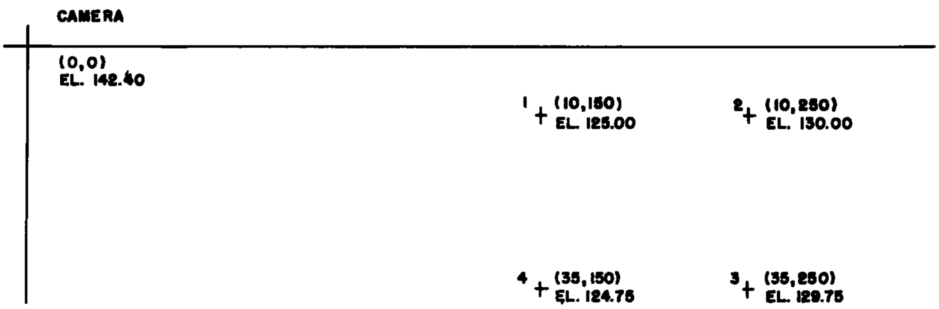

Figure B-6. Plan illustrating corrections to reference points.

light 4 is 6 in. above the plane. A ray from the camera to light 3 will intercept the pavement plane at a point L'_3 and to light 4 at L'_4. Before the XR,YR values can be used it is necessary to locate these adjusted points as follows:

Let: d = light elevation minus the pavement plane elevation;

Y_T = true distance to the reference point in the analysis plane;

Y_A = corrected distance to the reference point adjusted for elevation; and

MH = mounting height of camera above roadway plane.

By similar triangles:

$$d/(Y_A - Y_T) = (\mathrm{MH} - d)/Y_T \qquad \text{(B-15)}$$

$$(Y_A - Y_T) = Y_T\,[d/(\mathrm{MH} - d)] \qquad \text{(B-16)}$$

$$Y_A = Y_T\,[1 + d/(\mathrm{MH} - d)] \qquad \text{(B-17)}$$

For light 4: $d = +0.50$ ft, $Y_T = 148.75$ ft, and $Y_A = 148.75\,[1 + 0.50/(25.00 - 0.50)] = 151.73$ ft.

For light 3: $d = -0.25$ ft, $Y_T = 248.75$ ft, and $Y_A = 248.75\,[1 - 0.25/(25.00 - (-0.25))] = 246.26$ ft.

The corrections in the X axis are similarily applied. Assuming light 1 is 0.5 ft above the plane and light 2 is 0.25 ft below the plane the following become the XR,YR values used to locate the roadway plane:

Light No.	XR	YR
1	10.46	151.73
2	10.15	246.26
3	34.90	246.26
4	35.96	151.73

CORRECTIONS FOR WARPED SURFACES

Further corrections in location must be made if the study site is not a plane. For example, consider a section of tangent pavement 25 ft wide, at a point where superelevation is being introduced, as shown in Figure B-8.

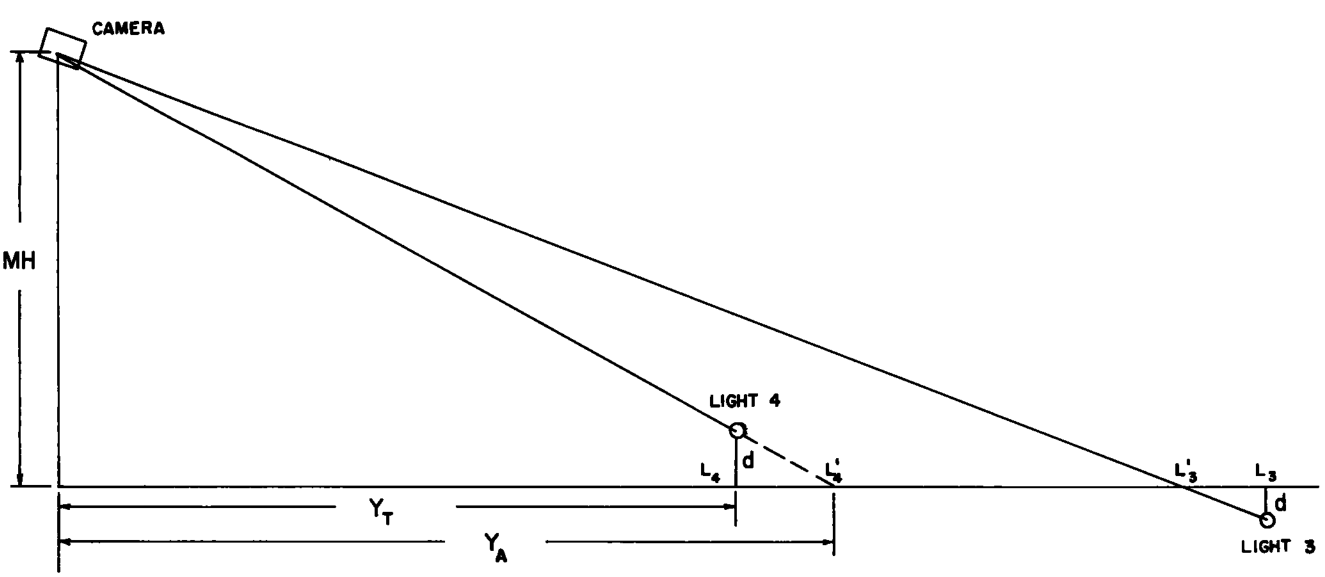

Figure B-7. Elevation illustrating corrections to reference points.

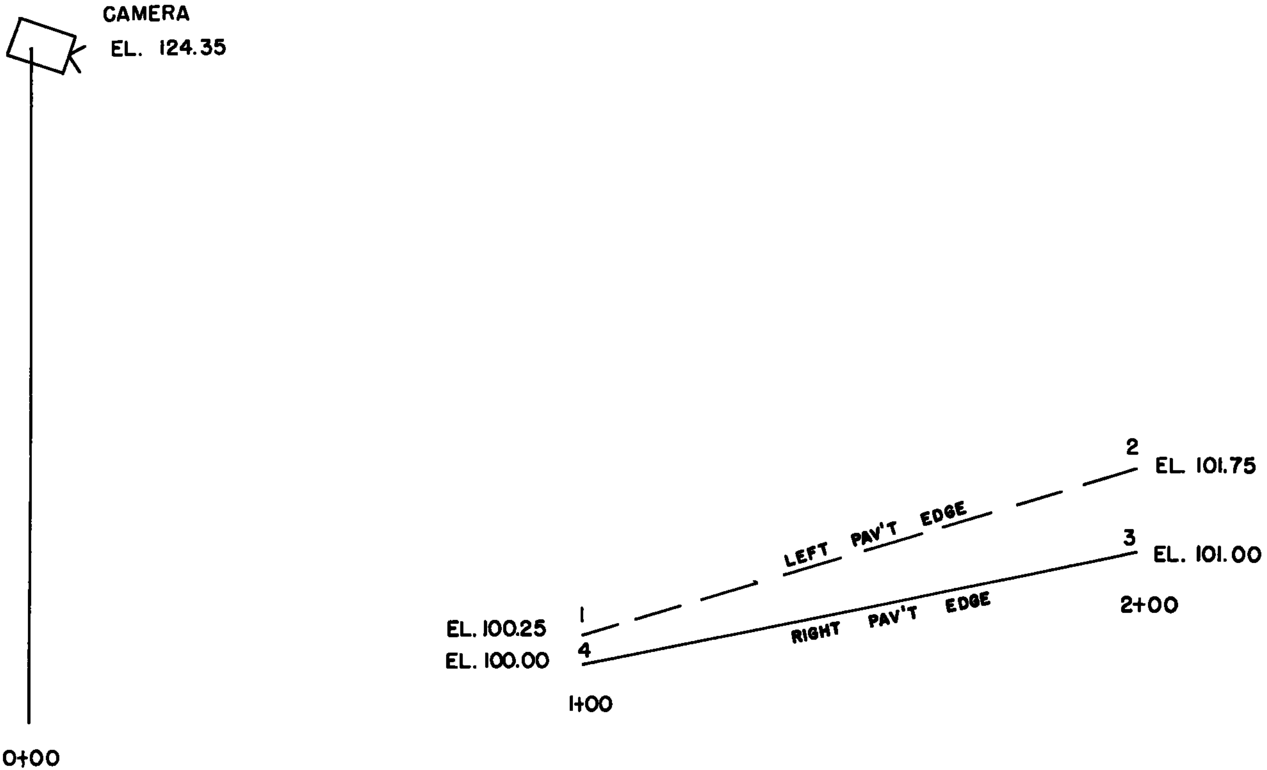

Figure B-8. Profile of a superelevated tangent section of roadway.

A plane is defined by any three points; in this case assume the plane defined by points 1, 3, and 4. This plane intercepts a line vertically through point 2 at an elevation of 101.25 ft. The camera image of point 2 will therefore be equivalent to a point that is further from the camera than the true 200 ft. Assume (after corrections for slopes) that the camera is located at station O + OO, 10 ft to the left of the roadway, at a camera height of 25 ft above the plane defined by points 1, 3, and 4. The correct distances (XR,YR) for point 2 are as follows:

$d =$ elevation of reference point [light] — elev. of plane projected $= 101.75 - 101.25 = 0.50$ ft.

$Y_T =$ true distance $= 200$ ft.

MH = mounting height = 25.00 ft.

By Eq. B-17 for the Y axis, $Y_A = 200\ [1 + 0.50/(25.00 - 0.50)] = 204.08$ ft, and in the X axis $X_A = 10\ [1 + 0.50/(25.00 - 0.50)] = 10.20$ ft.

The coordinates for the control points thus become:

Location	XR	YR
1	10.00	100.00
2	10.20	204.08
3	35.00	200.00
4	35.00	100.00

It is obvious that vehicle which is at or near point 2 on the warped roadway is not at the elevation supposed, but is about 0.50 ft above the plane defined by points 1, 3, and 4. The result of the previous calculations, including correction for headlight height, is to find the actual location of an observed point in the (assumed) pavement plane. It is therefore necessary to make an adjustment in the headlight height to reflect the warped pavement surface.

The elevation of a point (i) in the light plane (defined by 1, 3, and 4) at X_i, Y_i is given by:

$$\text{(Elevation of projected plane at camera base)} + (\text{Grade } Y_i) + (\text{Cross slope } X_i) \tag{B-18}$$

The elevation of a point on the warped plane of the surface (between stations 1 + 00 and 2 + 00) is given by:

$$\text{Elev.} = 98.65 + 0.017\ Y_i + 0.01X_i - 0.0002X_iY_i \tag{B-19}$$

The difference in elevation between the two surfaces at any given point (subtracting Eq. B-18 from Eq. B-19) is to be added to the headlight height correction. In this instance,

$$\text{Correction} = -0.70 + 0.007Y_i - 0.0002X_iY_i \tag{B-20}$$

The correction is dependent on the location of the vehicle, which in turn is dependent on the headlight height correction. An iterative procedure was used to solve the problem. The first approximation of the vehicle location is based on the original headlight height values. The first estimate of location is then used to determine the correction to be applied to the headlight height and the process is repeated. Experience has shown that the third estimate is sufficiently precise (the $X_{\text{℄}}$ location changes by ± 0.02 ft and the $Y_{\text{℄}}$ location by ± 0.1 ft at distances averaging 25.0 ft and 150.0 ft along the X and $Y_{\text{℄}}$ axis, respectively).

The correction developed in the foregoing example is applicable to the section between Sta 1 + 00 and Sta 2 ± 00 over the 25-ft wide roadway. The same arguments and correction can be applied to consecutive segments of roadway in increments ranging from 50 to 100 ft), by individual lanes, making it possible to apply the method to ramps, vertical curves, and other irregular pavements.

CORRECTION FOR HORIZONTAL CURVATURE

When the location of a vehicle on a curve is given in rectangular coordinates, it is necessary to adjust these coordinates to the horizontal curvature of the pavement. The first step is to locate the point of tangency (PT) of the edge of pavement with respect to the rectangular coordinate base line (Y axis), expressed in terms of X and Y from the camera location. The placement of the vehicle in the rectangular coordinate system is then determined as previously outlined. Figure B-9 shows the location of a point on a horizontal curve.

Given: R = radius to outside edge of pavement;

$X_{\text{PT}}, Y_{\text{PT}}$ = coordinates of PT (corrected for mounting height, etc.);

$X_{\text{V}}, Y_{\text{V}}$ = vehicular rectangular coordinates.

Required: P = placement of vehicle relative to outside edge of pavement;

Y_{arc} = distance vehicle travels along arc.

The curvilinear coordinates of the vehicle thus become

$$X = (R + X_{\text{PT}}) - X_{\text{V}} \qquad \text{(B-21)}$$

and

$$Y = Y_{\text{PT}} - Y_{\text{V}} \qquad \text{(B-22)}$$

The location of the vehicle along the radius in terms of the curvilinear coordinates is

$$R_{\text{V}} = \sqrt{X^2 + Y^2} \qquad \text{(B-23)}$$

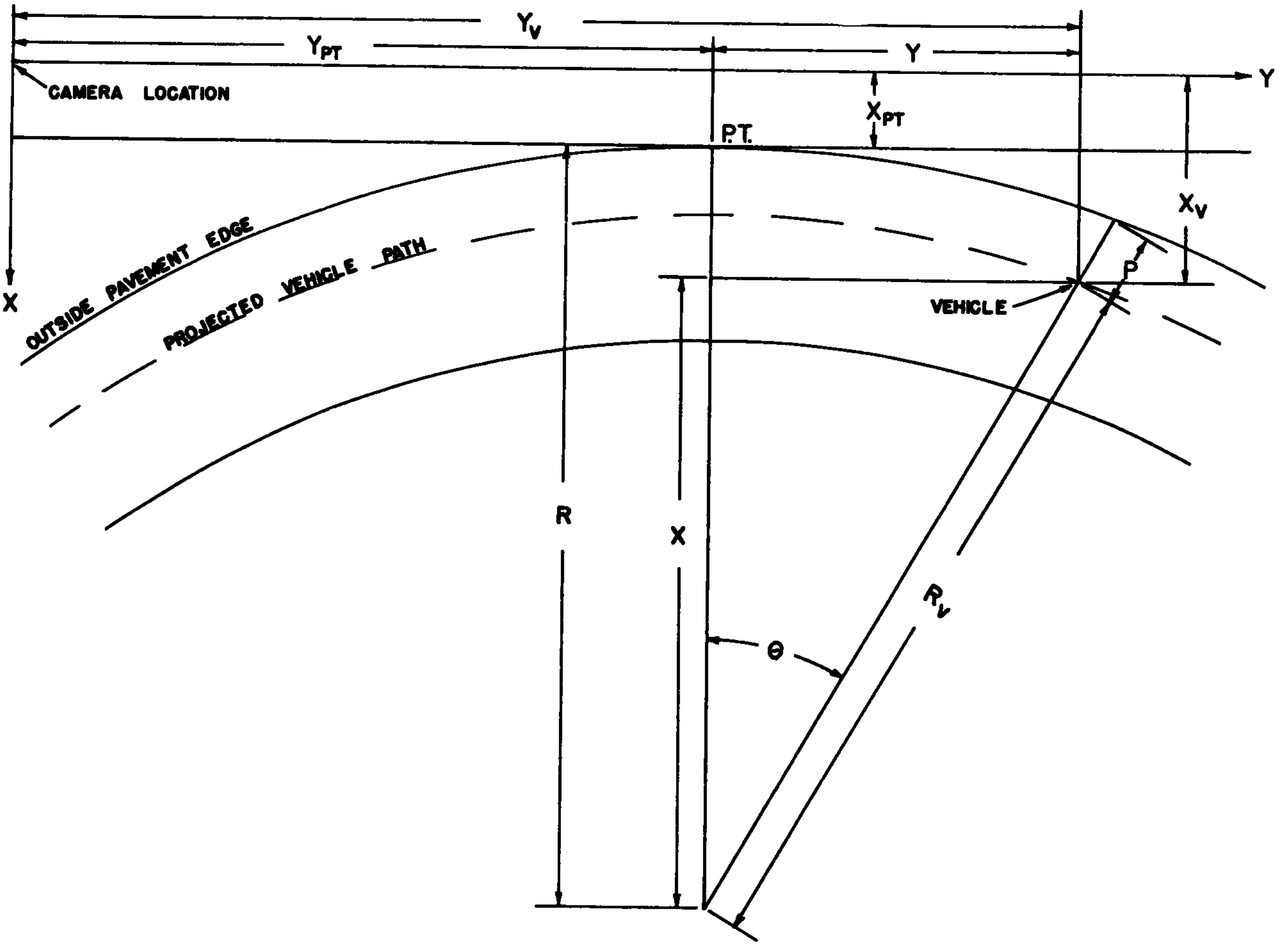

Figure B-9. Conversion of curvilinear coordinates of the vehicle location from rectangular system.

