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THE EFFECT OF HEADLIGHT GLARE ON VEHICLE CONTROL AND DETECTION OF HIGHWAY VISION TARGETS

by

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ABSTRACT

Typical night vehicle meeting engagements on unlighted two- three-, and four-lane highways were simulated. Vision tasks for subject drivers were provided utilizing common highway visual objects as targets. Various vehicle headlight systems including standard low and high beam, high-intensity and polarized lamps were studied under varied conditions of vehicle speed and separation distances between opposing single and multiple vehicles with respect to the vision targets with drivers having varied glare adaption response. Measurements were made of detection distance capabilities of the observers and their steering response to targets and oncoming glare vehicles.

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The psychological aspects of this study have been largely the responsibility of Dr. Bryce O. Hartman of the U.S. Air Force School of Aerospace Medicine at Brooks Air Force Base whose consultation, guidance, and assistance is gratefully acknowledged. The specially designed instrumentation for these studies was developed by the Department of Applied Physics of Southwest Research Institute and is the principal effort of J. Derwin King and George F. Munsch. A special note of thanks is due M. E. Locke, the principal test technician, for the many long nights of work represented by the more than 4000 test runs completed to date.

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I. INTRODUCTION

Glaring headlights on opposing vehicles on the highway have been recognized as a serious, although imprecisely categorized, contributor to nighttime highway accidents for as long as headlights have been utilized to illuminate the roadway.

Recognizing this problem, many ingenious designs have been developed over the years to control the beam pattern and light distribution to provide maximum illumination for the visual field ahead of the driver on his side of the roadway while reducing to a minimum the glare presented to the driver in the opposing traffic lane. The practical elimination of glare by beam control or variation of lamp intensity is a virtually impossible task, however, and the current standard dual light system is a compromise in light intensity and beam pattern between efforts to achieve maximum illumination for the visual tasks of the driver and minimum discomfort or vision disability to opposing drivers.

That a solution to this dilemma is imperative is attested to by the fact that it is now generally agreed that normal cruising speeds of vehicles on unlighted rural highways have reached the point that safe stopping distance exceeds the distance at which the driver can detect roadway obstacles in the illumination provided by present standard high beam headlights. Increasing roadway illumination by increasing headlight intensity to the point that stopping distances will be safely within visual detection distances seems essential, but such action alters the compromise which has been made to maintain headlight glare at an acceptable level. Even though this compromise could be altered, and has been constituted differently with respect to beam pattern and sharpness of beam cutoff in European and U.S./British standards, curves and undulations in the road give rise to situations in which the maximum intensity of the beam must be faced at times by an opposing driver.

The information presented here is a study of the multiplicity of factors of concern in the headlight glare problem. The overall project is, in effect, an extension of work which has been conducted by Richard N. Schwab, Lawrence D. Powers, David Solomon, Val Roper, Lewis Chubb, and others over the past several years as discussed[1,2].* It is also, in some respects, complementary to work recently reported by Webster and Yeatman, of the Department of Civil Engineering of the University of Illinois.[2] This latter work related specifically to the effects of lateral separation on glare but included a thorough historical review and detailed discussion of the overall headlight glare problem as well as an extensive bibliography. A further

*Superscript numbers in parentheses refer to the List of References at the end of this report.

major review of the whole problem of seeing under conditions of night driving, including the special aspects of headlight glare, is contained in Oscar W. Richard's recent publication for the Bureau of Public Roads.[1] Since these publications (Refs. 1 and 2) are so recent, no purpose would be served by repeating this material here, and the reader is referred to them for background information. The principal additions considered herein, to the work previously performed, are the evaluation of a greater range of factors considered to have influence on the ability of drivers to accomplish visual tasks in night driving and a closer approximation to real highway traffic encounters. A fresh look was also taken at polarization applied to current types of vehicle headlights since little work has been done in this field since the advent of four lamp headlight systems.

There are many factors in the highway/vehicle/driver system which influence and determine the ability of the driver to see adequately in the night driving situation. Some of these factors, such as driver visual performance, headlight intensity and beam pattern, target contrast, reflectivity, and luminance can be precisely measured and related to the distance at which a specific visual target or task can be detected and identified. The presence of opposing vehicle headlights on moving vehicles, where the intensity of the approaching lights is continually changing, alters these relationships drastically. Many of the referenced studies have examined specific aspects of these relationships under conditions ranging from theoretical and laboratory analyses to actual highway conditions. The effects of variations in these factors and influences of other factors such as speed, lateral separation, longitudinal separation, queues of approaching vehicles, dirty windshields, and others, have not been so evaluated in carefully controlled highway environments. It has been the objective of this study to provide such consideration.

Further studies are in progress which will provide additional data of concern in the particular case of polarized headlighting.

It is postulated that the use of polarized headlights on vehicles would decrease the tension inherent in many drivers in nighttime driving. Studies are in progress to determine the comparative development or onset of fatigue in drivers exposed to various types of opposing headlights, including polarized, over extended driving periods. The effects on drivers of meeting vehicles with and without headlight polarizing systems, as might be encountered during a transition period of adoption of polarization will likewise be investigated as will also the effects of combined polarized headlight systems and normal fixed, overhead lighting.

Upon conclusion of these studies and a review of the work of other investigators in this field, a cost/benefit analysis of the potential adoption of polarization as a solution to the headlight glare/night visibility problem will be developed.

Table 1 is a tabulation of the eight experiments comprising the first phase of this study, showing the factors considered in each and the scope of overall coverage.

Certain factors which have more or less impact on night vision and visibility have not been included in this phase of the study, although some may be of major importance and provide virtually complete solutions to the glare problem under limited conditions. Typical of these are background, overhead or fixed roadway illumination, and median glare screens or glare plantings. The latter are, of course, not applicable to two-lane rural highways which comprise the major portion of the highway system and the worst glare environment. Although fixed, overhead lighting may not be feasible as an overall solution for glare reduction on all two-lane roads, its use in high hazard locations prompted its inclusion in studies of the combined overhead lighting/headlight environment indicated above.

TABLE 1. HEADLIGHT EVALUATION EXPERIMENT PLAN[1]

Exp No.	Driver Subjects (D)	Targets* (T)	Separation of Lanes (S)	Intercept Distance† (I)	Headlight Configuration‡ (H)	Polarization	Speed of Vehicle (M)	Number of Glare Vehicles (V)	Windshield Conditions (W)	Road Environment (R)	Remarks
A1	5	SPL	**2, 3, and 4 Lane**	∞, 500, 200, 0, -200, 500	Std, 4-lamp, hi-beam	None	55	Single	Clean	Straight, dry	
A2	4	SPL	2 Lane	∞, 0	**LOB, 2HB, 4HH, 4HV**	None	55	Single	Clean	Straight, dry	Data for ∞ runs w/4HV headlights on subject car obtained from Exp A1
A3	4	S	2 Lane	∞, 0, -200, -500	Std 4HH	None	55	Single	**Dirty**	Straight, dry	Data for clean windshield from Exp A1
A4	4	S	2 Lane	∞, 0, -200, -500	Std 4HH	None	**30 55**	Single	Clean	Straight, dry	Data for 55 mph from Exp A1
A5	4	SPL	2 Lane	0	Std Hi Beam	None	55	**Three****	Clean	Straight, dry	Data for single glare car from Exp A1
A6A	4	SPL	2 Lane	∞, 500, 200, 0, -200, -500	4HH	45°	55	Single	Clean	Straight, dry	Data to be compared w/Exp A1 and each of the other polarization modes
A6B	4	SPL	2 Lane	∞, 500, 200, 0, -200, -500	4HH	HV	55	Single	Clean	Straight, dry	Data to be compared w/Exp A1 and each of the other polarization modes
A6C	4	SPL	2 Lane	∞, 500, 200, 0, -200, -500	Hi Int	45°	55	Single	Clean	Straight, dry	Data to be compared w/Exp A1 and each of the other polarization modes
A7	**20**	SPL	2 Lane	∞, 200, 0, -200	**LOB, 4HH, Std 4HH**	**w/45° Pol, HP w/45° Pol**	55	Single	Clean	Straight, dry	Principal Experiment
A8	4	S	2 Lane	∞, 0, -200, -500	Hi Int	45°	55	Single	**Dirty**	Straight, dry	Data to be included from Exp A1 and A3 as required

*Targets: (S) Sign, (P) Pedestrian, (L) "No Passing" Line.
†Control distance between cars when subject car passes the target (∞ indicates absence of glare car).
‡Symbols used to describe headlight configuration on glare car (or subject car on ∞ runs) are: (LOB)--low beam, (2HB)--two 7-in. diameter dual filament lamps, (4HH)--four 5-in. diameter lamps in horizontal orientation, (4HV)--same except in vertical orientation; (45° Pol)--(H/V Pol)--polarized standard headlights with orientation of polarization indicated, (HP)--hi intensity polarized headlights.
**Platoon of three at 50-ft intervals.

[1] Principal variable in bold type.

II. EXPERIMENT FACILITY AND INSTRUMENTATION

A. Test Course

In this series of studies, both the "Subject" car, driven by the observers assigned visual detection tasks, and the opposing "Glare" car are operated in a simulated highway environment of two-, three- or four-lane configuration. The highway has been laid out on a 5000-foot, weathered asphalt runway of an inactive airfield (Fig. 1). The driving lane for the subject car is marked by a 4-inch nonreflectorized white, solid pavement edge line on the right and a 4-inch reflectorized white, normal center dash line on the left (Figs. 1 and 2).

Glare car guide markers corresponding to two-, three- and four-lane highway separation from the subject car lane are provided by one-way, reflective pavement markers at 50-foot intervals, in lines visible only from the glare car, corresponding to the position of the glare car driver, with the car in the center of its lane (Fig. 3). A sighting device on the front of the glare car is positioned to enable the driver to maintain accurate guidance on these lane markers during each test run (Fig. 4). Eleven positions for placement of the vision task targets are located at the center of the course at100-foot intervals. Starting positions for the subject car and glare car are marked on the pavement at 50-foot intervals for 1000 feet at each end of the course for exact control of "Intercar" distance and "Subject Car to Target" distance at the beginning of each test run (Fig. 1). Three targets or visual detection tasks are utilized. These are as follows:

(1) "Sign" target--A quadrant contrast, 96.7% diffuse reflective white on 9.07% diffuse reflective black panel, 2.24-foot square, on a portable stand with the bottom of the panel at a height of 60 inches. When in position, the left edge of the sign is located 6 feet from the edge line of the driving lane (Fig. 5).

(2) "Pedestrian" target--A three-dimensional, 6-foot tall manikin with exposed features painted with 17.5% diffuse, reflective grey paint, wearing a 16.9% reflective grey topcoat. The target is normally positioned with his right arm 2 feet from the edge line of the driving lane (Fig. 6).

(3) "Line" target--A portable, 100-foot long, reflectorized, yellow, 4-inch wide, "no passing" line positioned in the normal location along the right side of the center dash line in the driving lane (Fig. 6).