Placement becomes

$$P = R - R_V \tag{B-24}$$

The distance the vehicle travels along the arc passing through the position of the vehicle and the corrected value Y_{arc} is given by

$$Y_{\text{arc}} = R_V\,\theta \text{ (radians)} \tag{B-25}$$

in which

$$\theta = \arctan\,(Y_V/X) \tag{B-26}$$

The correct curvilinear distance the vehicle travels between frames is given by the difference in Y_{arc} values on two successive frames.

A further correction for curvature is needed. The placement of a vehicle is determined relative to a plane, but the inside of a superelevated circular curve is the inside surface of a cone. The plane used in locating the vehicles is tangent at only one point to the cone. At any point other than along the radius to this point of tangency the rectangular coordinates place the vehicle closer to the center of the curve than it actually is. Because this calculation is in the plane of analysis, the true vehicle position is higher up on the superelevated curve than assumed in the grid. The amount of this correction is

$$\text{Correction} = (R_V - X)\ \text{(Rate of superelev.)} \tag{B-27}$$

in which

R_V = radius to path of vehicle; and

X = distance from curve center to X-coordinate of vehicle.

Example: rate of superelevation = 3 ft/48 ft = 1/16.

$X = 2300.00$ ft (approx. 2° 30′).

$Y = 100.00$ ft (distance from vehicle to PT).

Thus, $R_V = \sqrt{2{,}300^2 + 100^2} = 2{,}302.17$, and
Correction $= (2{,}302.17 - 2{,}300.00)\ 1/16 = 0.14$ ft.

This correction is then added to the headlight height and the new X_V and Y_V values are recalculated and corrected to the curved roadway.

SUMMARY OF CORRECTIONS

1. *Headlight height*

$$X_T = X_A\,[1 - (\text{HH}/\text{MH})] \tag{B-11}$$

$$Y_T = Y_A\,[1 - (\text{HH}/\text{MH})] \tag{B-10}$$

in which

X_T, Y_T = the true coordinates of the vehicle headlights;

X_A, Y_A = the apparent coordinates of the vehicle headlights;

MH = mounting height of camera above plane; and

HH = headlight height above pavement.

2. *Correction for pavement grade and cross slope*

$$Y_c = \text{MH percent grade}/100 \tag{B-12}$$

$$X_c = \text{MH cross slope (ft/ft)} \tag{B-14}$$

in which Y_c and X_c are the values to be *subtracted* from the surveyed coordinates of the reference points and MH is the mounting height of the camera.

3. *Elevation of reference points above and below analysis plane*

$$Y_A = Y_T\,[1 + d/(\text{MH} - d)] \tag{B-17}$$

in which

Y_A = the correct distance to the reference point;

Y_T = the nominal distance after correction 2 above); and

d = elevation of reference point — elevation of same point in analysis plane.

The same corrections are applied for the X coordinates.

4. *Correction for warped surfaces*

Any three of the reference points define a plane, the fourth is corrected as noted in step 3 above. The expression for the elevation of a point in the reference plane is subtracted from the expression for the elevation of a point in the pavement plane and the resulting expression is of the general form

$$\text{Correction} = A + B\,X_i + C\,Y_i + D\,X_i\,Y_i \tag{B-28}$$

in which A, B, C, and D are functions of the grades and slopes in the two surfaces and X_i, Y_i are the corrected positions for the vehicle.

The correction is added to the headlight height, and an iterative procedure is used to calculate the correct (X, Y) coordinates.

5. *Horizontal curvature correction*

$$\text{Placement relative to outside edge of pavement} = R - R_V \tag{B-24}$$

in which

R = radius of curve to outside edge;

$$R_V = \text{radius of vehicle path} = \sqrt{(X^2 + Y^2)} \tag{B-23}$$

$$X = (R + X_{\text{PT}}) - X_V \tag{B-21}$$

$$Y = Y_{\text{PT}} - Y_V \tag{B-22}$$

X_{PT}, Y_{PT} = coordinates of point of tangency of rectangular coordinate system; and

X_V, Y_V = coordinates of vehicle in rectangular system.

Difference in elevation because of conical effect of inside of circular curve

$$\text{Correction} = (R_V - X)\ \text{(Rate of superelev.)} \tag{B-27}$$

in which R_V and X are as defined for placement.

The correction is added to the headlight height and a second iteration is made to get the placement of the vehicle before applying the horizontal corrections.

APPENDIX C

DATA REDUCTION

EQUIPMENT

Data reduction was accomplished on a Benson-Lehner (Oscar F) film reading system consisting of three basic parts—a reading unit, a projector, and a decimal converter with automatic readout to an IBM keypunch.

In the system the film image is projected onto the rear side of a nearly vertical ground-glass screen by means of front surface mirrors. The operator then positions the reading head, containing the X-axis and Y-axis reference lines, such that the intersection of the two reference lines is the corresponding *X* and *Y* coordinates of the required data point on the film. The operator then initiates the readout cycle by depressing the record push-button switch. Each readout cycle consists of a sign and three digits in both *X* and *Y*. A key pack is mounted on the reading unit for operator control of data insertion at the keypunch.

The decimal converter is an analog-to-digital converter that converts potentiometer input resistances from the reading unit to decimal output. Internal circuitry of the converter is such that a proper resistance balance must be achieved during each readout cycle. If the balance is incorrect or the input changes during the balancing operation, an error detector is energized and the readout cycle is terminated. The digital range of output is ± 999 units in both *X* and *Y*. Format of the readout sequence is controlled by means of patchboard programming.

Each 35-mm frame, as projected, was magnified to approximately 9 by 7 in. Although scaling was set for maximum range of digital output (2,000 units in *X* and in *Y*), a total of approximately 1,450 units in *X* and 1,425 units in *Y* was actually usable within the limits of each frame. This represents a scaling of 160 ± units per inch in *X* and 200 ± units per inch in *Y*.

PROCEDURE

Initial editing of the film revealed various methods by which the filmed data could be reduced. Trial runs indicated that an operator would likely become confused if required to read individual vehicles a specified number of times and then reverse the film to record additional vehicles that appeared in the same frames. This "searching" method not only was time consuming but also could result in the loss of vehicles if the film was not reversed far enough.

It was decided that all vehicles be read in each frame and the film then advanced to the next frame. This "forward" method also proved to be time consuming. As vehicle type-coding was required, the vehicle had to be identified by advancing the film to a point where it was distinguishable and then reversing the film to begin data reduction.

The final decision was to record all vehicles in each frame and to reduce the filmed data in reverse order. That is, the last time the vehicle is recorded on film is the first time its position is recorded. Although this method yields more individual readings than required, a time saving is still realized against either of the other two methods and duplication of readings is minimized. The operators were requested to record vehicles as far back as possible.

The most distinguishable point on the vehicle (for nighttime filming) was the headlights. Recording the center of both headlights proved to be accurate and was no more time consuming than deciding on the point representing the center of the vehicle. In the computer analysis of the reduced data the vehicle center was calculated as the average of the two headlight readings. Investigation revealed only slight deviations in headlight mounting heights between vehicles of the same class in recent years.

The following general rules were established for data reduction:

1. Reference lights.—All reference lights were read at the start of each reel of film, at 50-frame intervals, and at the start and finish of each operator's reading period. The refenece lights were numbered in a clockwise direction starting at the lower left. One reference light must be recorded for each frame, but need not be the same reference point from frame to frame. The numbering sequence, however, must be retained at all times.

2. Vehicle coding.—The following classification was used for the coding of vehicle type:

Vehicle Type	Left Headlight	Right Headlight
Passenger car	7	8
Compact car	8	8
Truck or bus	9	8
Unknown	0	8

For one-headlight vehicles (either burned out or blocked), and for motorcycles, two readings were required of the visible headlight and coded as follows:

	Left Light Visible		Right Light Visible	
Vehicle Type	1st Read.	2nd Read.	1st Read.	2nd Read.
Passenger car	7	0	7	8
Compact car	8	0	8	8
Truck or bus	9	0	9	8
Unknown	0	0	0	8
Motorcycle	7	7		

3. Successive readings.—All vehicles were read in successive frames, as long as visible. If a vehicle was read in one or two frames and then became totally blocked in the following, no further readings were taken on that vehicle even if it became visible again. A vehicle recorded "close in" that became partially blocked in a later frame was recorded as a one-headlight vehicle for those frames in which it was partially blocked. If the vehicle became totally visible in a later frame normal coding again applied.

4. Vehicle reading order.—The order with which vehicles were read within a frame containing more than one vehicle was from left to right and top to bottom. The left-to-right order was determined by the X-axis alignment crosshair as it intersected the vehicle's left headlight (from the operator viewpoint), disregarding lane use. If two or more vehicles were aligned at the same *X* distance, the most distant vehicle (Y-axis) was read first and the nearest last.

Each data card contained the frame number, the reference light number and its coordinates, and a maximum of three vehicle readings (six headlight coordinate readings). The cards were automatically released after the third vehicle reading and operator released if there was less than three vehicles on a film frame. In frames containing more than three vehicles the operator activated the alternate program button on the key pack, duplicating the frame number and reference light data onto the next card, allowing the operator to continue vehicle readings without manually repeating the other information.

DATA PROCESSING

All observation cards were processed by computers to resolve the film coordinates to roadway coordinates and to match the observations of a vehicle in one frame with similar observations of the same vehicle in subsequent frames. The observations were processed in the reverse order from which they were filmed. In this approach, vehicles in successive frames appeared to be traveling backward from the camera position.

The computer program matched vehicles in the following manner. The first time a vehicle is seen on film its ground coordinates are calculated. Next a "box" is defined, within which limits the vehicle might be expected to appear on the next frame. The limits of the box were determined by the distance traveled at the minimum and maximum speeds expected on the roadway and the maximum rates of lateral movement anticipated. The ground coordinates of all vehicles in the following frame were then determined and compared with the box limits constructed for the vehicles in the previous frame.

When two observations on a vehicle had been matched, successive boxes were calculated from the speed observed and determined in the first two observations. Certain tolerances were allowed in calculating the dimension of the box, in order to compensate for random reading errors. Vehicle observations were matched until a vehicle had been recorded in ten successive frames or was no longer visible.

Vehicles which were found on three frames or less were listed by the computer with identifying information. The film was then reviewed to ascertain the reason for the limited number of observations. In some instances the vehicle was blocked by a truck in the adjacent lane and no further adjustments were possible. The other source of error was incorrect data transcription, in which case the vehicles were reread and the computer process completed.

A record was made of a vehicle's position each time it was observed. A printed summary of these records was manually scanned as a check on the accuracy of the matching technique. These records, which also include essential vehicle identification, lane numbers, time between successive observations, and the actual time of vehicle passage at a given point on the roadway, were stored on magnectic tape for later analysis and use.

APPENDIX D

PRECISION OF PHOTOGRAPHIC REDUCTION

The precision in locating vehicles was dependent on the accuracy with which the data were transcribed from the film to the data cards. Repeated readings of a series of points, by various operators, indicated that 95 percent of all readings were correct to ± 3 units in the X-axis and ± 5 units in the Y-axis.

A series of points were located in each of three lanes of pavement, at varying distances from the camera. These points were then read on the data reduction equipment and the locations calculated. The *X* and *Y* readings of each point were systematically changed; the results are given in Table D-1 for an error of 3 units in *X* and 5 units in *Y*.

The deviation in calculated location decreases as the point gets closer to the camera in both the X and Y axes. For a *Y*-deviation of 5 units (maximum *X*-deviations occurred for this case) the deviation in *X* at the point nearest to the camera in the three lanes varies from 0.15 ft in lane 1 to 0.48 ft in lane 3. It should be noted here that the camera location was 14.30 ft off the edge of the roadway, so that the points in lanes 1, 2, and 3 were offset approxi-

TABLE D-1

VARIATION IN VEHICLE LOCATION VS READING ERROR

	LANE 1		LANE 2		LANE 3	
LOCATION	X	Y	X	Y	X	Y
Actual	6.66	428.26	20.29	416.26	29.67	412.49
3 units in X	0.42	0.04	0.43	0.14	0.43	0.13
5 units in Y	0.54	11.38	0.90	11.04	1.08	10.36
Actual	9.40	384.86	20.51	367.07	32.14	359.03
3 units in X	0.38	0.03	0.38	0.11	0.37	0.09
5 units in Y	0.53	8.78	0.80	8.62	1.00	7.89
Actual	6.10	265.77	21.15	274.34	30.82	267.70
3 units in X	0.27	0.02	0.28	0.05	0.28	0.05
5 units in Y	0.33	4.44	0.58	4.65	0.73	4.44
Actual	6.91	203.12	21.04	220.72	31.15	213.76
3 units in X	0.20	0.01	0.23	0.03	0.23	0.03
5 units in Y	0.26	2.64	0.47	3.04	0.59	2.87
Actual	6.75	159.00	20.37	188.41	28.98	184.46
3 units in X	0.16	0.01	0.20	0.02	0.20	0.02
5 units in Y	0.21	1.64	0.42	2.34	0.48	2.13
Actual	6.69	115.15	19.89	128.75		
3 units2in2X	0.12	0.01	0.14	0.01		
5 units in Y	0.15	0.88	0.27	1.08		

mately 20, 34 and 43 ft, respectively, from the camera position.

Ideally, if the camera is located directly over the middle of a four-lane roadway all vehicles would be about 20 ft maximum deviation from the camera and the errors would be as noted for lane 1 (i.e., 95 percent of all readings would be with a precision of ± 0.15 ft or less).

In the present use of this method, with the camera mounted on a lighting standard off the edge of the shoulder, the placement for any vehicle was within ± 2 in. in the nearest lane, ± 3 in the second lane, and ± 6 in. in the most distant lane. Inasmuch as the accuracy in placement increases as the vehicle approaches the camera, calculations were based on the reading at the time the vehicle was nearest the camera.

The calculation of velocity is a function of two calculations of the Y-displacement of a vehicle, so the estimate of error is a function of the error of the two nearest Y-locations. It will be recalled that the sum or difference of two variables is equal to the sum of the two different variances.

The deviations given in Table D-1 are at the 95 percent level, so that the standard deviation is one-half of the reported values. As an example, consider a vehicle in lane 1. The standard deviation at the nearest point (115 ft) is 0.44 ft, and at the next point (159 ft) it is 0.82 ft. The variance of the difference between the locations is $(0.44)^2 + (0.82)^2 = 0.866$ ft. The standard deviation of the difference $= \sqrt{0.866} = 0.93$ ft, so that 95 percent of the velocities in lane 1 would be correct to ± 1.86 mph. Similarily, in lane 2 the 95 percent value is ± 2.58 mph and in lane 3 is 3.54 mph.

APPENDIX E

FILM SPEED DERIVATION

Analysis of the reduced data was based on the camera operating speed for the particular film run under study. Inasmuch as the cameras were battery powered, it was realized that the variable power supply would result in a true camera rate that would vary according to the decay curve of the battery being used.