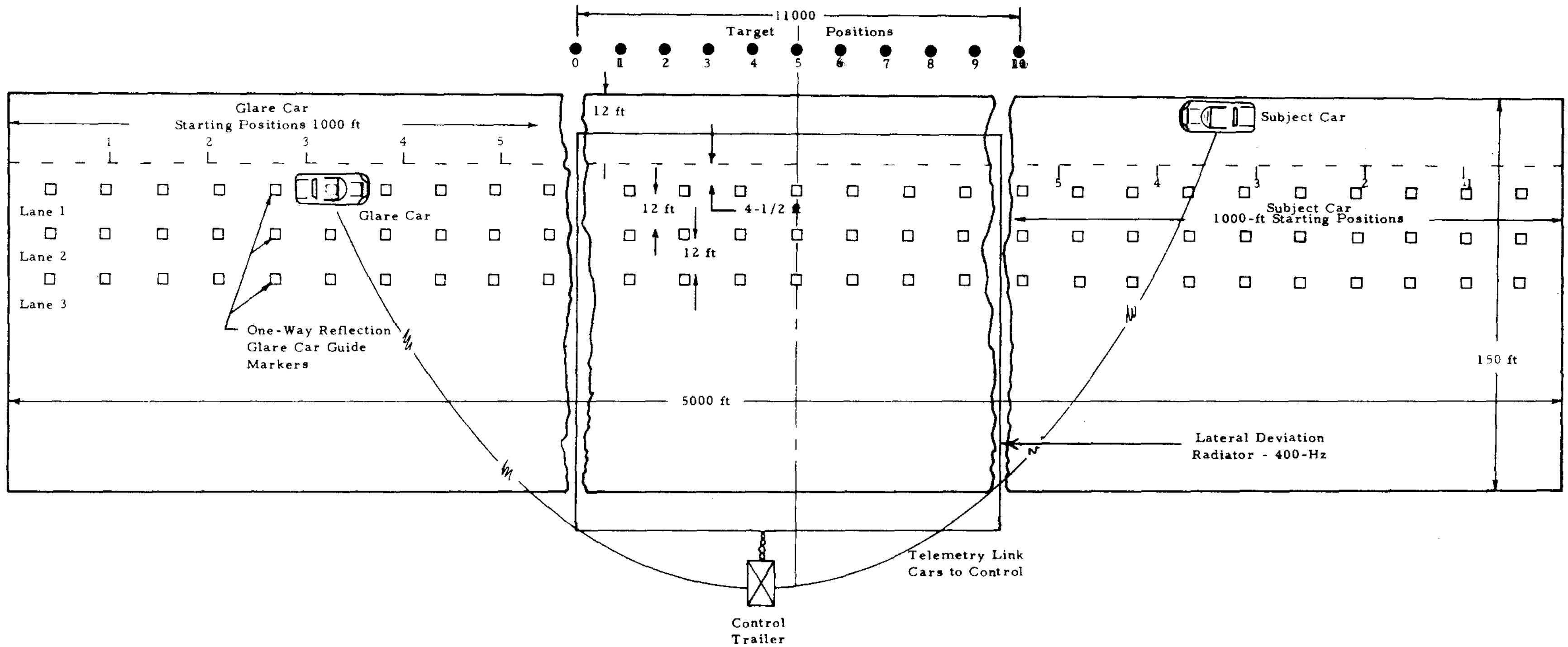


FIGURE 1. LAYOUT OF SIMULATED HIGHWAY FOR HEADLIGHT GLARE STUDIES

FIGURE 2. DAYTIME VIEW OF SUBJECT CAR LANE

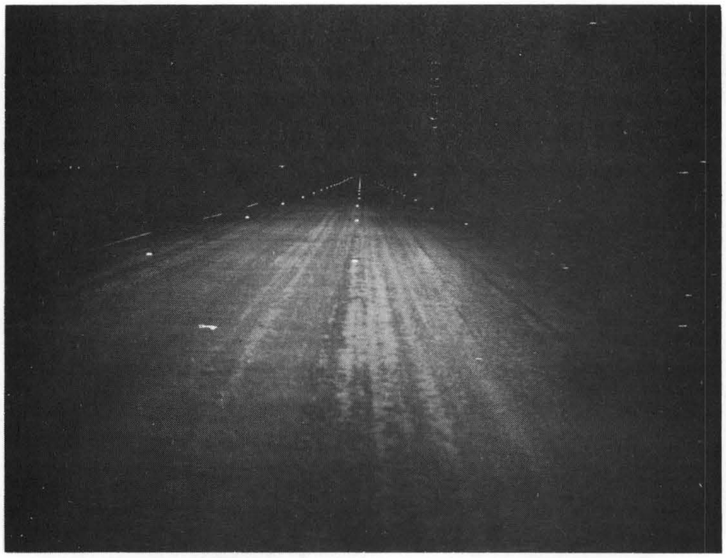


FIGURE 3. NIGHT VIEW OF REFLECTIVE LANE MARKERS VISIBLE ONLY TO GLARE CAR

FIGURE 4. DAYTIME VIEW OF GLARE CAR GUIDANCE SIGHT

FIGURE 5. "SIGN" TARGET ON RIGHT

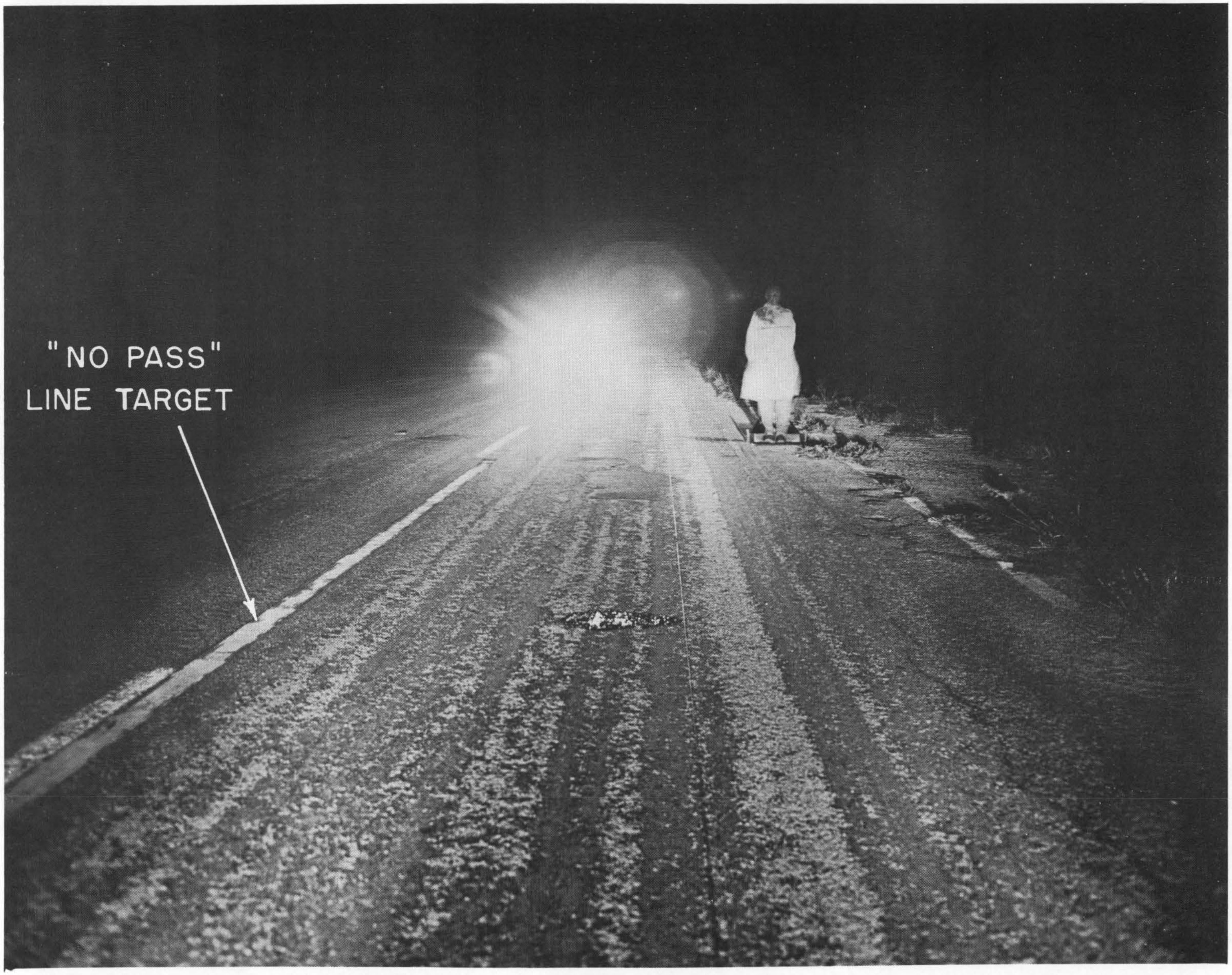


FIGURE 6. "PEDESTRIAN" ON RIGHT AND "LINE" TARGET ON LEFT

B. Instrumentation

Two principal criteria of subject car driver performance are of concern in evaluating the various factors influencing the effects of headlight glare. The first, and perhaps most important, is the distance at which the driver can distinguish typical highway targets or visual tasks in the presence of oncoming traffic. The second is the influence of the meeting environment on the position of his car, laterally, in relation to the target or oncoming vehicle as a potential collision hazard. Where feasible, the measurement and collection of pertinent data have been automated, utilizing on-vehicle sensors with telemetry to a central control/recording station.

1. Distance

The positions of the two vehicles on the test course are determined to ±1.0-foot accuracy at all times during a test run by fifth wheels. With known positions for the target and starting points of the vehicles at each end of the course for each run, it is possible to accurately determine the distance from the subject car to the target and the distance between the two vehicles at all times.

Pulses from the fifth wheels are transmitted by radio to a counter/recorder located in a control trailer to produce a digital printout of subject car to target and intercar distances at 0.2-second intervals (Fig. 7).

2. Steering Deviation

The position of the subject car laterally in its driving lane is determined, by a displacement sensor mounted on the front bumper, from a single wire radiator carrying a 400-cps current which is placed at the lane centerline (Fig. 8). The position of the radiator by its relative unbalancing effect on the coil bridge circuit in the sensor is determined with better than ±1.0-inch accuracy. Lateral deviation of the subject car from the lane centerline is telemetered to the recorder, where it is printed out at 0.2-second intervals to ±1.0 inch, and, simultaneously, a graphic plot of the subject car path is made on an X-Y Plotter.

3. Photometry

The Disability Veiling Brightness or glare intensity from the glare car is measured by a Photo Research Corp., Model 1970, Spectra Pritchard Photometer equipped with a Fry disability glare integrator lens. The photometer is mounted in the subject car, with its lens approximately 15 inches to the right of the driver's eye centerline, so that it is exposed,

FIGURE 7. COUNTER/RECORDER CONSOLE (IN TRAILER)

FIGURE 8. LATERAL DEVIATION SENSOR AND ANTENNA
(ON ROAD SURFACE)

essentially, to the same lighting environment as the driver (Fig. 9). Output from the photometer is transmitted to a counter/recorder for a digital record as percent of full scale photometer readout to ±1% accuracy.

4. Target Detection

During initial base line experiments, it was desired to have the subject car driver signal the detection point of all three targets and also the point at which he could identify the orientation of the "sign" target. A four-way, wobble stick switch provided the directional identification signal, while a pushbutton on the top of the wobble stick provided the detection signal (Fig. 10). The switch was mounted on the front seat to the right of the driver and operated by his right hand. The signal from the detection/identification switch was transmitted to the counter/recorder and appeared as a series of dashes on the output tape record during the time that the target was in view, with a time-coded dash interruption as an identification signal.

With the beginning of the main experiment, A7, utilizing a group of twenty typical drivers, it was decided that identification of the sign target had not provided essentially more consistent distance measurements than had the detection data alone and need not be continued. It may also have contributed to greater steering deviation because the driver was forced to remove his right hand from the steering wheel to operate the detection/identification switch. The identification switch was therefore deleted from the system, and the detection switch was moved to the steering wheel where it could be actuated by the driver's thumb, without removing the hands from the steering wheel.

5. Communication

Mobile radios were installed in the test vehicles and control trailer, utilizing separate communication channels for transmission from control to each of the two cars, with a common channel for transmission from the cars to control. Thus, instructions could be given to the glare car driver for selection and positioning of the target for a specific run without the subject car driver's knowledge.

6. Data Transmitters

Details of the equipment designed and constructed for data transmission to the control trailer, and the data counter/recorders and printer located in the control trailer are discussed in Appendix I.

FIGURE 9. PHOTOMETER MOUNTED IN SUBJECT CAR

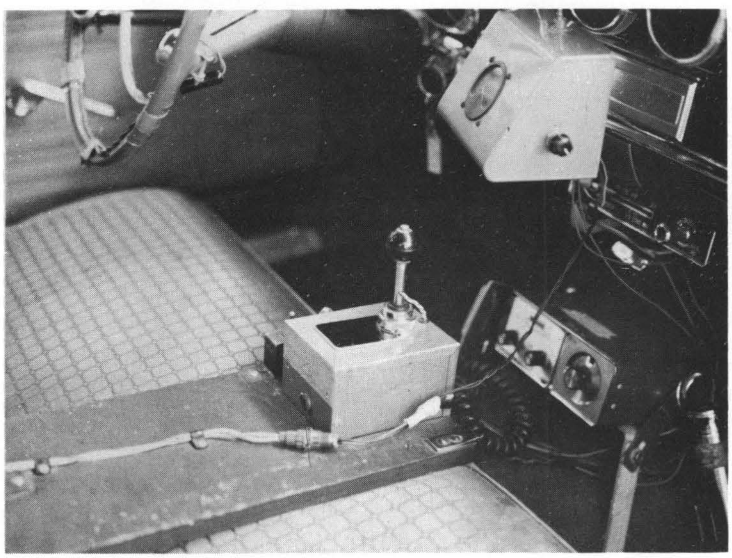


FIGURE 10. DETECTION/IDENTIFICATION CONTROL SWITCH

7. Test Vehicles

The test vehicles used are 1966, four-door sedans, equipped with automatic transmissions, standard (nonpower assisted) steering and brakes and untinted windshields. One has over-and-under oriented, four-lamp, 5-3/4-inch-diameter dual headlights, while those on the other are horizontally oriented.

8. Driver Subjects

For all of the Series A tests, except A7, four selected drivers were utilized. These individuals were screened, to determine that they had 20/20 or better visual acuity, corrected where necessary, with two having good and two having poor glare adaptation response in each experiment. Unfortunately, owing to the extended period over which this work was done and the daytime employment circumstances of these individuals, over which we had no control, it was not possible to use the same subjects throughout the whole series of subexperiments. In fact, only one subject has been common to the whole series, and a total of eight has been used in all. In each case, however, two or three replications have been utilized to enable mean performance of each subject to be more specifically determined and correlation between subexperiments to be maintained.

In Experiment A7, twenty driver subjects were utilized, without replication, the purpose here being to evaluate the average performance of the general public. These drivers were unselected except for the proviso that they be currently licensed and have at least 3 years of driving experience. Their vision characteristics were measured and recorded, but these were not criteria of selection for the experiment.