Each reel of film was viewed on a microfilm reader and the time and corresponding frame number were recorded

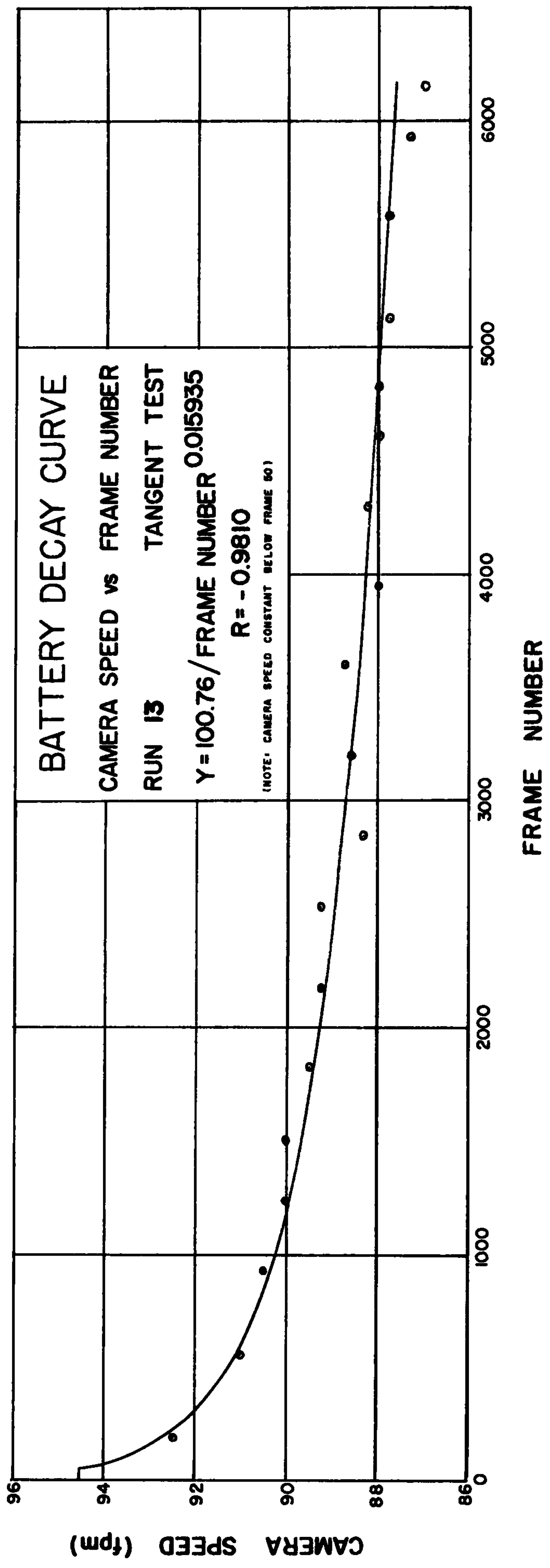

Figure E-1. Typical battery decay curve.

at 4-min intervals. Camera rates were calculated and the results plotted as rate vs frame count, as shown in Figure E-1.

Typical curve plots revealed a close resemblance between the plotted data and the general equation

$$Y = K/f^{s} \qquad \text{(E-1}a\text{)}$$

or

$$\log Y = \log K - s \log f \qquad \text{(E-1}b\text{)}$$

in which

Y = camera speed, in frames per minute;
K = the Y intercept;
s = constant frame exponent or slope; and
f = frame number.

Eq. E-1b is of the general form for any linear equation.

$$Y = a + b\,X \qquad \text{(E-2)}$$

in which

$$a = [(\Sigma X)(\Sigma XY) - \Sigma Y(\Sigma X^2)]/[(\Sigma X)^2 - n(\Sigma X^2)] \qquad \text{(E-3)}$$

$$b = (\Sigma XY - [(\Sigma X)(\Sigma Y)/n])/(\Sigma X^2 - [(\Sigma X)^2/n]) \qquad \text{(E-4)}$$

n = the number of frame counts and time recordings;
ΣX = sum of the log values of the frame count averaged between two successive readings;
ΣY = sum of the log values of the camera rates;
ΣX^2 = sum of squared log values of the frame count;
ΣY^2 = sum of squared log values of camera rates; and
ΣXY = sum of products of log of frame count and log of camera rate.

The Y-intercept, K, was determined from the antilog of a and the constant frame exponent, s, by multiplying b by -1.

The coefficient of correlation, R, was used as a measure of the variation between the actual film speed and that determined by the equation. The lower limit of acceptance for R was set at -0.90, below which the data for that run were rejected and the film was reread to obtain new frame counts and times. Of the 44 film runs analyzed, only 4 had initial values of R lower than -0.95.

APPENDIX F

TRAFFIC FLOW DATA

TABLE F-1

TRAFFIC FLOW DATA, TANGENT TEST SECTION

	VELOCITY (MPH)								PLACEMENT[a] (FT)					
	MEAN				STANDARD DEVIATION				MEAN			STANDARD DEVIATION		
RUN NO.	LANE 1	LANE 2	LANE 3	ALL LANES	LANE 1	LANE 2	LANE 3	ALL LANES	LANE 1	LANE 2	LANE 3	LANE 1	LANE 2	LANE 3
(*a*) ALL VEHICLES														
13	52.46	57.66	61.00	56.41	5.35	4.65	5.04	5.82	6.71	19.17	29.89	1.06	1.19	1.30
21	51.65	57.25	60.50	56.13	5.36	4.67	4.73	5.92	6.55	18.90	29.38	1.20	1.19	1.25
24	46.79	51.94	53.88	50.31	5.79	5.02	5.91	6.14	5.81	18.35	28.33	1.35	1.39	1.42
29	51.76	55.84	58.47	55.09	5.77	4.29	5.15	5.54	6.35	18.70	29.32	1.27	1.24	1.27
36	52.20	57.75	60.54	56.58	6.00	4.82	5.31	6.15	5.94	18.18	28.84	1.24	1.18	1.23
44[b]	51.69	56.61	58.92	55.88	6.07	4.59	4.65	5.74	6.07	18.48	29.68	1.43	1.49	1.16
(*b*) PASSENGER VEHICLES														
13	52.14	57.73	61.15	56.48	5.23	4.76	5.17	5.93	6.76	19.16	29.88	1.05	1.14	1.30
21	51.59	57.13	60.60	56.25	5.20	4.71	4.72	5.91	6.62	18.94	29.39	1.22	1.18	1.22
24	47.00	52.07	53.97	50.56	5.89	4.97	5.78	6.11	5.81	18.30	28.28	1.38	1.41	1.42
29	52.04	55.97	58.68	55.31	5.35	4.29	5.12	5.39	6.49	18.67	29.27	1.25	1.19	1.23
36	51.94	57.92	60.73	56.79	5.56	4.81	5.26	6.06	5.95	18.20	28.81	1.23	1.16	1.15
44[b]	51.92	56.69	58.90	56.13	5.80	4.75	4.65	5.65	6.10	18.47	29.67	1.46	1.45	1.18
(*c*) COMMERCIAL VEHICLES														
13	53.96	57.50	58.64	55.62	5.83	3.91	2.84	5.33	6.30	19.03	30.07	1.07	1.63	1.27
21	51.53	58.06	60.37	55.09	6.15	4.53	5.47	6.42	6.22	18.61	28.94	1.02	1.19	1.84
24	46.24	51.50	52.21	48.95	5.54	5.17	5.71	6.00	5.81	18.43	29.21	1.22	1.29	1.44
29	50.91	55.45	56.15	53.66	7.34	4.46	5.66	6.35	5.70	18.75	29.80	1.22	1.47	1.31
36	52.78	56.81	64.65	55.14	6.69	4.82	5.87	6.79	5.82	17.58	28.51	1.27	1.16	2.63
44[b]	50.18	55.79	57.24	52.95	7.00	3.65	4.26	6.36	5.86	17.97	29.43	1.38	1.84	0.82

[a] From outer edge of lane 1. [b] Daylight study.

TABLE F-2

TRAFFIC FLOW DATA, TANGENT CONTROL SECTION

	VELOCITY (MPH)								PLACEMENT[a] (FT)					
	MEAN				STANDARD DEVIATION				MEAN			STANDARD DEVIATION		
RUN NO.	LANE 1	LANE 2	LANE 3	ALL LANES	LANE 1	LANE 2	LANE 3	ALL LANES	LANE 1	LANE 2	LANE 3	LANE 1	LANE 2	LANE 3
(*a*) ALL VEHICLES														
13	48.71	57.75	62.61	54.36	6.53	4.76	5.25	7.72	6.76	19.55	30.63	1.27	1.52	1.61
21	48.34	56.86	62.49	54.45	6.86	6.61	6.12	8.58	6.93	19.63	30.49	1.29	1.33	1.66
24	41.33	50.35	53.83	46.91	5.14	5.08	5.25	7.20	6.43	19.45	29.79	1.43	1.42	1.40
29	47.44	55.89	59.22	53.38	5.66	4.64	4.75	6.95	6.34	19.40	30.62	1.17	1.30	1.47
36	49.48	58.48	62.47	55.10	6.10	5.45	5.32	7.68	6.45	19.05	29.94	1.37	1.34	1.47
44[b]	49.22	57.39	64.03	55.85	5.90	4.82	4.69	7.72	6.81	19.66	30.85	1.21	1.36	1.52
(*b*) PASSENGER VEHICLES														
13	48.91	57.90	62.68	54.71	6.65	4.76	5.44	7.75	6.76	19.55	30.63	1.27	1.52	1.61
21	48.63	57.20	62.28	54.99	7.04	6.67	5.94	8.64	7.00	19.61	30.56	1.27	1.36	1.62
24	41.69	50.75	53.96	47.45	5.16	5.14	5.34	7.21	6.38	19.41	29.82	1.45	1.45	1.38
29	47.90	56.14	59.34	53.84	5.64	4.52	4.82	6.82	6.37	19.42	30.63	1.13	1.36	1.41
36	49.98	58.98	62.67	55.72	6.00	5.39	5.40	7.61	6.39	19.05	29.98	1.42	1.30	1.42
44[b]	49.51	57.68	64.10	56.31	6.00	4.73	4.68	7.66	6.81	19.61	30.83	1.17	1.41	1.49
(*c*) COMMERCIAL VEHICLES														
13	47.41	55.68	58.42	50.94	6.24	4.30	2.00	6.90	6.72	19.56	31.69	1.27	1.41	0.77
21	47.00	54.91	58.56	50.96	6.25	5.58	9.10	7.59	6.54	19.68	30.19	1.28	1.23	1.38
24	39.39	48.19	51.73	43.58	4.79	4.27	4.70	6.58	6.58	19.45	30.16	1.37	1.39	1.82
29	45.04	53.53	57.35	49.62	5.91	4.24	6.40	7.08	6.18	19.29	30.98	1.29	1.34	1.86
36	46.70	55.33	58.72	50.72	6.25	5.11	5.15	7.29	6.53	19.03	28.82	1.22	1.67	2.41
44[b]	47.40	54.30	59.45	50.00	5.42	4.52	2.11	6.16	6.69	19.77	29.42	1.29	1.10	0.35

[a] From outer edge of lane 1. [b] Daylight study.

TABLE F-3

TRAFFIC FLOW DATA, CURVE TEST SECTION

	VELOCITY (MPH)										PLACEMENT[a] (FT)							
	MEAN					STANDARD DEVIATION					MEAN				STANDARD DEVIATION			
RUN NO.	LANE 1	LANE 2	LANE 3	LANE 4	ALL LANES	LANE 1	LANE 2	LANE 3	LANE 4	ALL LANES	LANE 1	LANE 2	LANE 3	LANE 4	LANE 1	LANE 2	LANE 3	LANE 4
(*a*) ALL VEHICLES																		
12	46.69	49.87	53.40	59.56	51.73	8.80	6.50	6.55	6.71	7.75	7.29	19.25	31.01	42.39	1.41	1.77	1.77	1.56
16	48.61	50.47	55.63	59.97	53.86	5.70	6.19	5.66	6.27	7.04	7.44	19.62	31.55	43.22	1.28	1.45	1.60	1.89
20	48.30	48.67	53.09	56.99	51.76	5.81	5.36	4.80	4.71	5.95	7.43	19.23	30.93	42.17	1.55	1.53	1.55	1.63
31	46.93	48.47	52.54	55.32	51.04	5.32	5.54	4.48	5.21	5.79	7.82	19.52	31.17	42.56	1.27	1.53	1.49	1.72
34	46.25	48.91	53.56	58.74	52.10	8.64	5.53	4.82	5.52	6.86	7.80	18.92	30.88	42.20	1.18	1.64	1.58	1.86
38	46.75	49.12	53.53	56.85	51.32	6.24	5.22	5.23	5.48	6.25	8.32	19.72	31.45	42.51	1.39	1.66	1.55	1.51
42[b]	46.78	48.58	52.30	55.17	51.00	5.32	4.56	4.23	4.33	5.32	7.31	19.10	30.95	42.60	1.27	1.36	1.46	1.51
(*b*) PASSENGER VEHICLES																		
12	46.98	50.24	53.46	59.81	51.97	8.79	6.81	6.50	6.96	7.90	7.31	19.29	31.01	42.40	1.43	1.79	1.70	1.29
16	48.93	50.43	55.68	59.82	53.87	5.55	5.92	5.83	6.44	7.01	7.52	19.64	31.49	43.16	1.27	1.37	1.60	1.94
20	48.40	48.65	53.05	56.69	51.81	5.82	5.39	4.93	4.67	5.98	7.47	19.27	30.93	42.26	1.55	1.55	1.52	1.60
31	47.20	48.64	52.63	55.34	51.21	4.90	5.65	4.40	5.28	5.74	7.83	19.55	31.15	42.16	1.27	1.56	1.49	1.71
34	46.44	48.63	53.56	58.86	52.12	8.84	5.28	4.96	5.24	6.94	7.85	18.90	30.81	42.19	1.16	1.68	1.60	1.84
38	46.95	48.63	53.39	56.85	51.19	6.33	5.24	5.27	5.59	6.37	8.34	19.66	31.45	42.55	1.40	1.74	1.52	1.46
42[b]	46.99	48.58	52.35	55.26	51.09	5.30	4.57	4.31	4.22	5.35	7.30	18.98	30.92	42.56	1.29	1.33	1.48	1.48
(*c*) COMMERCIAL VEHICLES																		
12	41.33	48.35	53.53	58.56	49.83	8.74	5.41	8.19	4.32	7.38	6.75	18.96	30.50	39.78	0.62	1.74	2.23	2.81
16	44.56	50.40	55.78	58.58	52.39	6.57	7.43	5.34	4.51	7.47	6.73	19.48	31.60	42.80	1.30	1.79	1.68	1.65
20	43.71	48.54	52.87	57.24	50.14	4.98	5.37	4.39	5.26	5.78	6.59	19.02	30.66	41.62	0.98	1.40	1.70	1.65
31	42.03	47.69	51.91	55.56	49.34	9.52	5.24	5.54	3.87	6.46	7.55	19.20	31.03	40.44	1.45	1.37	1.52	1.57
34	43.36	50.32	53.12	54.42	51.17	7.44	6.42	4.06	8.62	6.29	6.63	18.97	31.09	40.88	1.06	1.51	1.49	3.39
38	39.22	51.06	54.65	51.21	51.96	2.94	4.98	4.29	0.00	5.52	7.40	19.86	31.39	42.78	1.86	1.26	1.60	0.00
42[b]	42.66	48.71	51.68	51.11	49.93	6.59	4.55	4.01	2.43	4.91	7.28	19.38	31.18	42.18	0.98	1.35	1.38	1.61

[a] From outer edge of lane 1. [b] Daylight study.

TABLE F-4

TRAFFIC FLOW DATA, CURVE CONTROL SECTION

	VELOCITY (MPH)								PLACEMENT[a] (FT)					
	MEAN				STANDARD DEVIATION				MEAN			STANDARD DEVIATION		
RUN NO.	LANE 1	LANE 2	LANE 3	ALL LANES	LANE 1	LANE 2	LANE 3	ALL LANES	LANE 1	LANE 2	LANE 3	LANE 1	LANE 2	LANE 3
							(*a*) ALL VEHICLES							
12	48.28	54.34	59.61	52.62	5.41	4.60	5.32	6.58	7.90	20.27	31.59	1.23	1.34	1.18
16	49.18	56.25	60.92	54.33	6.43	5.99	5.93	7.66	7.58	19.79	31.53	1.21	1.30	1.39
20	49.25	55.26	60.90	54.33	5.37	5.14	4.26	6.71	7.79	20.11	31.36	1.24	1.41	1.40
31	49.13	55.38	61.13	54.09	6.37	5.38	4.36	7.16	7.86	19.93	31.50	1.37	1.61	1.68
34	48.66	55.81	60.95	53.91	5.60	5.00	4.95	6.96	7.41	18.66	30.89	1.31	1.49	1.52
38	49.19	55.81	60.85	53.91	6.14	5.59	5.06	7.17	7.63	19.89	31.41	1.43	1.53	1.57
42[b]	49.33	56.51	60.68	55.13	5.38	4.28	4.42	6.57	7.13	19.38	31.31	1.22	1.42	1.50
							(*b*) PASSENGER VEHICLES							
12	48.00	54.22	59.62	52.69	5.19	4.75	5.47	6.67	7.92	20.25	31.55	1.23	1.30	1.21
16	48.73	55.93	60.94	54.18	5.86	5.76	5.85	7.53	7.61	19.82	31.53	1.19	1.28	1.35
20	48.91	55.14	61.19	54.39	5.30	5.29	4.18	6.91	7.84	20.13	31.31	1.24	1.42	1.41
31	49.24	55.57	61.05	54.25	6.34	5.15	3.76	6.97	7.82	19.93	31.47	1.39	1.67	1.64
34	48.41	55.64	60.81	53.73	5.52	5.17	5.03	7.01	7.40	19.64	30.88	1.28	1.56	1.49
38	48.47	55.89	60.79	53.73	6.14	5.58	5.33	7.36	7.61	19.83	31.40	1.46	1.53	1.38
42[b]	49.12	56.44	60.48	55.02	5.16	4.39	4.45	6.60	7.10	19.33	31.27	1.21	1.47	1.48
							(*c*) COMMERCIAL VEHICLES							
12	49.59	54.17	58.91	51.53	5.32	3.75	5.18	5.53	7.87	20.33	31.93	1.24	1.42	0.73
16	51.68	57.22	61.97	54.68	8.24	5.72	8.56	7.99	7.38	19.45	31.46	1.30	1.52	1.39
20	50.70	55.50	57.09	53.16	6.16	4.91	4.85	6.13	7.57	19.76	31.39	1.17	1.45	1.53
31	48.75	54.83	59.14	51.95	6.45	5.63	3.30	6.87	7.86	19.89	31.45	1.17	1.13	2.49
34	50.25	57.13	60.23	54.50	6.16	4.20	3.13	6.29	7.36	19.76	30.69	1.49	1.21	1.91
38	51.73	55.96	58.33	53.53	5.53	6.42	2.70	6.14	7.67	20.16	29.73	1.39	1.35	3.45
42[b]	50.49	57.27	62.92	54.69	6.01	3.63	2.72	6.18	7.20	19.24	31.50	1.28	1.11	1.61

[a] From outer edge of lane 1. [b] Daylight study.