Visual performance profiles were obtained with a Bausch and Lomb Orthorater for distance vision only. Glare adaptation response was determined by the instrument illustrated in sketch, Figure 11, developed to provide binocular evaluation of glare adaptation response rather than the more familiar monocular methods since it was considered that this configuration more nearly represented the real driving situation, and no standard method has yet been established. In the "Glare Adaptation Tester," a 10° circular bleach light of 650-foot lambert luminance is exposed for 5 seconds after a preliminary preparation of the subject for 15 minutes in a room with blinds closed, and 3 minutes with the eyes in position at the tester with only illumination from the target light. The target is a 2° circular light of 0.004-foot lambert luminance, blinking at 3 cps. Time to detect the target light after the bleach light is turned off is the criterion of glare adaptation performance. The glare exposure time of 5 seconds was chosen as representative of the time of exposure in a vehicle meeting

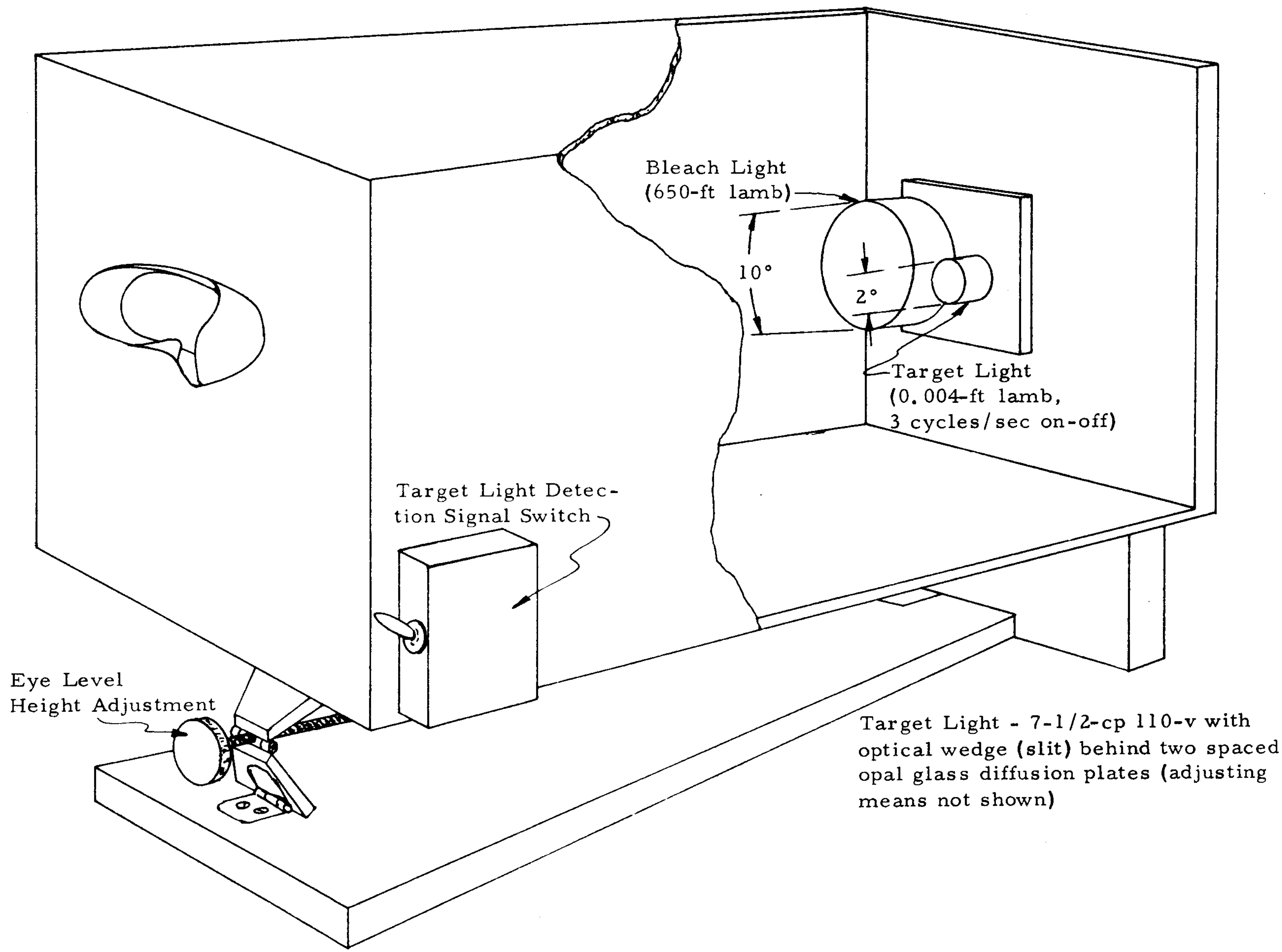


FIGURE 11. GLARE ADAPTATION TESTER

situation on the highway with both vehicles traveling at 55 mph. It will be noted, in Figure 12, that there is a gradual increase in disability veiling brightness to about 800 to 1000 feet intercar distance. At this point, the disability veiling brightness increases rapidly to a peak at about 200 feet in the two-lane case, and then falls to a minimum as the cars pass. The period of rapid buildup and decay is approximately 5 seconds at the 55-mph test speed; hence, this was the time selected for bleach light exposure. Although the approaching headlights would be visible from the beginning of the test run and would undoubtedly have a psychological influence on the observer, the light intensity would not be sufficiently great to have appreciable physiological influence at much over 1000 feet.

The subjects' reaction times for finger response in operation of a pushbutton switch were also measured and used for adjustment of detection distance data to the point of actual detection.

The comparative ratings for the drivers in this series of experiments are shown in Table 2.

9. Headlights

The two vehicles were equipped with 12-volt, four-lamp, 5-3/4-inch-diameter, type 4001 and 4002 sealed unit headlights of 37.5- and 37.5/50-watt ratings, respectively. Additionally, the vehicle with over-and-under headlight orientation was equipped with a two-lamp system of 7-inch-diameter, type 6012, 50/40-watt headlights mounted on a horizontal line midway between and immediately inboard the normal headlights (Fig. 8).

A second set of 4001 type headlamps of 100-watt ratings were used in Experiments A6C and A7 in conjunctionwith polarizing filters.

Headlamps were operated at all times during experiment runs at a standard voltage at the headlamp terminals of 12.8 volts. This voltage was monitored and adjusted by means of a voltmeter and rheostat located on the vehicle dash adjacent to the driver.

Headlamp output and aiming were in accordance with SAE Standard J579 and J599a Recommended Practice. Adjustment and aiming were maintained with Hopkins headlight testing equipment, and headlight intensity was measured with the Hopkins headlight intensity meter and the Pritchard telephotometer.

10. Polarization

For subexperiments A6 and A7 glass laminated, dichroic polarizers (Polaroid Type K) were placed in front of the normal headlamps in specially