TABLE F-5

TRAFFIC FLOW DATA, ON-RAMP SECTION

	VELOCITY (MPH)										PLACEMENT [a] (FT)							
	MEAN					STANDARD DEVIATION					MEAN				STANDARD DEVIATION			
RUN NO.	RAMP	LANE 1	LANE 2	LANE 3	ALL LANES	RAMP	LANE 1	LANE 2	LANE 3	ALL LANES	RAMP	LANE 1	LANE 2	LANE 3	RAMP	LANE 1	LANE 2	LANE 3
(*a*) ALL VEHICLES																		
11	47.48	48.23	54.79	60.77	52.03	7.17	6.85	5.08	5.78	7.79	−8.03	5.97	19.67	28.89	3.36	1.90	1.48	1.68
15	47.80	48.85	55.22	62.13	53.31	7.68	6.34	4.76	4.57	7.77	−8.31	5.63	19.49	30.08	3.08	2.13	1.44	1.51
17	48.57	49.20	55.22	61.78	53.37	8.47	6.45	5.33	5.41	8.06	−7.62	5.91	19.26	30.09	3.14	1.99	1.36	1.18
22	47.45	50.07	55.06	60.30	52.70	8.61	6.95	5.09	6.85	8.13	−7.64	5.69	19.24	29.66	3.13	2.05	1.53	1.57
27	46.84	48.01	53.94	60.46	51.53	10.61	8.18	5.24	4.86	9.00	−6.95	5.94	19.46	29.92	3.04	1.98	1.40	1.44
32	49.70	49.87	55.72	62.41	54.05	11.34	8.77	6.27	5.57	9.37	−7.47	5.69	19.02	29.57	3.47	1.98	1.45	1.32
37	47.62	49.53	56.04	62.39	53.50	6.95	6.90	5.17	5.59	7.93	−7.32	5.99	19.37	29.57	2.88	1.89	1.34	1.47
39	46.31	49.91	56.58	63.18	53.50	6.79	8.28	6.06	6.37	8.95	−7.21	5.63	19.49	29.89	3.19	2.18	1.55	1.42
43 [b]	46.59	50.40	57.87	64.22	54.90	6.86	6.38	5.64	5.81	8.69	−11.00	5.68	18.46	29.25	4.08	1.72	1.43	1.48
(*b*) PASSENGER VEHICLES																		
11	47.89	48.89	55.16	61.08	52.43	7.20	6.94	5.21	5.91	7.92	−7.87	5.90	19.78	29.89	3.29	1.99	1.45	1.67
15	47.88	49.20	55.45	62.31	53.58	7.70	6.25	4.79	4.61	7.87	−8.34	5.51	19.46	30.07	3.11	2.23	1.49	1.54
17	48.65	49.49	55.70	62.09	53.78	8.56	6.35	5.43	5.38	8.23	−7.56	5.86	19.31	30.16	3.17	2.07	1.36	1.19
22	47.88	50.43	55.32	60.53	52.98	8.54	6.76	5.13	6.79	8.14	−7.52	5.60	19.29	29.72	3.10	2.12	1.51	1.56
27	47.24	48.42	54.20	60.60	51.77	10.68	8.57	5.37	4.78	9.18	−6.91	5.94	19.47	29.87	3.05	2.02	1.42	1.44
32	49.93	50.17	55.78	62.65	54.35	11.04	9.29	5.98	5.24	9.40	−7.37	5.59	19.06	29.57	3.44	2.09	1.44	1.28
37	47.81	50.32	56.33	62.39	53.79	6.93	6.79	5.27	4.85	7.82	−7.34	5.92	19.41	29.55	2.92	2.02	1.37	1.48
39	46.37	50.56	57.00	63.48	53.82	6.84	8.54	6.11	6.49	9.16	−7.21	5.63	19.49	29.89	3.19	2.18	1.55	1.42
43 [b]	46.97	51.00	58.14	64.55	55.19	6.74	6.36	5.51	5.83	8.69	−10.98	5.53	18.45	29.27	4.07	1.79	1.42	1.45
(*c*) COMMERCIAL VEHICLES																		
11	41.94	45.74	52.93	56.68	49.17	7.22	6.03	3.99	3.39	6.60	−9.05	6.21	18.82	30.15	1.22	1.57	1.56	1.45
15	40.35	46.75	53.93	58.34	50.91	4.96	6.89	4.81	2.05	6.98	−7.72	6.36	19.30	30.29	1.96	1.20	1.20	1.80
17	43.86	47.26	52.88	58.82	50.40	9.92	6.88	4.33	5.90	7.51	−8.28	5.96	18.78	29.79	2.73	1.79	1.37	0.96
22	39.16	47.78	53.36	58.26	49.91	7.14	7.63	4.48	5.24	7.91	−9.39	6.01	18.65	28.87	3.51	1.72	1.46	1.46
27	38.48	45.98	52.12	58.55	49.23	8.16	6.10	4.45	3.48	7.52	−7.37	5.76	19.12	29.94	2.17	1.84	1.28	1.41
32	44.31	48.67	54.82	58.06	51.83	17.05	7.08	4.91	7.19	8.53	−8.45	6.03	18.54	29.71	3.85	1.45	1.42	1.90
37	38.70	46.26	53.12	59.55	49.25	5.15	6.73	3.80	3.59	7.29	−6.39	6.12	18.93	29.20	1.70	1.44	1.05	1.64
39	43.05	47.26	54.11	58.21	50.61	6.78	7.15	5.34	3.97	7.47	−9.35	5.74	19.08	28.43	1.22	1.59	1.48	2.50
43 [b]	38.39	48.03	55.10	60.45	51.13	6.63	6.05	5.03	4.62	7.54	−10.90	6.26	18.25	29.67	4.32	1.31	1.66	0.74

[a] From outer edge of lane 1.

[b] Daylight study.

TABLE F-6

TRAFFIC FLOW DATA, OFF-RAMP SECTION

	VELOCITY (MPH)										PLACEMENT[a] (FT)							
	MEAN					STANDARD DEVIATION					MEAN				STANDARD DEVIATION			
RUN NO.	RAMP	LANE 1	LANE 2	LANE 3	ALL LANES	RAMP	LANE 1	LANE 2	LANE 3	LANES ALL	RAMP	LANE 1	LANE 2	LANE 3	RAMP	LANE 1	LANE 2	LANE 3
(*a*) ALL VEHICLES																		
10	38.78	52.66	55.93	60.46	49.20	5.83	5.51	6.33	8.59	10.25	−30.53	5.81	19.51	30.96	4.93	1.95	1.95	2.32
14	37.01	49.33	56.03	59.99	49.48	5.56	5.83	5.57	5.85	10.22	−30.75	5.97	19.82	31.54	5.17	1.24	1.37	2.01
19	38.34	49.92	55.93	60.25	63.03	7.55	4.91	5.53	5.56	9.94	−31.01	6.64	20.12	31.77	4.56	1.24	1.57	2.13
23	36.33	48.21	53.61	58.31	48.01	6.21	6.03	5.27	5.66	10.04	−30.57	5.83	19.43	31.21	5.48	1.37	1.45	2.07
28	35.96	47.76	53.37	58.28	47.21	6.38	5.35	5.87	5.76	10.19	−30.87	5.44	19.39	31.51	5.33	1.81	1.79	2.15
30	37.27	50.15	54.28	59.30	48.65	7.65	6.25	6.13	6.51	10.38	−30.06	6.30	20.08	31.73	4.80	1.47	1.59	2.26
35	35.43	49.51	54.65	59.93	48.85	5.78	5.57	6.00	6.45	10.70	−31.12	6.15	20.03	31.13	4.09	1.87	1.81	1.91
40	34.49	48.92	54.13	60.01	46.88	5.80	4.67	6.04	5.36	10.79	−31.21	5.64	19.41	30.54	4.08	1.42	1.52	2.22
41[b]	37.42	50.55	56.30	61.22	50.18	5.65	5.31	5.35	4.31	10.21	−31.22	5.54	19.80	31.96	3.41	1.27	1.53	2.10
(*b*) PASSENGER VEHICLES																		
10	38.70	52.33	55.94	60.71	48.62	5.85	5.66	6.38	8.67	10.54	−30.67	5.79	19.52	30.95	4.69	2.02	1.95	2.41
14	36.94	49.25	55.96	60.04	49.21	5.62	5.72	5.49	5.96	10.45	−30.82	5.92	19.79	31.57	5.15	1.25	1.38	1.89
19	38.37	49.77	55.99	60.41	49.55	7.71	4.74	5.60	5.54	10.24	−31.04	6.63	20.15	31.73	4.59	1.26	1.54	2.15
23	36.35	48.35	53.78	58.32	48.05	6.25	6.17	5.32	5.68	10.31	−30.59	5.77	19.47	31.23	5.54	1.44	1.42	2.06
28	35.98	47.84	53.50	58.42	47.13	6.50	5.35	6.00	5.89	10.49	−30.98	5.43	19.41	31.56	5.23	1.82	1.80	2.07
30	37.28	50.29	54.43	59.29	48.38	7.74	6.39	6.24	6.64	10.74	−30.16	6.32	20.16	31.79	4.65	1.50	1.57	2.25
35	35.37	49.36	54.73	60.32	48.57	5.68	5.64	6.15	6.39	11.05	−31.18	6.09	20.02	31.11	3.93	1.85	1.84	1.94
40	34.45	48.65	54.24	60.09	46.41	5.79	4.69	6.23	5.42	11.13	−31.13	5.64	19.45	30.58	4.13	1.45	1.50	2.25
41[b]	37.27	50.25	56.30	61.09	49.74	5.51	5.16	5.46	4.32	10.46	−31.24	5.51	19.79	31.92	3.40	1.32	1.47	2.13
(*c*) COMMERCIAL VEHICLES																		
10	33.86	53.26	55.54	59.31	53.75	4.71	5.10	5.86	5.95	6.39	−25.88	5.78	19.33	31.05	15.97	1.74	2.02	1.09
14	37.47	49.59	56.91	58.52	51.39	4.00	6.30	6.41	1.96	7.88	−30.21	6.05	19.80	30.83	5.74	1.11	1.42	3.65
19	38.76	50.84	55.06	56.25	51.47	5.06	5.54	4.88	3.25	6.79	−28.86	6.64	19.77	33.24	3.48	1.20	1.81	1.11
23	35.58	47.60	51.99	57.97	47.87	7.24	5.94	4.68	6.79	7.71	−30.75	5.92	18.91	29.98	4.69	1.21	1.66	2.63
28	35.60	47.88	52.33	55.07	48.23	4.90	5.26	4.51	4.26	7.17	−29.34	5.42	19.27	31.26	6.81	1.69	1.79	3.46
30	34.23	50.16	53.19	61.30	50.47	3.77	6.19	4.96	4.68	7.53	−26.37	6.14	19.40	30.28	8.96	1.36	1.78	2.45
35	36.27	49.90	53.89	55.57	50.13	8.65	5.50	4.50	5.63	7.77	−28.35	6.21	19.98	32.17	7.07	1.93	1.49	1.51
40	33.16	49.84	52.71	59.13	50.42	5.63	4.58	4.86	3.65	6.46	−31.19	5.60	19.10	29.91	3.76	1.36	1.80	2.94
41[b]	41.62	51.46	55.02	60.87	52.21	9.20	5.86	3.76	5.20	6.87	−30.65	5.58	19.45	31.50	3.98	1.14	2.10	2.20

[a] From outer edge of lane 1. [b] Daylight study.

APPENDIX G

PASSENGER VEHICLE SPEEDS AND PLACEMENTS

TABLE G-1

PASSENGER VEHICLE SPEEDS BY LANE AND HEADWAY

LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	VEHICLE SPEED (MPH) FOR HEADWAY CATEGORY [a]							
			TEST SECTION				CONTROL SECTION			
			GG	GL	LG	LL	GG	GL	LG	LL
(*a*) TANGENT SECTIONS										
0.2	13	1	52.77	52.14	51.92	51.53	51.16	48.77	49.26	47.42
		2	58.97	57.80	58.02	57.02	58.03	57.75	58.13	57.77
		3	61.77	60.10	61.33	59.27	63.73	60.95	61.25	63.01
	21	1	52.69	51.92	52.10	50.08	50.13	49.68	48.97	47.67
		2	57.92	57.18	57.88	56.66	58.74	57.06	57.87	56.64
		3	61.53	60.32	61.08	59.28	62.51	61.65	64.20	62.40
0.6	29	1	53.42	50.80	52.95	51.15	51.28	48.03	48.41	46.97
		2	57.95	55.27	56.59	55.72	57.01	56.31	56.69	55.81
		3	59.82	59.54	58.68	56.64	60.04	59.20	60.53	57.97
	36	1	52.92	52.93	51.63	49.88	50.56	51.43	50.93	48.47
		2	58.24	58 86	58.16	57.21	59.47	58.81	60.12	58.16
		3	61.92	59.20	60.70	60.19	63.26	62.10	61.71	62.17
Day	44	1	53.90	52.82	52.21	50.14	51.26	50.40	50.07	48.73
		2	59.89	57.34	58.03	56.11	59.41	57.66	58.40	57.30
		3	59.97	59.42	59.44	57.98	64.22	63.92	64.76	63.71
(*b*) CURVE SECTIONS										
0.2	12	1	46.55	47.62	47.70	46.68	48.18	47.40	48.97	47.38
		2	50.27	51.28	50.39	48.19	54.99	54.18	54.26	53.52
		3	53.17	52.69	54.89	53.27	60.33	59.44	58.81	58.80
		4	60.05	58.07	60.49	—				
	16	1	48.90	49.58	48.86	47.99	50.19	49.37	49.37	47.53
		2	51.97	50.28	50.20	49.35	56.29	55.68	56.13	55.85
		3	56.39	55.86	56.60	55.01	63.43	60.08	58.92	60.59
		4	60.15	59.62	60.20	58.62				
	20	1	48.80	47 62	49.89	45.22	49.89	49.22	49.66	47.92
		2	48.51	48.93	49.72	47.61	56.56	55.31	55.85	54.43
		3	54.43	52.47	54.21	52.45	61.40	60.84	61.66	60.85
		4	56.54	56.17	57.85	56.48				
0.6	31	1	48.23	46.85	46.01	44.72	51.14	48.52	49.03	49.09
		2	49.64	48.94	49.02	47.38	57.44	55.07	56.37	54.96
		3	53.31	53.01	53.33	51.92	61.72	60.71	60.90	60.36
		4	56.35	53.64	55.53	55.15				
	34	1	45.48	44.59	48.30	50.38	50.39	48.10	48.51	47.77
		2	49.69	49.07	48.78	47.37	56.90	55.12	56.17	55.06
		3	54.49	52.47	53.90	53.71	60.69	59.89	61.48	61.01
		4	59.42	58.85	58.61	58.13				
	38	1	47.03	46.21	47.68	46.00	50.40	47.14	48.90	47.66
		2	49.47	47.95	48.55	47.93	56.31	55.65	56.94	54.90
		3	54.76	52.90	53.72	52.07	61.87	58.76	59.86	60.52
		4	57.37	55.84	55.90	54.32				
Day	42	1	47.32	46.89	46.43	47.19	51.06	49.76	50.77	48.20
		2	50.03	48.11	48.94	48.23	58.04	56.68	57.62	55.91
		3	54.31	52.12	53.12	51.95	61.47	61.69	61.21	59.61
		4	57.28	55.58	55.63	54.10				

TABLE G-1—*Continued*

			VEHICLE SPEED (MPH) FOR HEADWAY CATEGORY [a]							
LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	TEST SECTION				CONTROL SECTION			
			GG	GL	LG	LL	GG	GL	LG	LL
			(*c*) ON-RAMP SECTION							
0.2	11	1	51.09	49.32	49.38	46.24				
		2	56.49	54.88	55.42	54.43				
		3	62.33	60.36	60.03	60.67				
		Ramp	48.44	50.04	47.20	46.77				
	15	1	51.20	49.12	49.63	47.83				
		2	56.57	56.27	55.99	54.58				
		3	63.21	61.66	62.68	61.45				
		Ramp	49.73	48.39	48.35	45.05				
	17	1	51.76	50.87	48.99	47.73				
		2	57.97	56.06	55.78	55.15				
		3	62.94	62.23	61.99	61.29				
		Ramp	50.16	49.05	47.08	48.68				
	22	1	51.69	51.04	51.02	48.96				
		2	55.44	56.06	55.69	54.87				
		3	62.10	61.01	60.18	58.69				
		Ramp	48.82	50.71	45.84	47.04				
0.6	27	1	49.62	50.30	48.66	47.20				
		2	56.63	54.47	55.12	53.20				
		3	61.88	60.74	60.33	59.15				
		Ramp	48.19	46.61	46.35	47.72				
	32	1	64.13	50.25	48.93	60.82				
		2	58.08	56.46	56.42	54.94				
		3	51.29	62.75	62.94	50.46				
		Ramp	50.43	49.05	47.87	51.11				
	37	1	52.86	49.06	50.36	49.28				
		2	56.39	56.10	56.69	56.23				
		3	62.74	62.36	62.53	61.25				
		Ramp	48.39	49.83	46.59	46.51				
	39	1	52.33	52.28	48.65	49.05				
		2	57.94	56.56	47.86	56.39				
		3	63.97	64.00	63.24	61.71				
		Ramp	48.79	47.04	45.63	44.41				
Day	43	1	51.14	51.57	50.79	50.70				
		2	58.96	57.93	59.26	57.70				
		3	65.55	65.30	65.06	62.77				
		Ramp	49.12	49.92	46.63	44.75				
			(*d*) OFF-RAMP SECTION							
0.2	10	1	55.35	51.35	52.18	50.44				
		2	57.53	55.90	55.92	55.01				
		3	62.57	59.97	57.82	56.31				
		Ramp	41.21	38.44	39.32	38.04				
	14	1	49.98	49.61	49.05	48.83				
		2	57.67	55.70	57.12	55.19				
		3	60.20	60.62	59.48	59.69				
		Ramp	38.40	36.24	38.36	36.28				
	19	1	51.10	49.38	50.24	48.56				
		2	56.61	54.71	57.09	55.86				
		3	60.11	61.07	60.10	60.65				
		Ramp	39.36	36.91	38.22	38.88				
	23	1	50.73	47.81	48.98	46.83				
		2	53.55	53.82	55.70	53.24				
		3	58.34	58.58	59.97	56.37				
		Ramp	39.36	36.21	36.99	35.70				
0.6	28	1	49.50	48.61	47.67	46.70				
		2	55.33	53.39	54.82	52.79				
		3	59.33	57.51	59.31	57.30				
		Ramp	38.22	35.96	38.06	35.07				

TABLE G-1—*Continued*

LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	VEHICLE SPEED (MPH) FOR HEADWAY CATEGORY [a]							
			TEST SECTION				CONTROL SECTION			
			GG	GL	LG	LL	GG	GL	LG	LL
	30	1	51.27	49.07	50.12	50.73				
		2	55.48	54.35	54.62	54.17				
		3	60.24	56.94	59.70	59.04				
		Ramp	38.51	37.02	37.56	36.92				
	35	1	50.36	50.49	49.94	47.44				
		2	55.73	54.59	55.44	54.35				
		3	61.66	58.80	60.61	60.02				
		Ramp	37.11	34.85	34.45	35.01				
	40	1	49.05	48.73	48.67	48.20				
		2	54.03	54.20	55.07	53.76				
		3	60.50	58.38	61.46	59.05				
		Ramp	37.17	33.64	35.23	33.46				
Day	41	1	51.17	50.22	50.63	49.47				
		2	56.15	57.02	57.03	55.66				
		3	61.64	60.31	61.79	60.63				
		Ramp	39.82	37.76	38.20	35.99				

[a] For definition of headway categories see Figure 22.

TABLE G-2
PASSENGER VEHICLE PLACEMENTS BY LANE AND HEADWAY

LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	VEHICLE PLACEMENT [a] (FT) FOR HEADWAY CATEGORY [b]							
			TEST SECTION				CONTROL SECTION			
			GG	GL	LG	LL	GG	GL	LG	LL
			(*a*) TANGENT SECTIONS							
0.2	13	1	6.77	6.79	6.82	6.65	6.71	6.74	6.77	6.79
		2	19.16	19.32	19.23	19.01	19.45	19.19	19.75	19.73
		3	29.82	29.89	29.82	30.09	30.52	31.25	30.31	30.49
	21	1	6.60	6.85	6.63	6.49	7.11	7.00	7.03	6.95
		2	19.17	18.82	18.98	18.93	19.80	19.59	19.62	19.57
		3	29.43	29.43	29.39	29.28	30.54	30.52	30.62	30.58
0.6	29	1	6.27	6.36	6.60	6.63	6.64	6.29	6.35	6.37
		2	18.50	18.59	18.75	18.69	19.07	19.43	19.39	19.47
		3	29.04	29.16	29.21	29.66	30.51	30.35	30.61	30.93
	36	1	5.95	5.72	6.24	5.88	6.24	6.46	6.50	6.35
		2	18.04	18.09	18.33	18.23	19.02	18.90	19.00	19.19
		3	28.55	28.74	29.02	29.06	29.75	30.19	30.32	30.30
Day	44	1	5.97	6.15	6.25	6.00	7.03	6.81	6.84	6.78
		2	18.30	18.46	18.23	18.54	19.20	19.78	19.69	19.58
		3	29.67	29.25	29.91	29.77	30.42	31.06	30.71	31.01
			(*b*) CURVE SECTIONS							
0.2	12	1	7.39	7.12	7.26	7.30	7.98	8.00	7.96	7.76
		2	19.12	19.24	19.34	19.64	20.33	20.21	20.37	20.10
		3	30.94	31.04	31.30	30.77	31.55	31.44	31.55	31.74
		4	42.44	42.33	42.26	—				
	16	1	7.39	7.90	7.48	7.52	7.70	7.73	7.64	7.49
		2	19.89	19.67	19.64	19.38	20.24	19.94	19.61	19.73
		3	31.48	31.32	31.40	31.63	31.52	31.51	31.32	31.86
		4	43.11	43.31	43.07	43.23				

TABLE G-2—*Continued*

LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	VEHICLE PLACEMENT[a] (FT) FOR HEADWAY CATEGORY[b]							
			TEST SECTION				CONTROL SECTION			
			GG	GL	LG	LL	GG	GL	LG	LL
	20	1	7.46	7.28	7.66	7.46	7.97	7.92	7.90	7.73
		2	19.70	19.09	19.50	18.99	19.91	20.35	19.96	20.15
		3	30.79	31.03	30.80	30.97	31.45	31.17	31.38	31.28
		4	42.14	41.82	42.73	42.36				
0.6	31	1	7.86	7.70	7.92	7.69	7.93	8.00	7.86	7.68
		2	19.47	19.42	19.65	19.63	20.09	20.07	20.09	19.76
		3	31.36	31.20	31.06	31.12	31.28	31.91	31.32	31.49
		4	42.44	42.67	42.58	42.95				
	34	1	7.88	7.81	7.83	7.84	7.53	7.34	7.41	7.39
		2	18.52	19.19	19.09	18.85	19.89	19.51	19.86	19.52
		3	30.54	30.91	30.87	30.79	30.57	31.15	31.03	30.93
		4	41.79	42.18	42.49	42.66				
	38	1	8.34	8.41	8.28	8.28	7.64	7.74	7.76	7.32
		2	19.85	19.32	19.85	19.45	20.05	19.71	19.64	19.90
		3	31.47	31.36	31.44	31.53	31.29	31.60	31.44	31.53
		4	42.48	42.74	42.67	42.66				
Day	42	1	7.60	7.05	7.11	7.21	7.44	7.19	7.16	7.01
		2	18.98	19.08	19.02	18.93	19.42	19.28	19.21	19.38
		3	30.98	30.81	30.93	30.93	30.88	20.94	31.35	31.43
		4	42.29	42.34	42.64	42.76				
			(*c*) ON-RAMP SECTION							
0.2	11	1	6.28	5.73	5.79	5.83				
		2	19.64	19.89	19.94	19.65				
		3	29.76	29.95	29.76	29.46				
		Ramp	−8.31	−7.70	−7.83	−7.73				
	15	1	5.44	5.51	5.46	5.58				
		2	19.34	19.74	19.43	19.38				
		3	29.99	30.00	30.13	30.18				
		Ramp	−8.25	−8.73	−7.67	−8.64				
	17	1	5.99	5.71	5.91	5.87				
		2	19.01	19.20	19.47	19.32				
		3	29.94	30.20	30.28	30.24				
		Ramp	−7.45	−7.20	−7.42	−7.89				
	22	1	5.61	5.39	5.82	5.59				
		2	19.46	19.09	19.45	19.25				
		3	29.46	29.72	29.74	30.00				
		Ramp	−7.56	−7.46	−7.49	−7.55				
0.6	27	1	5.75	6.18	5.55	6.05				
		2	19.39	19.40	19.73	19.40				
		3	29.57	29.94	30.03	30.03				
		Ramp	−7.22	−6.84	−6.82	−6.91				
	32	1	5.58	5.51	5.81	5.51				
		2	19.26	19.08	19.13	18.99				
		3	29.48	29.60	29.69	29.49				
		Ramp	−7.22	−8.19	−7.33	−7.09				
	37	1	5.83	5.62	6.13	6.03				
		2	19.33	19.34	19.37	19.50				
		3	29.58	29.30	29.60	29.73				
		Ramp	−7.12	−7.22	−7.59	−7.34				
	39	1	6.03	5.54	5.62	5.08				
		2	19.49	19.63	19.50	19.52				
		3	29.58	30.11	30.06	30.66				
		Ramp	−6.73	−7.06	−7.37	−7.31				
Day	43	1	5.60	5.59	5.26	5.68				
		2	18.78	18.29	18.39	18.50				
		3	29.05	29.24	29.27	29.43				
		Ramp	−11.48	−10.48	−10.62	−11.14				

TABLE G-2—*Continued*

LIGHTING CONDITION (FC)	RUN NO.	LANE NO.	VEHICLE PLACEMENT[a] (FT) FOR HEADWAY CATEGORY[b]							
			TEST SECTION				CONTROL SECTION			
			GG	GL	LG	LL	GG	GL	LG	LL
			(*d*) OFF-RAMP SECTION							
0.2	10	1	5.51	5.68	6.06	5.82				
		2	19.68	19.51	19.70	19.28				
		3	31.21	30.21	31.18	30.58				
		Ramp	−29.75	−31.25	−29.78	−30.98				
	14	1	6.12	5.81	6.06	5.79				
		2	19.56	19.60	19.94	19.84				
		3	31.63	31.25	31.60	31.75				
		Ramp	−31.08	−31.17	−30.49	−30.74				
	19	1	6.55	6.57	6.76	6.62				
		2	20.31	19.99	20.17	20.17				
		3	31.74	31.75	31.95	31.45				
		Ramp	−30.43	−32.07	−31.25	−30.57				
	23	1	5.85	5.81	5.84	5.63				
		2	19.03	19.53	19.56	19.46				
		3	31.30	30.95	31.32	31.37				
		Ramp	−30.66	−31.87	−31.24	−30.01				
0.6	28	1	5.27	5.47	5.65	5.32				
		2	19.14	19.63	19.60	19.32				
		3	31.63	31.42	31.66	31.54				
		Ramp	−29.97	−31.30	−30.35	−31.19				
	30	1	6.41	6.44	6.42	6.12				
		2	20.24	20.12	20.37	20.06				
		3	31.91	31.49	32.05	31.56				
		Ramp	−30.66	−30.64	−29.48	−30.14				
	35	1	6.14	6.34	5.98	5.95				
		2	19.69	20.04	20.08	20.04				
		3	31.09	30.79	31.24	31.37				
		Ramp	−30.90	−31.43	−31.39	−31.01				
	40	1	5.94	5.66	5.54	5.44				
		3	19.45	19.54	19.41	19.43				
		2	30.04	31.22	31.06	31.08				
		Ramp	−31.87	−31.58	−30.99	−30.71				
Day	41	1	5.35	5.50	5.29	5.75				
		2	19.80	19.64	19.88	19.82				
		3	31.90	32.02	31.45	32.33				
		Ramp	−31.41	−31.63	−30.85	−31.20				

[a] For definition of headway categories see Figure 22.

APPENDIX H

PLACEMENT AND VELOCITY BY VEHICLE TYPE AND LIGHTING INTENSITY

TABLE H-1

MEAN PLACEMENT AND STANDARD DEVIATION WITH LEVELS OF SIGNIFICANCE BY VEHICLE TYPE BY LANE FOR BOTH LIGHTING INTENSITIES

			VEHICLE PLACEMENT (FT)												
			MEAN							STANDARD DEVIATION					
			TEST SITE			SIGNIF. LEVEL[b] OF TEST—CONTROL	CONTROL SITE			TEST SITE			CONTROL SITE		
SITE	VEH. TYPE	LANE NO.	0.2 FC	SIG. LEVEL[a, b]	0.6 FC		0.6 FC	SIG. LEVEL[a, b]	0.6 FC	0.2 FC	SIG. LEVEL[a, b]	0.6 FC	0.2 FC	SIG. LEVEL[a, b]	0.6 FC
Tangent	Pass.	1	6.7	0.01	6.2	NS	6.9	0.01	6.4	1.15	0.05	1.27	1.27	NS	1.26
		2	19.0	0.01	18.4	0.01	19.6	0.01	19.3	1.17	NS	1.20	1.43	0.05	1.35
		3	29.6	0.01	29.1	0.01	30.6	NS	30.4	1.27	NS	1.21	1.62	0.05	1.44
	Comm.	1	6.3	0.01	5.8	NS	6.6	0.05	6.3	1.04	0.05	1.24	1.28	NS	1.27
		2	18.8	0.05	18.4	NS	19.6	0.01	19.2	1.37	NS	1.48	1.30	NS	1.45
		3	29.3	NS	29.5	NS	30.5	NS	30.6	1.72	NS	1.80	1.40	0.05	2.10
Curve	Pass	1	7.4	0.01	8.0	0.01	7.8	0.01	7.6	1.42	0.05	1.30	1.22	0.01	1.39
		2	19.4	NS	19.4	0.01	20.1	0.05	19.8	1.56	0.05	1.67	1.35	0.01	1.59
		3	31.2	NS	31.1	0.01	21.4	0.05	31.2	1.61	0.05	1.55	1.35	0.01	1.54
		4	42.5	NS	42.5		—		—	1.75	NS	1.73	—		—
	Comm.	1	6.7	NS	7.2	NS	7.6	NS	7.6	1.11	NS	1.41	1.25	NS	1.38
		2	19.2	NS	19.3	NS	19.8	NS	19.9	1.64	0.05	1.42	1.50	0.01	1.24
		3	31.0	NS	31.1	0.01	31.6	NS	30.5	1.87	0.01	1.53	1.29	0.01	2.45
		4	41.9	NS	40.9		—		—	2.08	NS	2.46	—		—
On-ramp	Pass.	1	5.7	NS	5.8		—		—	2.11	NS	2.11	—		—
		2	19.4	NS	19.4		—		—	1.46	NS	1.45	—		—
		3	30.0	0.01	29.7		—		—	1.48	0.01	1.38	—		—
		Ramp	−7.8	0.01	−7.2		—		—	3.18	NS	3.18	—		—
	Comm.	1	6.1	NS	5.9		—		—	1.62	NS	1.59	—		—
		2	18.9	NS	18.9		—		—	1.41	NS	1.36	—		—
		3	29.7	NS	29.5		—		—	1.37	0.05	1.87	—		—
		Ramp	−8.8	NS	−7.9		—		—	3.00	NS	2.86	—		—
Off-ramp	Pass.	1	6.1	0.01	5.8		—		—	1.52	0.01	1.72	—		—
		2	19.7	NS	19.7		—		—	1.58	0.01	1.74	—		—
		3	31.4	NS	31.4		—		—	2.10	NS	2.14	—		—
		Ramp	−30.8	NS	−30.8		—		—	5.02	0.01	4.65	—		—
	Comm.	1	6.1	0.01	5.8		—		—	1.37	0.01	1.63	—		—
		2	19.5	NS	19.4		—		—	1.76	NS	1.75	—		—
		3	31.0	NS	31.0		—		—	2.50	NS	2.78	—		—
		Ramp	−29.8	NS	−28.8		—		—	6.11	NS	7.01	—		—

[a] Significance level of difference. [b] 0.01 = significant at 1% level, 0.05 = significant at 5% level; NS = difference not statistically significant.