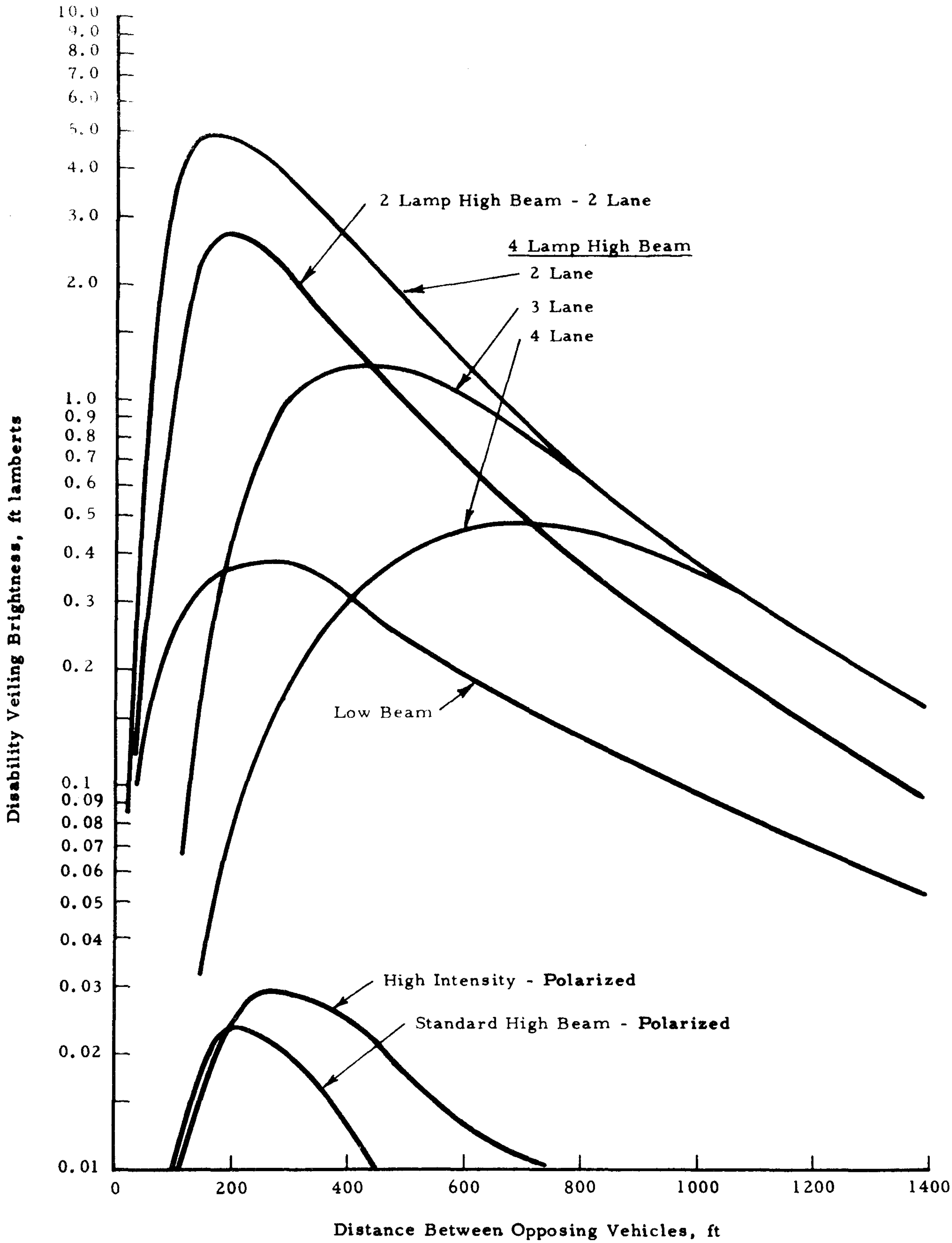


FIGURE 12. HEADLIGHT DISABILITY VEILING BRIGHTNESS ON TWO-, THREE-, AND FOUR-LANE HIGHWAYS

TABLE 2. DRIVER CHARACTERISTICS

Driver	Phoria		Acuity			Depth, %	Color	Glare Response, seconds	Reaction Time, seconds	Age, years
	Vert	Lat	R	L	Both					
				Experiments A1-A8, except A7						
A	0.17 LH	+0.33	20/17	20/17	20/17	106.5	Normal	**2.01**	0.222	37
B	0.17 LH	+2.33	20/17	20/17	20/17	106.5	Normal	2.05	0.215	25
C	0.17 LH	+0.33	20/17*	20/18*	20/17*	84.4	Normal	4.05	**0.375**	**52**
E	0.5 LH	-0.66	20/18	20/22	20/20	84.4	Normal	5.22	0.255	**53**
F	0.17 LH	+1.33	20/25	20/20	20/20	102.4	Normal	2.75	0.203	23
G	0.5 LH	+2.33	20/18	20/18	20/18	88.5	Normal	5.62	0.245	27
H	0.5 LH	+2.33	20/18	20/18	20/17	106.5	Normal	4.16	0.159	30
				Experiment A7						
1	0.17 RH	+0.33	20/17	20/17	20/17	106.5	Normal	2.10	0.182	28
2	0.17 LH	-1.66	20/17	20/20	20/17	106.5	Normal	2.94	0.233	30
3	0.17 RH	+4.33	20/25	20/29	20/25	96.0	Normal	1.73	0.243	32
4	0.17 RH	+0.33	20/20	20/20	20/20	103.6	Normal	6.33	0.154	27
5	0.50 RH	**+6.33**	20/20	20/29	**20/33**	84.4	Normal	7.47	0.336	39
6	0.17 LH	+0.33	20/20	20/18	20/18	103.6	Normal	2.40	0.277	26
7	0.17 LH	+4.33	20/17	20/17	20/20	103.6	Normal	4.46	0.258	35
8	0.17 RH	+1.33	20/17	20/20	20/17	103.6	Normal	2.90	0.256	31
9	0.17 RH	-1.66	20/20	20/17	20/17	106.5	Normal	2.70	0.274	32
10**(F)**†	0.17 RH	-1.66	20/22	20/29	20/20	106.5	Normal	5.66	0.175	35
11	0.50 LH	+0.33	20/18	20/22	20/17	88.5	Normal	3.17	0.258	21
12	0.50 LH	+1.33	20/25	20/20	20/20	103.6	Normal	2.44	0.189	21
13	0.17 LH	+1.33	20/22	20/22	20/22	88.5	Normal	3.65	0.160	38
14**(F)**†	0.50 LH	-0.66	20/22	20/20	20/18	106.5	Normal	4.15	0.170	20
15	0.17 LH	**-3.66**	20/22	20/20	20/17	103.6	Normal	2.92	0.282	**17**
16	0.17 LH	+0.33	20/18	20/17	20/17	106.5	Normal	4.16	0.319	18
17**(F)**†	0.17 LH	-2.66	20/22	20/20	20/20	106.5	Normal	4.06	0.206	34
18	0.17 LH	-0.66	20/22*	20/22*	20/20*	96.0	Normal	5.96	0.192	33
19	0.50 LH	+2.33	20/18	20/17	20/18	106.5	Normal	4.17	**0.144**	31
20	0.17 RH	-1.66	20/20	20/22	20/20	103.6	Normal	**8.00**	0.301	**54**

*Corrected
†(F) - Female

fabricated headlight frames. Viewing analyzers were provided in the form of visors which could be attached to the normal sun visor and pulled down manually into position before the driver's eyes.

Two orientations of the polarization system were studied. Subexperiment A6A employed a nominal 45° orientation of the headlight polarizers with a parallel orientation of the analyzer on the same vehicle. This provided maximum transmission of polarized reflected light from the car's own headlights back through its analyzer, but maximum extinction of opposing vehicle polarized, direct, headlight beams. It was found by experimentation that an angle of approximately 35° from the vertical (rather than 45°) was necessary to compensate for the effect of curve and slope of the windshields.

In subexperiment A6B, the headlight polarizers were rotated to horizontal and the analyzers to vertical orientation. It has been postulated that such orientation would not only provide for elimination of daytime glare on the highway but would also return a greater portion of the light to the viewer because a greater proportion of the polarized light striking a target would be reflected in a depolarized, diffuse manner. Although this thesis is not agreed with, it could not be specifically refuted on the basis of theoretical factors alone, hence, its inclusion in the experiment.

In subexperiment A6C, high intensity (100-watt) headlamps with 45° polarization were placed in the No. 1 positions in place of the standard lamps. In setting up for the specific test operations utilizing polarized headlights, the visors were adjusted in each case to obtain maximum extinction of the opposing car headlights at 600 feet on the two-lane road.

Experiment A7 utilized the same polarization configurations as A6A and A6C.

III. PROCEDURES

A. Test Procedure

The fifth wheels were calibrated by running a 2300-foot, subject car to target distance and a 4600-foot, intercar distance check from specified starting positions at each end of the course to a common target meeting point. Calibration within ±5 feet of actual distances travelled was considered acceptable, and fifth wheel tire pressures were adjusted to meet this tolerance. Calibration was rechecked at the end of each night's test period.

The lateral deviation sensor was referenced to the roadway transmission line and periodically checked for balance and linearity of response.

The photometer was mounted in the subject car and aimed at a point midway between the headlights of the glare car in its normal position in the center of its lane of the two-lane road configuration at a distance of 600 feet from the subject car, also in the center of its lane. After adjusting the line of sight of the photometer, with the driver in place in the subject car, the integrating glare lens was placed on the photometer. Although the aiming of the photometer is a compromise, it is considered logical to aim it at the glare car headlights at some median intercar distance because the subject drivers did not know at the beginning of a run which target, if any, would be in place. Thus, they were forced to look directly at the oncoming glare car headlights to try to see the "line" target as well as toward the right-hand edge of the road where the "Sign" and "Pedestrian" targets might be located. They could not avoid exposure to the full glare intensity of the oncoming headlights or the resultant glare disability effects induced by such a level of lighting.

In each experimental series, the sequence of drivers and test factors was randomized where feasible. Target positions in the center of the course and starting points for the two cars at the ends of the runway were selected to avoid clueing the subject car drivers to the distance to the target on any given run.

The engines were run at a fast idle to insure that the battery voltage was maintained and the voltage to the headlights adjusted to the standard 12.8 volts. This was done before each run and checked at the end of each run while returning to the starting position. Headlights were either turned off completely or turned to "park" during any waiting periods between runs in order to keep the batteries at or near peak levels.

B. Experiment Design

The rather large number of factors having influence on the ability of the driver to perform visual tasks in the presence of headlight glare predisposed division of the task into a series of subexperiments. Eight groupings were developed, therefore, to cover the ten factors to be considered as follows:

(1) Drivers	-	As previously described.
(2) Lighting	-	Low beam, high beam with two 7-inch diameter headlamps; high beam with four 5-3/4-inch diameter headlamps in horizontal, and over-and-under orientations.
(3) Intercept distance	-	Distance between cars when subject car passes target - used as control for distance relationships between cars and targets. These were -500, -200, 0, 200, and 500 feet and ∞ (no glare car).
(4) Separation	-	Simulating two-, three- and four-lane highways. With both cars in the center of appropriate lanes, distances of 10-1/4, 22-1/4 and 34-1/4 feet between subject car driver and centerline of glare car would exist.
(5) Targets	-	Sign, pedestrian, line.
(6) Speed	-	30 and 55 mph.
(7) Polarization	-	Dichroic polarizers and analyzers oriented at ±45°; horizontal polarizers with vertical analyzers; and 100-watt, 5-3/4-inch diameter type 4001 headlamps with ±45° polarization. Type 4002 headlamps when present were also polarized.
(8) Road	-	Dry, straight.
(9) Glare vehicle configuration	-	Single glare vehicle and platoon of three vehicles at 50-foot intervals.
(10) Windshield	-	Dry, clean and dirty.

The individual subexperiments involving these factors are shown on Table 2.

IV. RESULTS--PRELIMINARY EXPERIMENTS

With this background of facilities and procedures, the results obtained may be discussed. From the outset, it must be recognized that the principal parameter by which individual performance is to be judged, the distance at which the subject driver detects the roadside target, is not capable of being precisely controlled by him. Many factors having influence on the results are changing rapidly during the test run. The glaring headlights of the oncoming car, in most experiments, are approaching at 160 fps, and the subject car to target distance is changing at 80 fps. **With a reaction time of 0.3 second, momentary indecision on the part of the subject driver as to when the target becomes visible can easily mean a difference of 25 to 50 feet in the recorded detection distance.**

The subject car was not restrained in its course--the driver was told only to drive as he normally would on the highway. The "Lateral Displacement" traces indicated that the subject car frequently was aimed toward or away from the approaching glare car at angles which were small but sufficient to affect the headlight glare received by the subject driver. This is confirmed by the maximum photometer readings obtained during specific runs. These varied by as much as 10 to 20% from those obtained during photometer calibrations when the glare car was moved at slow speed on its controlled path past the stationary subject car. Relationships involving detection distance and glare intensity, as well as other similar characteristics, must be considered statistically, therefore, in analyses of mean effects.

A. Disability Veiling Brightness

As a basis for relating the effects of glare to the other factors involved, it is of interest to note the variation in disability veiling brightness (DVB) observed with the glare car in the two-, three- and four-lane road positions as it approached the subject car with the various headlight systems.

The DVB values reported herein must be considered as relative between the various experiment factors under consideration, rather than absolute values. It will be noted that the photometer position was fixed with respect to the subject car axes, rather than being aligned with the target being used in a given test run, which would be necessary if absolute values of DVB were to be obtained. Likewise the direction of glare sources is continually changing during the run, which virtually precludes determination of absolute values of DVB. It is considered, however, that relative values of DVB, as measured herein, are completely adequate for the comparative analyses desired.

These DVB values are shown in Figures 12 and 13. The peak values are reached at varying distances between the cars, depending on the lateral separation, from about 200 feet for the two-lane highway to 700 feet when both cars are in the outer lanes of a four-lane highway. It is also seen that, except perhaps for the psychological, discomfort glare aspect, high beam DVB on the four-lane highway is no worse than low beam on the two-lane road and becomes appreciably less intense at intercar distances inside 400 feet. It will be observed in later data that seeing distances with both vehicles on high beam are geater than when both are on low beam. It may be concluded from this that, in general, if the drivers do not look directly at oncoming headlights, they will see better (further down the road) if both use their high beams than if they switch to low beams.

The change in DVB accompanying a change in target viewing direction may be seen by comparing Figures 12 and 13. In the latter, the photometer was aimed at the sign target at a 300-foot observation distance rather than at the glare car at 600 feet (viewing direction for line target, see p. 22). The maximum DVB for the two-lane road situation is reduced from 4.8 to 1.25-foot lamberts.

The maximum low beam DVB is approximately 8% of that produced by high beams in the two-lane road meeting due, of course, to the normal offset of beam direction as well as to the decrease in beam intensity.

The effectiveness of polarization is clearly evident by the reduction of DVB to -0.02-foot lambert maximum for polarized standard high beam headlamps on the two-lane highway, about 0.2% of that produced by unpolarized headlamps. Even when the headlamp power is increased to 100 watts, polarization still holds the DVB to 0.03-foot lambert as may be seen in Figure 12.

B. Detection of Targets and Lateral Deviation

The analytical format is that of the Biomedical Computer Programs (20 May 1964) of the Health Sciences Computing Facility, UCLA.

Two areas of interest in these data are analyzed: (1) The distance at which the varied targets could be detected under different vehicle/road/driver conditions; and (2) the deviation in steering of the subject car caused by the driver's conscious or unconscious avoidance of the targets or approaching glare car.

Analyses of variances have been performed on the data in several different ways to try to obtain a better understanding of the influences of the individual and interrelated factors, if any. A summary of these analyses of variance is shown in Table 3, 4, and 5. Interactions of interest in understanding the influence of the specific factors are shown graphically.

As expected, there was a wide variation in performance among the individual drivers, but there are significant consistent patterns with all drivers for the different targets and lane separations or lateral displacements of the glare car from the subject car.

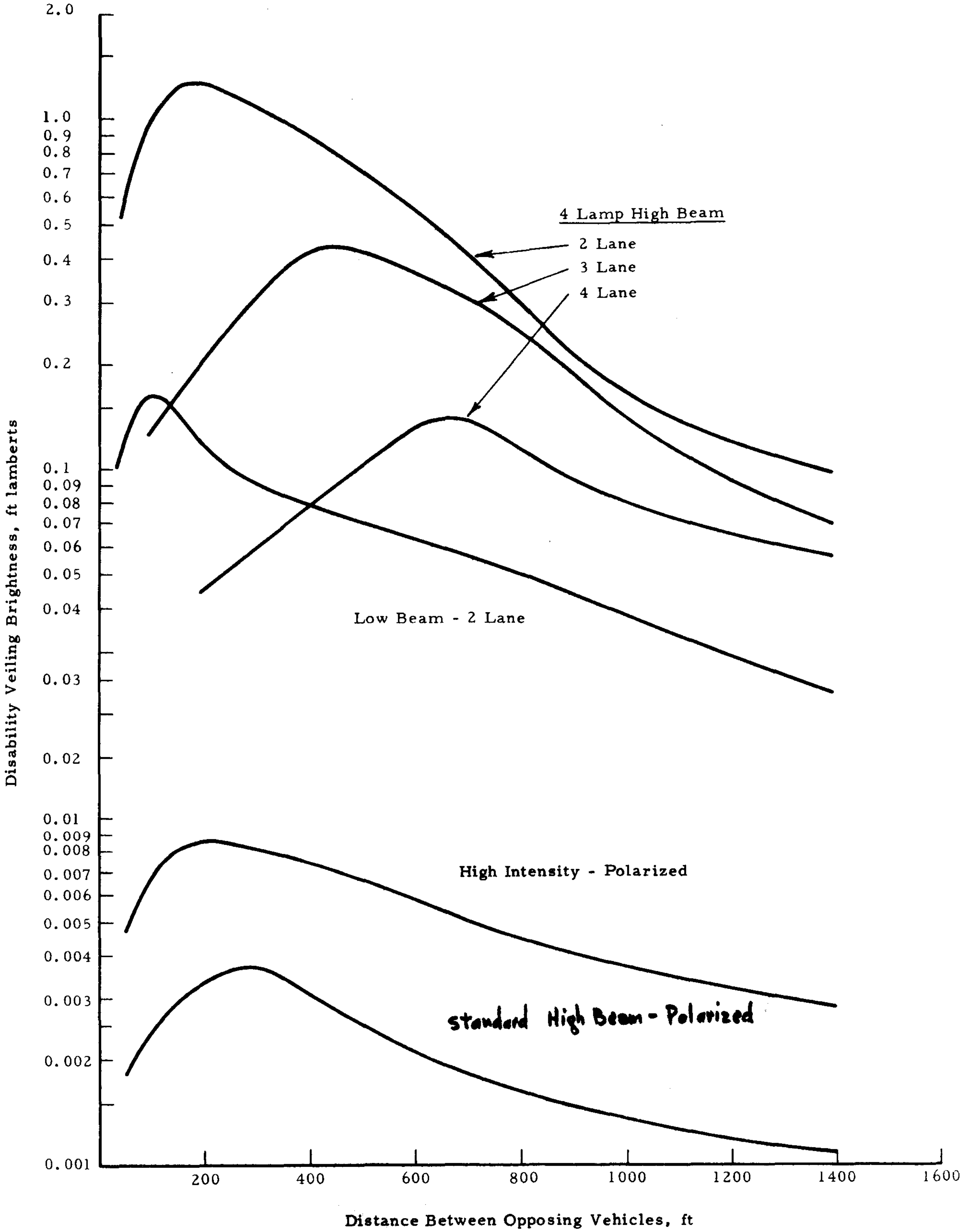


FIGURE 13. HEADLIGHT GLARE INTENSITY ON TWO-, THREE-, AND FOUR-LANE HIGHWAYS

TABLE 3. SUMMARY OF ANALYSES OF VARIANCE ON DETECTION DISTANCE

F RATIOS AND SIGNIFICANCE LEVELS ( )