TABLE H-2

MEAN VELOCITY AND STANDARD DEVIATION WITH LEVEL OF SIGNIFICANCE BY VEHICLE TYPE BY LANE FOR BOTH LIGHTING INTENSITIES

			VELOCITY (MPH)												
			MEAN							STANDARD DEVIATION					
			TEST SITE			SIGNIF. LEVEL[b]	CONTROL SITE			TEST SITE			CONTROL SITE		
SITE	VEH. TYPE	LANE NO.	0.2 FC	SIG. LEVEL[a, b]	0.6 FC	OF TEST—CONTROL	0.6 FC	SIG. LEVEL[a, b]	0.6 FC	0.2 FC	SIG. LEVEL[a, b]	0.6 FC	0.2 FC	SIG. LEVEL[a, b]	0.6 FC
Tangent	Pass.	1	51.84	NS	52.00	NS	48.75	NS	48.81	5.22	NS	5.44	6.87	0.01	5.88
		2	57.41	0.05	56.91	NS	57.49	NS	57.25	4.74	NS	4.65	5.95	0.01	5.07
		3	60.79	0.01	59.62	0.01	62.68	0.01	60.42	4.88	NS	5.28	5.79	0.05	5.25
	Comm.	1	52.66	NS	51.72	NS	47.16	0.05	45.58	5.62	0.01	7.10	6.23	NS	6.06
		2	57.85	0.01	55.87	NS	55.18	NS	54.06	3.31	NS	4.60	5.11	NS	4.58
		3	59.71	NS	58.35	NS	58.53	NS	57.60	4.64	0.05	6.77	8.00	NS	6.14
Curve	Pass.	1	48.26	0.01	46.93	0.01	48.55	NS	48.69	6.60	NS	6.51	5.47	0.01	6.00
		2	49.69	0.01	48.63	0.01	55.10	0.01	55.70	6.99	0.01	5.43	5.32	NS	5.30
		3	54.14	0.01	53.10	0.01	60.68	NS	60.89	5.77	0.01	4.80	5.17	0.01	4.71
		4	58.46	0.01	56.75		—		—	5.98	0.05	5.54	—		—
	Comm.	1	43.66	NS	42.10	NS	50.56	NS	50.51	6.61	NS	7.97	6.63	NS	6.07
		2	49.10	NS	49.50	NS	55.74	NS	56.10	6.17	NS	5.77	5.06	NS	5.41
		3	54.23	0.05	52.94	0.05	59.22	NS	59.44	5.89	0.01	4.90	6.58	0.01	3.03
		4	58.09	NS	54.77		—		—	4.60	NS	6.35	—		—
On-ramp	Pass.	1	49.54	NS	49.75		—		—	6.59	0.01	8.50	—		—
		2	55.42	NS	55.74		—		—	5.15	0.01	5.78	—		—
		3	61.57	0.05	62.23		—		—	5.73	0.05	5.43	—		—
		Ramp	48.09	NS	47.88		—		—	8.08	0.01	9.47	—		—
	Comm.	1	46.88	NS	47.07		—		—	6.87	NS	6.83	—		—
		2	53.30	NS	53.60		—		—	4.43	NS	4.82	—		—
		3	58.21	NS	58.49		—		—	4.94	NS	4.95	—		—
		Ramp	41.03	NS	41.40		—		—	7.93	0.01	11.62	—		—
Off-ramp	Pass.	1	49.81	0.01	49.83		—		—	5.73	NS	5.63	—		—
		2	55.35	0.01	54.14		—		—	5.74	0.01	6.15	—		—
		3	59.63	NS	59.34		—		—	6.30	NS	6.16	—		—
		Ramp	37.56	0.01	35.84		—		—	6.42	NS	6.58	—		—
	Comm.	1	50.29	0.01	49.35		—		—	5.10	0.05	5.50	—		—
		2	54.89	0.01	52.94		—		—	5.13	0.01	4.69	—		—
		3	58.21	NS	57.37		—		—	4.96	NS	5.13	—		—
		Ramp	36.72	NS	35.26		—		—	5.96	NS	6.05	—		—

[a] Significance level of difference.

[b] 0.01 = significant at 1% level; 0.05 = significant at 5% level; NS = difference not statistically significant.

APPENDIX I

SUPPLEMENTAL DATA FROM CONNECTICUT TESTS

Table I-1 quantitatively describes the sampling zones shown in Figure 25.

Table I-2 gives some additional correlations for the pooled data without regard to lighting level. The negative correlations between cycle number and traffic volume indicate the decrease in traffic as the evening testing session progressed.

Information about the test subjects is given in Table I-3. Performance, on a subject-to-subject basis, is shown by Figures I-1 through I-12, prepared by pooling data for zones 7, 11, and 13 for the 3% upgrade grouping and zones 6, 8, and 12 for the 3% downgrade grouping. Zones 5 and 14 were not included because of the horizontal curve.

TABLE I-1

BRIDGEPORT TEST SITE ZONAL GEOMETRY DATA

ZONE	GRADE (FT/100 FT)	HORIZONTAL CURVATURE (°/100 FT)
	(*a*) WESTBOUND	
1	—0.50	0
2	1.00	0
3	0.91	0
4	—0.50	3 (lt)
5	3.00	3 (lt)
6	—3.00	0
7	3.00	0
8	—3.00	0
9[a]	1.00	0
	(*b*) EASTBOUND	
10[a]	—1.00	0
11	3.00	0
12	—3.00	0
13	3.00	0
14	—3.00	3 (rt)
15	0.50	3 (rt)
16	—0.91	0
17	—1.00	0
18	0.50	0

[a] Not used in analysis.

TABLE I-2

ADDITIONAL COMPUTED CORRELATIONS FROM CONNECTICUT TESTS. ALL TRIALS

CORRELATION	COEFF.
Steering wheel activity—gas pedal activity	0.269
Elected speed—gas pedal activity	—0.142
Elected speed—steering activity	—0.301
Adjacent volume—oncoming volume	0.823
Cycle number—oncoming volume	—0.282
Cycle number—adjacent volume	—0.260

TABLE I-3

CHARACTERISTICS OF SUBJECTS FOR CONNECTICUT TRIALS

SUBJECT NO.	SEX	AGE
1	M	28
2	F	22
3	F	21
4	F	22
5	F	20
6	F	55
7	F	23
8	F	52
9	M	26
10	F	22

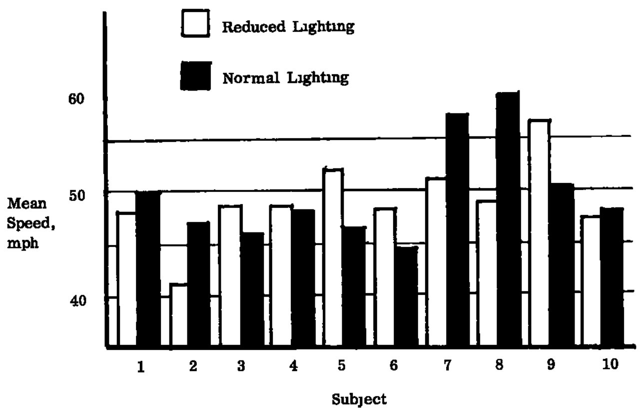

Figure I-1. Subject's mean speed on 3% upgrades.

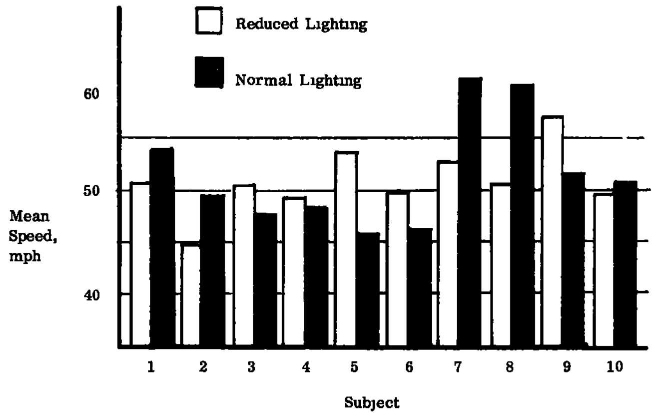

Figure I-2. Subject's mean speed on 3% downgrades.

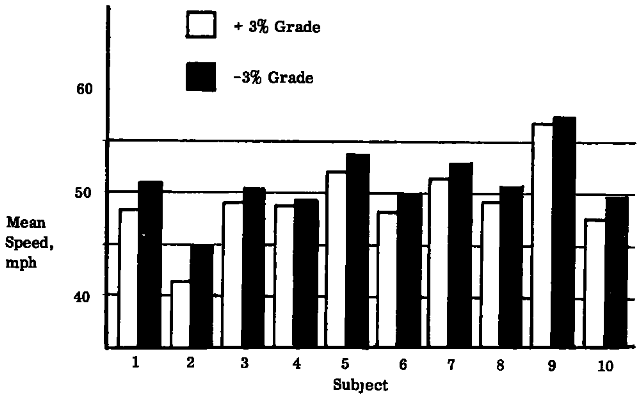

Figure I-3. Subject's mean speed on grades under reduced lighting.

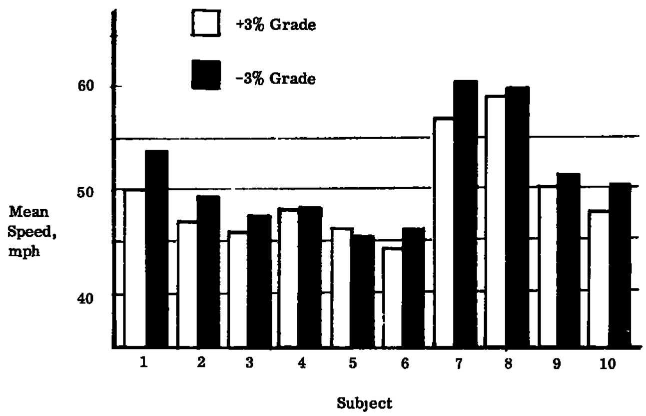

Figure I-4. Subject's mean speed on grades under normal lighting.

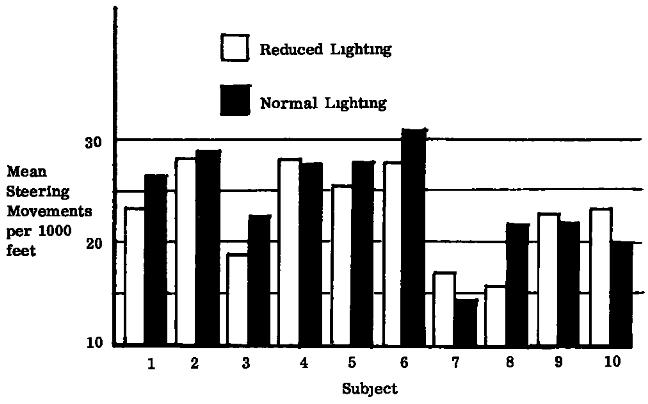

Figure I-5. Subject's steering activity on 3% upgrades.

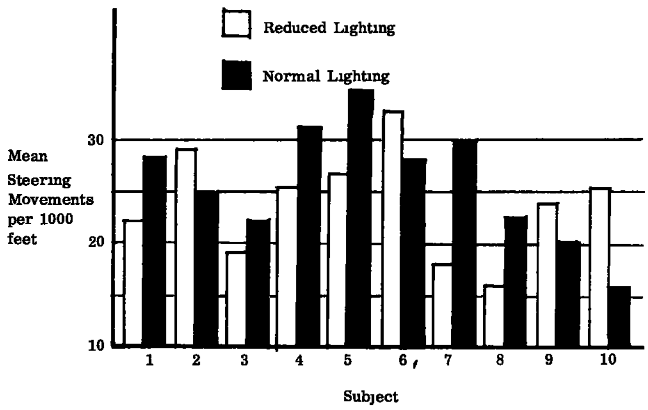

Figure I-6. Subject's steering activity on 3% downgrades.

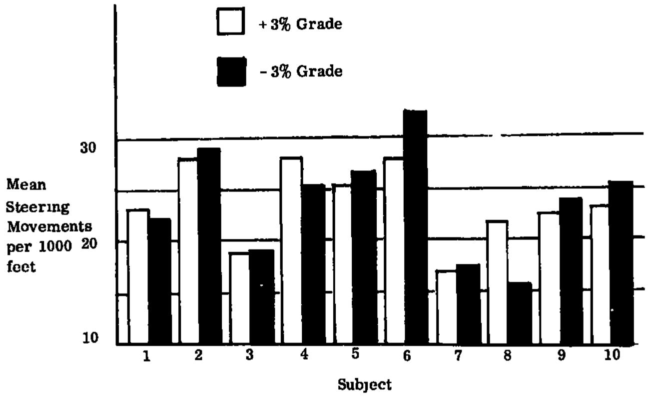

Figure 1-7. Subject's steering activity on grades under reduced lighting.

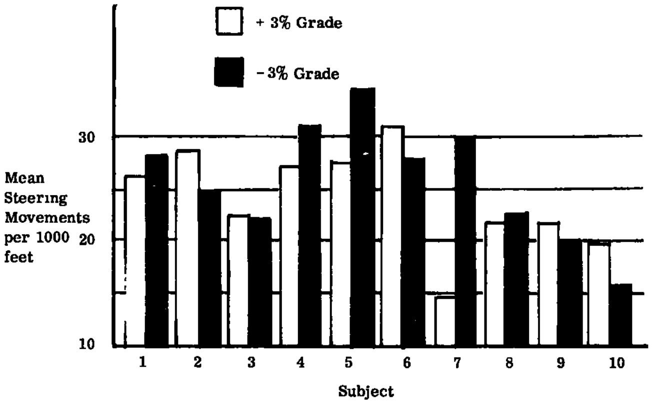

Figure 1-8. Subject's steering activity on grades under normal lighting.

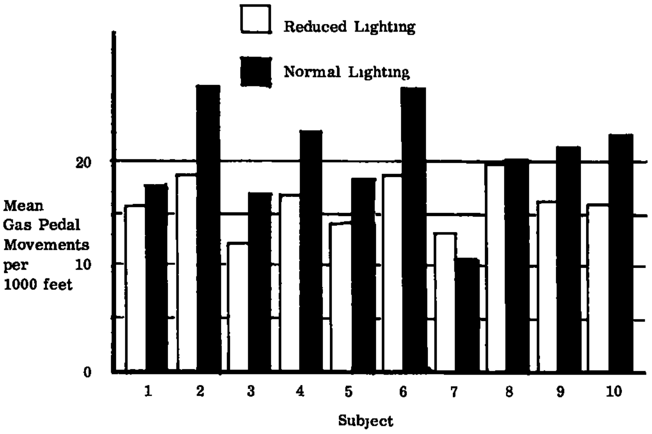

Figure 1-9. Subject's gas pedal activity on 3% upgrades.

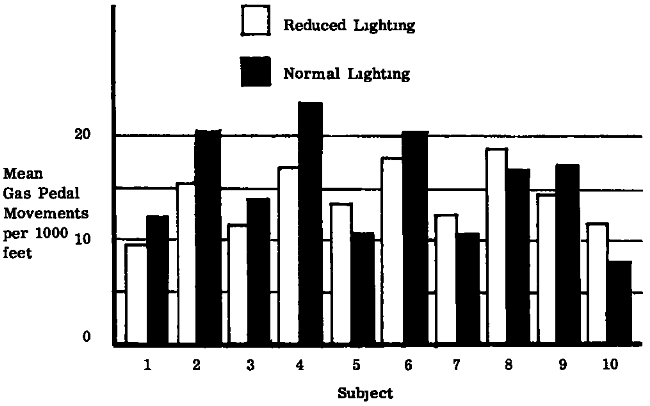

Figure 1-10. Subject's gas pedal activity on 3% downgrades.