EXPERIMENT	Drivers(D)	Targets(T)	Lanes(S)	Intercept(I)	DxT	DxS	DxI	TxS	TxI	SxI	DxTxS	DxTxI	DxSxI	TxSxI
A1-Overall														
F-Ratio	213	1495	77	99	22.4		4.57	7.53	20.3	6.47	1.80	2.06		
Significance Level	1%	1%	1%	1%	1%	NS	1%	1%	1%	1%	5%	1%	NS	NS
	(Drivers - ABCEF, Targets - SPL, Lanes - 2, 3, 4, Intercepts - ∞, 500, 200, 0, -200, -500)													
A1-(less ∞)														
F-Ratio	129	938	84		12.7		2.04	8.21	2.99	3.81	2.01			
Significance Level	1%	1%	1%	NS	1%	NS	5%	1%	1%	1%	5%	NS	NS	NS
	(Drivers - ABCEF, Targets - SPL, Lanes - 2, 3, 4, Intercepts - 500, 200, 0, -200, -500)													
A1-Ident Distance														
F-Ratio	77		9.14											
Significance Level	1%		1%	NS		NS	NS			NS			NS	
	(Drivers - ABCEF, Targets - sign only, Lanes - 2, 3, 4, Intercepts - 500, 200, 0, -200, -500)													
EXPERIMENT	Drivers(D)	Targets(T)	Headlights (H)	Intercept(I)	DxT	DxH	DxI	TxH	TxI	HxI	DxTxH	DxTxI	DxHxI	TxHxI
A2-Headlights														
F-Ratio	18.7	150	2.67	198				3.43	12.9	5.68			2.62	
Significance Level	1%	1%	5%	1%	NS	NS	NS	1%	1%	1%	NS	NS	1%	NS
	(Drivers - AEGH, Targets - SPL, Intercepts -0,[illegible] Headlights - LoBeam, 2 Hi-Beam, 4 Hi Hor, 4 Hi Vert)													
EXPERIMENT	Drivers(D)	Targets(T)	Speeds(M)	Intercept(I)	DxM	DxI	MxI	TxH	TxI	HxI	DxMxI	DxTxI	DxLxI	TxLxI
A4-Speed														
F-Ratio	44.8		6.08	125	2.94	2.41								
Significance Level	1%		5%	1%	5%	5%	NS				NS			
	(Drivers - ACEG, Speeds - 30, 55 mph, Intercepts - ∞, 0, -200, -500, Targets - sign only)													
EXPERIMENT	Drivers(D)	Targets(T)	Vehicles(V)	Intercept(I)	DxT	DxV	TxV				DxTxV			
A5-Multi Vehs														
F-Ratio	8.53	170	21.5											
Significance Level	1%	1%	1%		NS	NS	NS				NS			
	(Drivers - AEGH, Targets - SPL, Vehicles - Single, 3-car platoon)													
EXPERIMENT	Drivers(D)	Targets(T)	Polarization(L)	Intercepts(I)	DxT	DxL	DxI	TxL	TxI	LxI	DxTxL	DxTxI	DxLxI	TxLxI
A6-Overall														
F-Ratio	110	60	42	3.64		11.15		2.96						
Significance Level	1%	1%	1%	5%	NS	1%	NS	5%	NS	NS	NS	NS	NS	NS
	(Drivers - AE, Targets - SPL, Intercepts - ∞, 200, 0, -200, Polarization - Std ± 45°, H/V HiInt ± 45°													
A6 - Std. Only														
F-Ratio	78	337	19.9		7.69	13.0		20.6						
Significance Level	1%	1%	1%	NS	1%	1%	NS	1%	NS	NS	NS	NS	NS	NS
	(Drivers - ACEG, Targets - SPL, Intercepts - ∞, 500, 200, 0, -200, -500, Polarization - Std. ± 45°, H/V)													
EXPERIMENT	Drivers(D)	Targets(T)	Lighting (L)	Intercepts(I)	DxT	DxL	DxI	TxL	TxI	LxI	DxTxL	DxTxI	DxLxI	TxLxI
A1/A6 A&B														
F-Ratio	105	379		17.7	5.85	8.23		10.9		9.33	2.70			
Significance Level	1%	1%	NS	1%	1%	1%	NS	1%	NS	1%	1%	NS	NS	NS
	(Drivers - ACE, Targets - SPL, Lighting - Std, Pol. ± 45°, H/V, Intercepts - , 500, 200, 0, -200, -500)													
EXPERIMENT	Drivers(D)	Intercept(I)	Windshield (W)	Lighting(L)	DxI	DxW	DxL	IxW	IxL	WxL	DxIxW	DxIxL	DxWxL	IxWxL
A3-A8 Windshield														
F-Ratio	14.8	64.6		55.3					26.1					
Significance Level	1%	1%		1%	NS		NS		1%			NS		
	(Drivers - AEHQ, Intercepts - ∞, 0, -200, -500, Lighting - 4HH, HI Pol., Targets - sign only)													
A1/A6C-A3/A8	(All drivers averaged)													
F-Ratio		18.83	1.51	4.07					3.69					
Significance Level		5%	NS	NS				NS	NS	NS	NS			NS

The variation in detection distance of the three targets is shown in Figures 14a, b, and c, in Target × Intercept Distance, Target × Lane Separation Distance and Target × Driver interaction plots. For comparison, the ∞ condition (no glare car) is included as the maximum limit of separation in the first two of these interactions. Except for the ∞ condition, Intercept Distance (distance between subject and glare cars when the subject car passes the target) was not significant. Whether it is the mere presence of a glare car which was sufficiently distracting to cause a reduction in detection distance of the Sign and Pedestrian targets could not be established, but this reduction is clearly evident. It does not appear in relation to the line target, probably because detection of this type of target--horizontal, small angular field--is much more difficult under any condition, and, therefore, occurs at a much closer distance, where these differences would be obscured by inherent observer variability.

Much greater variability of detection was observed in the runs involving the line target for all drivers. Because of the horizontal orientation of this target, it was occasionally observed, particularly in the two-lane road encounter, not by illumination from the subject car headlights but by an entirely different mode of lighting, reflection from the glare car headlights, owing to its location on the road between the subject observer and the glare car. In these cases, detection distance might jump to 400 feet or more from the normal, under 200-foot range. This was observed most frequently on runs with negative intercepts, i.e., when the glare car was closer to and passed the target before the subject car. However, deleting the -200 and -500-foot portion of the line target curve in Figure 14a does not change the statistical results, because these long detection distance observations were compensated by short distance observations (under 100 feet) which also occurred in the two-lane road case. In the three- and four-lane cases, the geometry of the meeting engagement generally precluded this effect because the point at which illumination of the line target by the glare car's headlights occurs places the target at too great a distance for it to be seen by this mode of lighting, and it is observed by subject car illumination alone.

Particularly in the two-lane road encounter, the maximum veiling glare occurs at about the same distance that the line target is detected when glare is not present or at a low level. This has the effect at times of delaying the detection of this target, for those drivers most sensitive to such glare, until they are within 50 to 75 feet of it. The analysis of variance averaged these two effects, but they must be considered separately for this type of target.

In the case of variations in lane separation, detection distances increased with all of the targets as the glare car moved over to three- and then four-lane configurations (Fig. 14b).