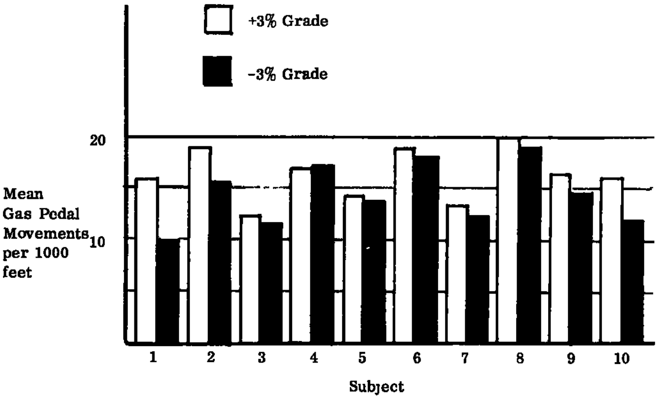

Figure 1-11. Subject's gas pedal activity on grades under reduced lighting.

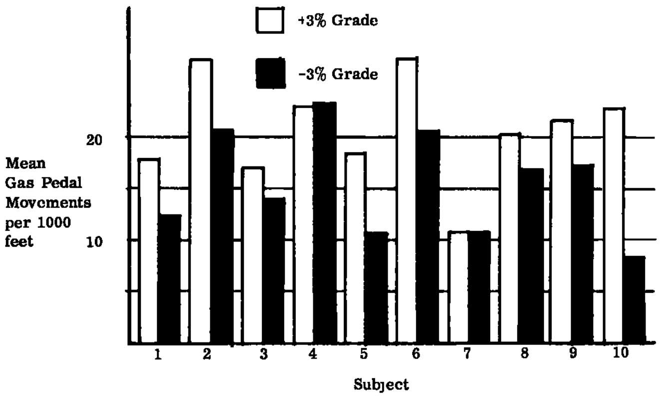

Figure 1-12. Subject's gas pedal activity on grades under normal lighting.

APPENDIX J

DETERMINATION OF GLARE EFFECT

The visibility analyses described in Part III were made with and without allowance for disability glare. The value of the without glare condition is academic. However, the analyses together reveal clearly the significance of disability glare effects in the visual field of a driver.

As described in Chapter Eight, the glare evaluation was made by using an optical analog for the flux weighting function shown in Figure 43. This analog integrates the glare sources regardless of their location or their intensity, and hence operates like the human eye.

The glare lens calibration curve (Fig. 43) depicts the close agreement between the performance of this analog and the human eye. It should be noted that from fovea to periphery the sensitivity to glare varies over a range from 1 to 0.00001. This large change over a displacement of approximately 90° indicates the importance of the relative spatial placement of the glare sources in the visual field. One could consider this in the way of relative glare values; e.g., a glare source with an intensity of 10 candela's toward the driver's eye at approximately 5° from the optical axis of the eye will have to be increased by a factor of 10^4 to produce the same glare at an angle 80° off-axis. When driving in a roadway environment, the driver is exposed to the fixed roadway lighting system in a cyclical manner, the oncoming headlamps in a random manner, and the glare sources in the off-roadway developments in a random manner. Obviously, he moves through a variable environment, changing the position of these sources in relation to his eye from moment to moment.

An attempt was made to evaluate the magnitude as well as the origin of the glare. Five wide-angle photometers (Fig. 41) were clustered to cover the hemisphere field ahead of the driver. This visual field was divided into glare-flux collecting areas (Fig. 42) following the usual rationale, as follows:

Area 1: oncoming headlights and left-hand off-roadway random light sources.

Area 2: fixed roadway lighting at the left-hand side of the driver.

Area 3: fixed roadway lighting at the right-hand side of the driver.

Area 4: off-roadway light sources at the right-hand side of the driver.

Area 5: the roadway and its shoulders.

The view of each photometer included part of the car interior. This, as well as the imperfect optical transfer, produced some cross-feeding. These photometers had a good linear response over their wide range. Pooled photometric data for the reduced and normal lighting conditions on the four sections studied in detail are shown in Figures J-1 through J-8.

The weighting of the glare fluxes in relation to the human eye glare function was an approximation. Of each solid angle of the collecting cone of the zonal glare flux photometers, the percentile of the hemisphere was established and a suitable weighting coefficient was computed from the glare equation. This weighting coefficient was used in a point-to-point computation of the partial disability glare, PDG_v, from each area. That is,

$$PDG_1 = \frac{\overline{M}_1}{\overline{M}_1 + \ldots \overline{M}_5} B_v \qquad \text{(J-1)}$$

in which

$PDG_{1 \text{ to } 5}$ = partial disability glare for zones 1 through 5, respectively;

$M_{1 \text{ to } 5}$ = continuous measured weighted variables of glare photometer for zones 1 through 5; and

B_v = integrated glare flux as measured simultaneously.

This coarse approximation was used to compute the contrasts and the relative visibility factor (RVF) for objects with reflectivities of 10, 30, 50, and 70 percent. After all these values were computed the data were pooled in terms of the six repetitive locations between light standards (200 ft apart). The same RVF computation was used as before, but using the partial glare factors instead of the integrated glare used originally.

These computations for the relative visibility as affected by partial glare were executed for sections 1 and 18 for normal and reduced illumination, for targets with reflectances of 10, 30, 50, and 70 percent. The results of these pooled data have been plotted in two ways. The first manner of plotting is similar to the plotting method in the main report, where the six locations within one luminaire span of 200 ft are on the horizontal axis and the relative visibility factors (RVF) on the vertical. For each glare zone and condition the normal and reduced illumination were printed together to facilitate comparison.

A more meaningful representation was found by plotting the object reflectivities on the horizontal and the RVF on the vertical and comparing the interrelations of the glare origin zones per location point. The normal and reduced illumination cases were again printed together. A cursory glance revealed the similarity of these graphs with the corresponding graphs in the main report.

The absolute values of the partial glare RVF (PGRVF's) and the RVF's obtained show some disparity, which indicates that the weighting factor for the glare zones was biased on the small side; the linear performance of the zonal photometers is incompatible with the steep change in the eye glare function (Fig. 43). This disparity does not affect the intercomparisons of the results.

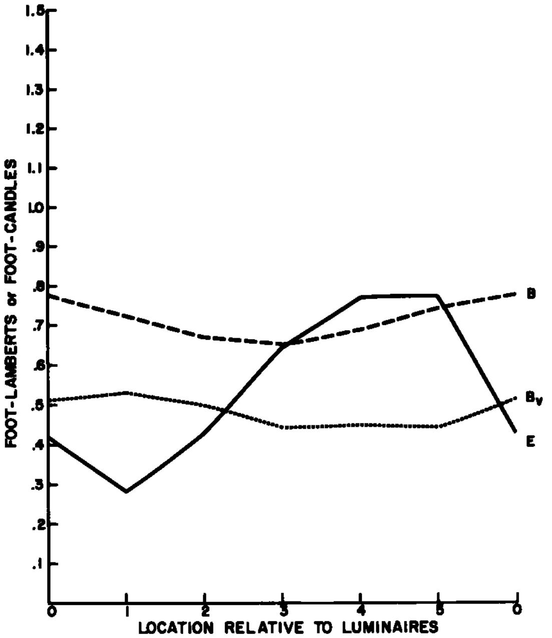

Figure J-1. Pooled photometric data, section 1, reduced illumination.

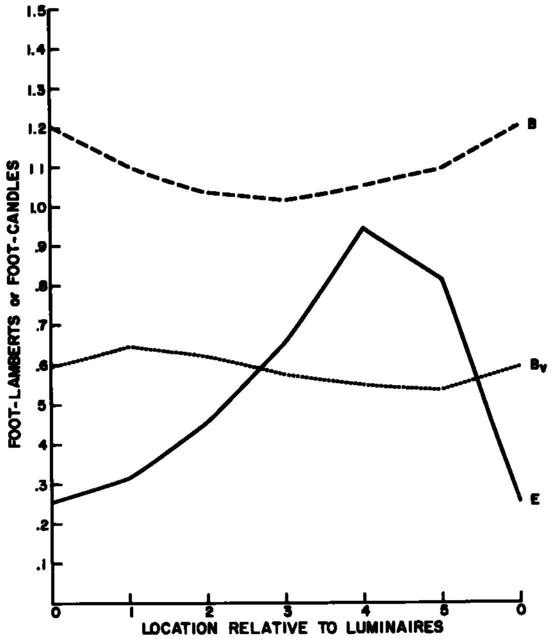

Figure J-2. Pooled photometric data, section 1, normal illumination.

Comparing the absolute values as well as the fitting of the curves for section 1 (westbound) and 18 (eastbound) for the normal illumination condition, one notices a minimal change in relative visibility for all glare zones. It should be kept in mind that a comparison by section means an evaluation of the contribution of the vehicular lighting to the glare and the object contrast or visibility. In section 1 during the data taking, the instrumented vehicle was facing high-density traffic, whereas the vehicle was traveling in low-density traffic. However, when comparing the same sections 1 and 18 under the reduced illumination, not only do the absolute values change, but the non-fitting curves

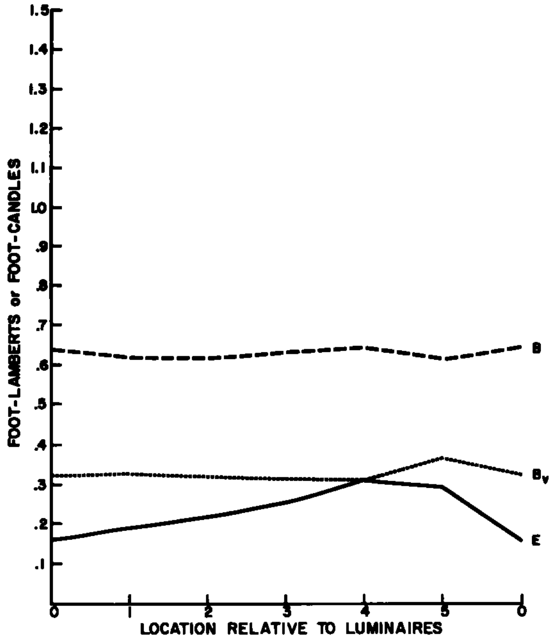

Figure J-3. Pooled photometric data, section 6, reduced illumination.

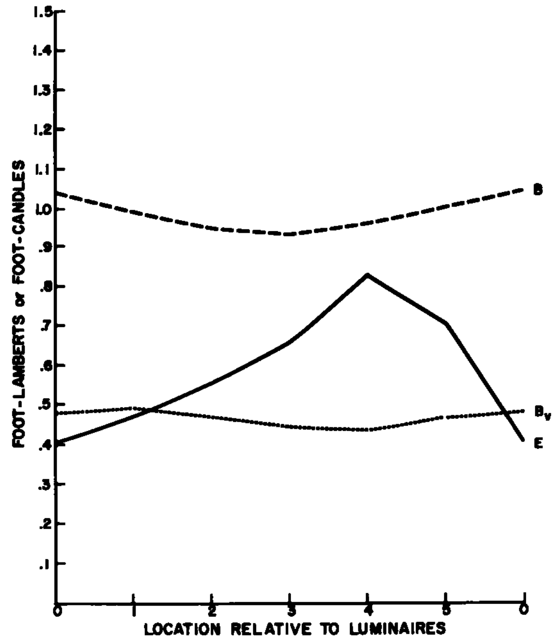

Figure J-4. Pooled photometric data, section 6, normal illumination.

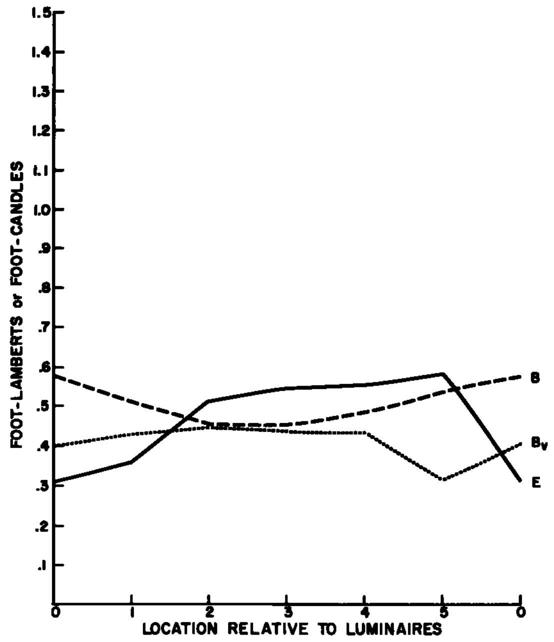

Figure J-5. Pooled photometric data, section 13, reduced illumination.

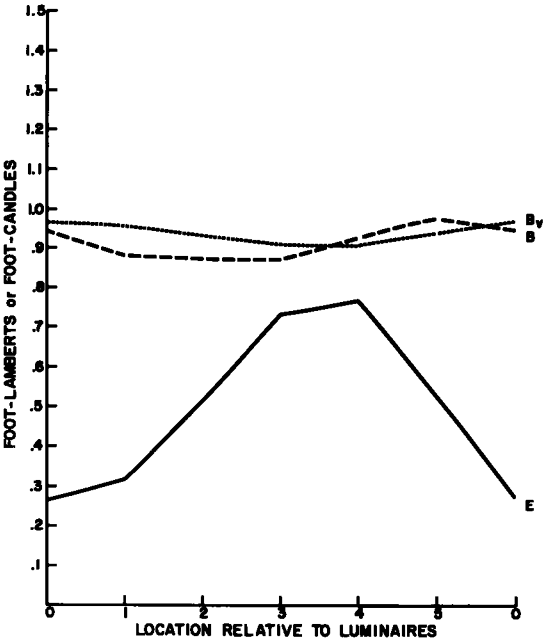

Figure J-6. Pooled photometric data, section 13, normal illumination.

also point to possible reversals when traveling through a representative stretch of the system.

The second method of plotting indicated this even more clearly. Each series of graphs represents the changes in PGRVF for the five glare zones per data location point. If one visualizes these six series of graphs for each section and illumination condition ranked in order, one can see not only the changes in numerical value of the PGRVF but also dominance in contribution to the decrease of the PGRVF by each glare zone.

In sections 1 and 18 under normal lighting conditions, the glare originating in zone 5 has the dominant effect

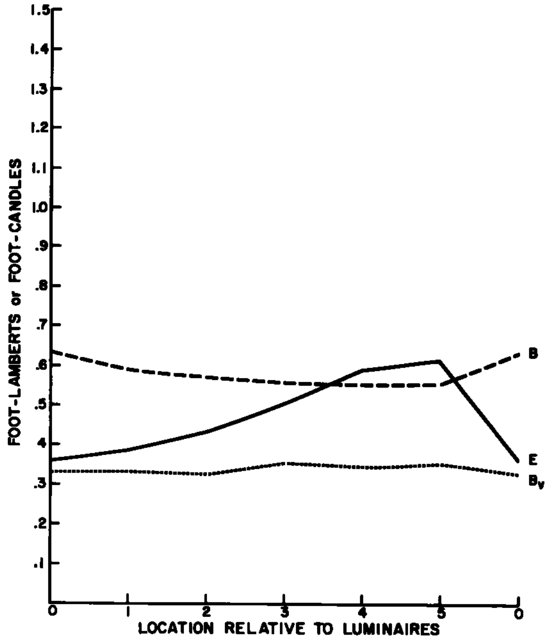

Figure J-7. Pooled photometric data, section 18, reduced illumination.

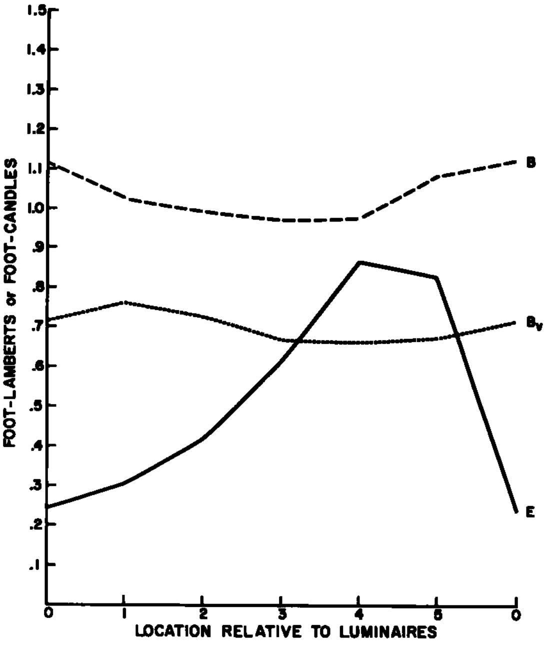

Figure J-8. Pooled photometric data, section 18, normal illumination.

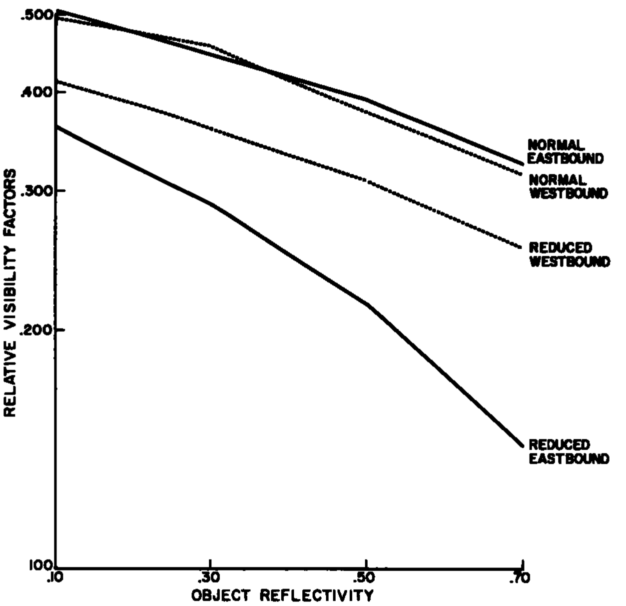

Figure J-9. Eastbound-westbound comparison of relative visibility factors, glare effect omitted.

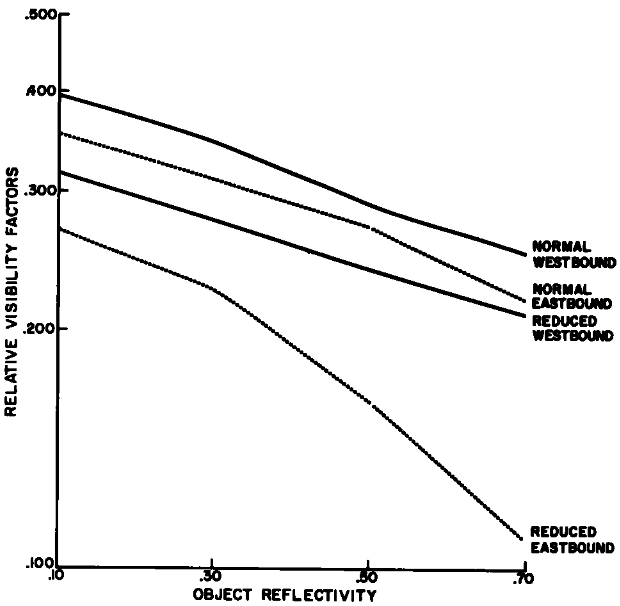

Figure J-10. Eastbound-westbound comparison of relative visibility factors, glare effect included.

TABLE J-1

GLARE ZONE RANKING BY DOMINANCE IN REDUCING THE RELATIVE VISIBILITY FACTOR

SECTION NO.	ILLUMINATION	STUDY LOCATION NO.	GLARE DOMINANCE RANKING 1	2	3	4	5
1	Normal	0	5	4	2	1	3
		1	5	2	4	3	1
		2	5	2	4	3	1
		3	5	4	2	1	3
		4	5	4	2	1	3
		5	5	4	2	1	3
	Reduced	0	5	2	4	1	3
		1	5	2	1	4	3
		2	5	2	1	4	3
		3	5	4	2	1	3
		4	5	4	2	1	3
		5	4	5	2	1	3
18	Normal	0	5	4	2	1	3
		1	5	2	4	1	3
		2	5	2	4	1	3
		3	5	4	2	1	3
		4	5	4	2	1	3
		5	5	4	2	1	3
	Reduced	0	4	5	2	3	1
		1	5	4	2	1	3
		2	5	4	2	1	3
		3	5	4	2	1	3
		4	4	5	2	1	3
		5	4	5	2	1	3

throughout the section. This section takes in the roadway, the hood, and the dashboard of the car.

Zone 4, which takes in the right-hand side of the roadway, follows closely just when one passes under the luminaire (point 0) but then after point 0, through points 1 and 2 (68 ft.), it seems that the glare flux from the luminaire at the left-hand side of the driver starts to prevail. At point 3 the glare flux from zone 2 becomes more dominant.

The lesser effect of the glare flux in zone 3, which takes

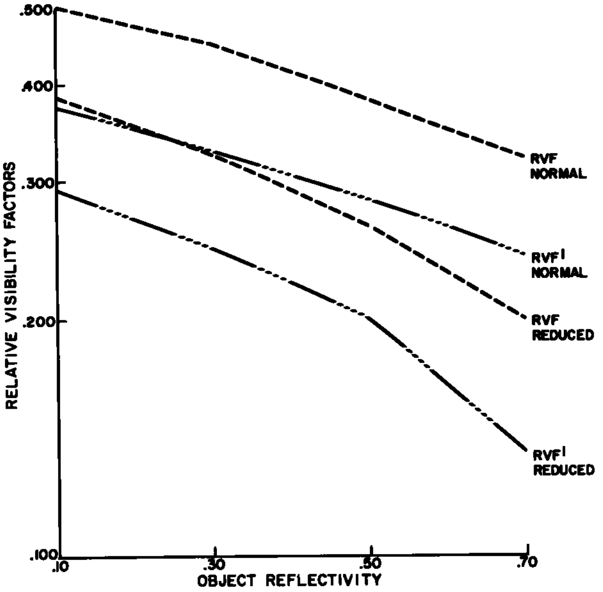

Figure J-11. Over-all comparison of relative visibility factors.

in the luminaires close to the driver at his right side, could be caused by the more favorable cutoff produced by the windshield opening and roofline geometry. Throughout the representative 200 ft under normal illumination, the rate of contribution of the partial glare seems constant.

Scanning through the graphs in a similar way for the reduced illumination, it was found that the glare flux from zone 5 again is dominant. The same pattern emerges, except for section 18 (eastbound facing low-density traffic), where at points 4 and 5 the glare-flux from zone 4 becomes more dominant in decreasing the PGRVF.

Traveling in section 1 and facing high-density traffic, the influence of the glare-flux from zone 1 becomes stronger. The relative change as analyzed in this manner does not reveal large differences in PGRVF. The small differences justify the procedure of ranking the zonal glare zones according to their dominance in reducing the RVF. In Table J-1 the glare zones are ranked according to their dominance in reducing the RVF. The highest rank number indicates the strongest effect in a location point. Comparisons of eastbound and westbound RVF's are shown in Figure J-9 for glare effect omitted, in Figure J-10 for glare effect included, and over-all in Figure J-11.

Summary

Under high traffic density conditions the normal illumination seems to balance the visual environment better than the reduced illumination did. The measuring system and the subsequent analyses, after improvement, can be considered as an additional tool for use in evaluating visibility aspects of highway safety research.

APPENDIX K

THE QUESTIONNAIRE

The form of the questionnaire presented herein was used for daytime data collections. A similar form was used at night, the only change being the instructions paragraph in the Nighttime Driving Section. For nighttime handout the paragraph read:

"This section contains a list of statements which can be used to describe some of the problems of nighttime driving. Keeping in mind the five-mile section of the Turnpike following the toll station at which you received this questionnaire, please check those of the following items which describe things that made your drive difficult or unpleasant."

Institute for Research
P.O. Box 254
State College, Pennsylvania

DRIVER QUESTIONNAIRE

We appreciate your cooperation in this research effort and would like to thank you in advance.

INSTRUCTIONS

Please fill out this questionnaire as soon as possible. All questions refer to a five mile section of the turnpike following the toll station at which you received the questionnaire. The longer you wait to fill out the questionnaire, the more difficult it will be to remember your drive.

This questionnaire has four pages and is divided into three sections: Personal Information Section, Driver Comfort Scale, and Nighttime Driving Questions. Each section has its own special instructions.

It should not require more than ten to fifteen minutes to complete the questionnaire. When you finish, please mail the questionnaire back to the Institute for Research in the stamped, self-addressed envelope.

NOTE: This questionnaire should be filled out only by the driver who received it.

I. PERSONAL INFORMATION SECTION

Instructions

In this section we are interested in finding out some of the characteristics of the drivers who use the Connecticut Turnpike System. Please read each question, and then indicate by a check mark ( ) which category is applicable to you and fill in the blanks on questions 1, 2, 3, 7, and 8.

Questions:

1. If you know the city closest to your exit, please write it here: ____________________ (city), ____________________ (state).
2. If you know the name of the road or highway on which you left the Connecticut Turnpike, please write it here______________.
3. If you know the number of the exit at which you left the Connecticut Turnpike, please write it here__________________.
4. Approximate number of miles you drive per year:
   0-5,000 ______; 5,000-8,000 ______; 8,000-12,000 ______;
   12,000-40,000 ______; over 40,000 ______.
5. Select one of the following that best describes the frequency with which you drive on this part of the turnpike.
   Several times per week___________
   Several times per month__________
   Very seldom____________________
   Never before___________________
6. Have you filled out one of these driver questionnaires for the Institute for Research before? Yes______, No ______.
7. Please print clearly the initials of your full name. For example, John Paul Jones would be J. P. J.

   ____
   Your initials*
8. Please print the date on which you filled out this questionnaire

   __________________________.

* We need your initials in case you have already filled out our questionnaire or in case you do so again. We will make no other attempt to identify you. If you prefer, ignore item 7.

(see next page)

II. DRIVER COMFORT SCALE

Instructions

These questions refer to a five mile section of the turnpike following the toll station at which you received this questionnaire. Keeping in mind that part of your trip, please indicate which of the following statements you agree with by checking the box to the left of the statement. If you do not agree with the statement, do not check it. Please check only those statements with which you agree.

Statements

Agree

☐ 1. I drove in accordance with my usual driving habits.
☐ 2. I found I had ample time to think about things not related to driving.
☐ 3. I tried to be more careful than usual.
☐ 4. At times other drivers seemed quite thoughtless.
☐ 5. I felt slightly apprehensive.
☐ 6. I felt the drive was completely free from hazards.
☐ 7. I would not like to drive on this road at night more frequently than is necessary.
☐ 8. For the most part, I felt no great demands on my driving ability.
☐ 9. I wish I could have felt more safe on my trip.
☐ 10. I was always confident that I was safe.
☐ 11. I felt uneasy about passing other vehicles or being passed by them.
☐ 12. Most of my driving involved rather automatic responses.
☐ 13. Actually, the driving was not a simple task.
☐ 14. I felt completely relaxed.
☐ 15. I thought the drive was extremely hazardous.
☐ 16. At no time did I feel unsafe.
☐ 17. I didn't feel that the drive was particularly stressful.
☐ 18. I was extremely careful.
☐ 19. The drive required almost my full concentration to insure against accidents.
☐ 20. I thought some other drivers were discourteous in their driving.
☐ 21. The thought that I might have an accident never entered my mind.

(see next page)

III. NIGHT-TIME DRIVING

Instructions

This section contains a list of statements which can be used to describe some of the problems of night-time driving. Please check those of the following items which you feel make night-time driving difficult or unpleasant.

☐ 1. Distraction due to headlights of vehicles traveling in the opposite direction.
☐ 2. Difficulty in telling if a light was on a car, on a truck, on a sign, etc.
☐ 3. Difficulty in seeing the edge of the road.
☐ 4. Temporary blinding due to glare in rear view mirror from headlights behind you.
☐ 5. Inability to see far enough.
☐ 6. Confusion due to presence of too many lights.
☐ 7. Temporary blinding due to headlights of vehicles traveling in the opposite direction.
☐ 8. Difficulty in judging distance.
☐ 9. Distraction due to glare in rear view mirror from headlights behind you.
☐ 10. Difficulty in reading signs.
☐ 11. Eyes became tired or strained.
☐ 12. Difficulty in judging velocities of other vehicles.
☐ 13. Glare from street lights.
☐ 14. Difficulty in seeing the outlines of the lanes.
☐ 15. None of above.

Please list any additional things which you feel made your drive difficult or unpleasant:

APPENDIX L

SCALING PROCEDURES

This outline is based on discussions in Torgerson (*22*) and Guttman (*21*).

Definitions of terms:

r = number of responses per subject (= number of questionnaire items);

n = number of categories ($= 2r$);

N = total number of subjects (615);

N_k = number of subjects responding to category k;

N_{jk} = number of subjects responding to both categories j and k;

F = an nxn matrix with elements $N_{jk}/\sqrt{N_j N_k}$;

D = a diagonal matrix whose matrix elements are N_k;

χ_k = weight for category k, $k = 1, \ldots, 42$;

X = an n-vector with elements χ_k;

e_{ik} = 1 if subject i checks category k, 0 otherwise; and

s_i = score of subject i, or $1/r \sum_k^n e_{ik}\chi_k$.

The problem is to chose X so as to maximize η^2, which is given by

$$\eta^2 = \frac{\sum_i^N (s_i - \frac{1}{N}\sum_i^N s_i)^2}{\sum_i^N \sum_k^n (e_{ik}\chi_k - \frac{1}{N}\sum_i^N s_i)^2} \qquad \text{(L-1)}$$

in which

$$s_i = 1/r \sum_k^n e_{ik}\chi_k. \qquad \text{(L-2)}$$

The solution is obtained by differentiating η^2 with respect to χ_k. This is done after setting $\Sigma\Sigma e_{ik}\chi_k = 0$, which entails no loss of generality because η^2 is invariant with respect to the choice of the origin of χ_k. The solution is given by the characteristic equation

$$X\, D^{1/2}\, (F - r\,\eta^2\, I) = 0. \qquad \text{(L-3)}$$

After determining matrix F from the data, Eg. L-3 is solved for the eigenvector, $X\, D^{1/2}$, corresponding to the second largest eigenvalue, $r\eta^2$. From these X and η^2 are easily determined. (The solution using the largest eigenvalue gives $\eta^2 = 7$, and all $\chi_k = 1$, which violates $\Sigma e_{ik}\chi_k = 0$.)

Other solutions are available, such as Mosteller's; however, the characteristic equation given in the foregoing, which is Guttman's, has the advantage that matrix F is symmetric, thus facilitating extraction of the eigenvalues.

APPENDIX M

DERIVATION OF MOON BRIGHTNESS INDEX

Using Rougier's and Bullrich's data as given in Minnaert (*27*), a number proportional to the intensity of the moonlight outside the earth's atmosphere was determined. This value is a function of α, the angle between lines from the sun through the earth and from the moon through the earth, defined so that at full moon the angle equals 0°. Let this intensity be referred to as $I(\alpha)$.

Given $I(\alpha)$, atmospheric extinction was computed as proportional to the antilogarithm of $-0.4K \sec z$, in which z is the zenith angle and K, which refers to atmospheric conditions, was taken as 0.5. The value chosen for K involves no loss of generality because ultimately it simply contributes only to a constant of proportionality. The fact that it was held constant does entail a loss of accuracy even for clear weather. This was accepted as error of measurement inasmuch as there was no reason to believe it would bias the results. The previous factor was then rewritten as $0.631^{1/\sin E}$, in which E is the elevation angle of the moon.

Finally, a third factor was employed to account for the zenith angle; this factor can be written as $\sin E$.

Thus, the index of the light from the moon was given by:

$$L = \text{Const. } I(\alpha)\ (0.631^{1/\sin E})\ \sin E \qquad \text{(M-1)}$$

Rep. No.	*Title*
42	Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index (Proj. 14-1), 144 p., $5.60
43	Density and Moisture Content Measurements by Nuclear Methods (Proj. 10-5), 38 p., $2.00
44	Traffic Attraction of Rural Outdoor Recreational Areas (Proj. 7-2), 28 p., $1.40
45	Development of Improved Pavement Marking Materials—Laboratory Phase (Proj. 5-5), 24 p., $1.40
46	Effects of Different Methods of Stockpiling and Handling Aggregates (Proj. 10-3), 102 p., $4.60
47	Accident Rates as Related to Design Elements of Rural Highways (Proj. 2-3), 173 p., $6.40
48	Factors and Trends in Trip Lengths (Proj. 7-4), 70 p., $3.20
49	National Survey of Transportation Attitudes and Behavior—Phase I Summary Report (Proj. 20-4), 71 p., $3.20
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52	Measurement of Pavement Thickness by Rapid and Nondestructive Methods (Proj. 10-6), 82 p., $3.80
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Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

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