Figure 14c shows the influence of overall visibility of the target as affected by size and reflectivity. The reduction in variability of detection

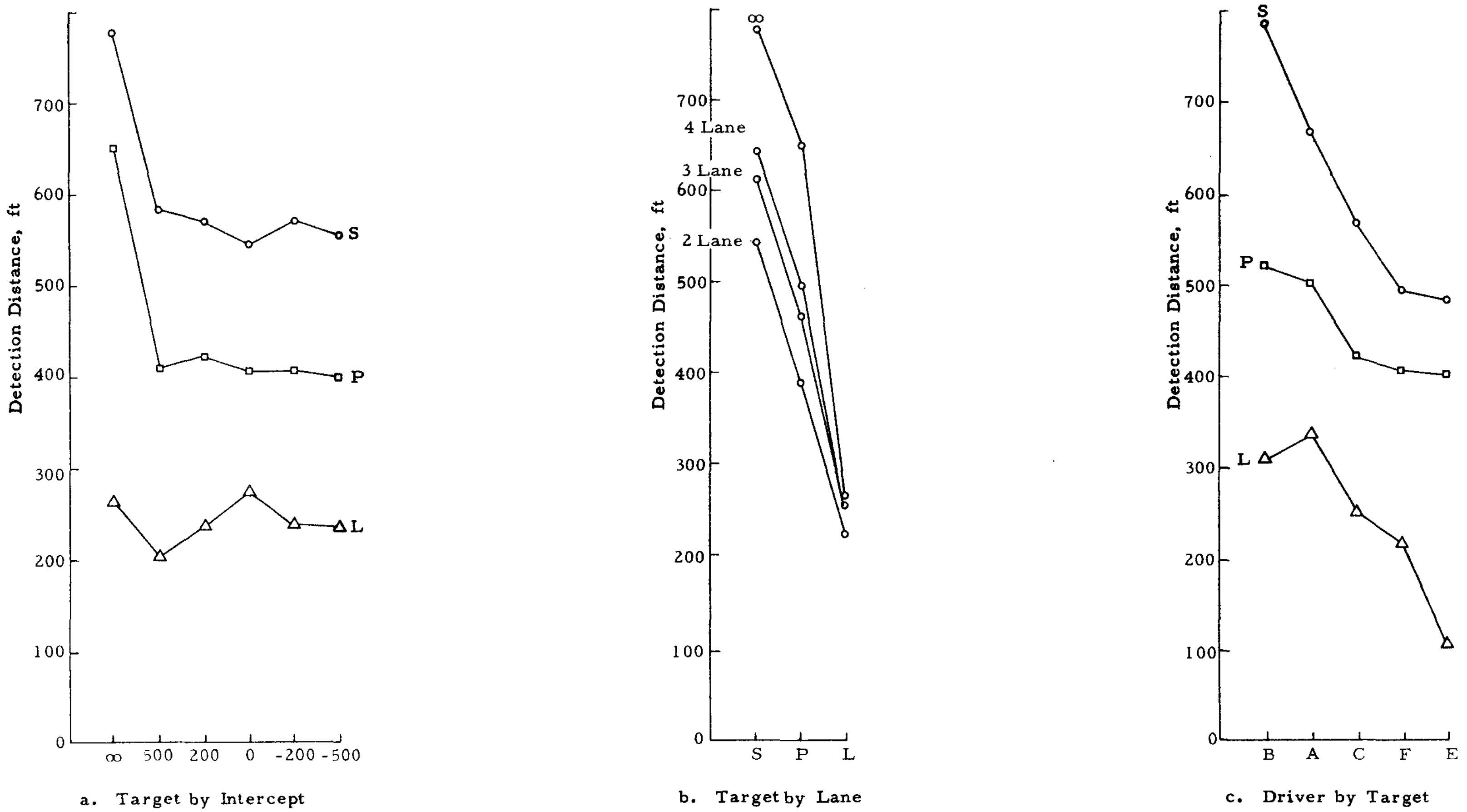


FIGURE 14. EXPERIMENT A1, INTERACTION EFFECTS ON DETECTION DISTANCE

distance between drivers, noted for the pedestrian target, can be attributed, it is believed, to the larger size of this target even though its reflectivity is considerably below that of the sign or the line targets. The greater variability in the case of the line target may be in part attributed to the small visual angle it intercepts but is also undoubtedly a result of the position it occupies in the visual field which, as previously stated, under some intercept distance cases, places it almost directly in line with the oncoming glare car headlights during the meeting engagement. With greater or lesser glare sensitivity of the subject drivers, the maximum scatter of detection distances should, and does, occur in this case.

Lateral separation variation, from the two- to the four-lane highway, was expected to show significant effect on detection distances,and did for all drivers, Figures 14b and 15a. In the case of the interaction of lateral separation and intercept distance, the analysis of variance shows a significant effect (Fig. 15c). This disappears, however, if the negative intercept distances are removed from consideration, and is considered to be largely the result of the peculiar effect of this lighting situation on the line targets in the two-lane road situation, as previously explained.

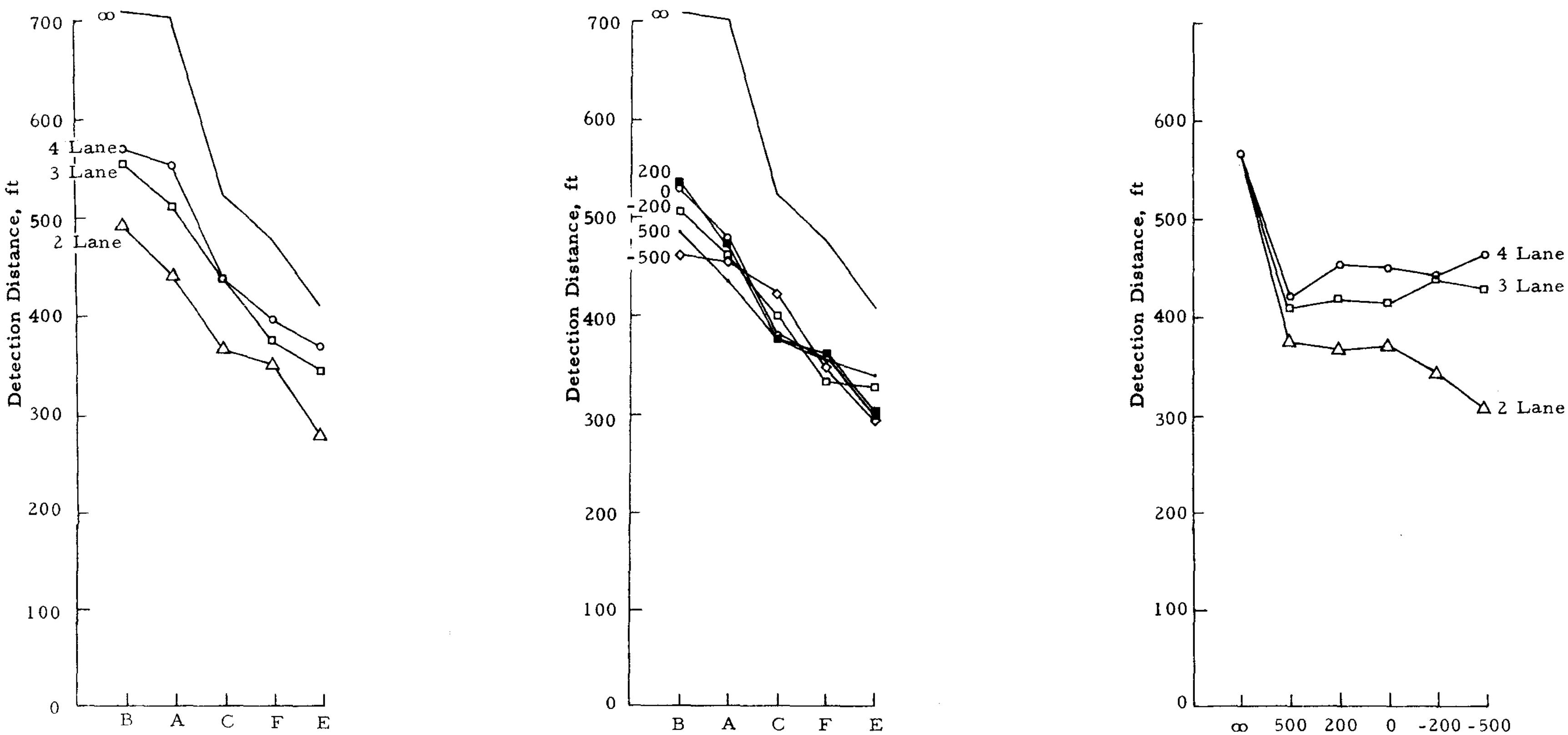
It should be noted here also that detection distances with no glare car (∞ runs) are shown in the graphs for reference. Analyses of variance including the ∞ cases were made which show some significant interactions, but these must be considered as artifacts or noncorrelative situations because of the complete absence of the glare car in these cases.

1. Glare at Detection

The observations of principal interest, it is believed, are those relating the intercept distances with the three targets and the three-lane configurations (Figs. 14a and 15c). These follow essentially from the geometrical relationships of the vehicles on the highway at the time the targets are detected. As previously indicated in the case of the line target, the normal detection distance is so short that for negative intercept distances the peak glare condition will be reached before the target is close enough to be detected. On the other hand, in the case of the highly reflective sign, the detection distance will be reached at about the point of peak glare in the maximum negative intercept condition. This is shown clearly in Figures 12 and 14.

Because of the lateral displacement, the resulting glare at detection begins to decrease for negative intercept distances in the three- and four-lane road configurations. This relationship results directly from the headlight glare intensity patterns shown in Figure 12, with their shift of maximum glare intensity with separation distance.

As previously explained, headlight intensity was as accurately maintained as reasonably possible; however, glare intensity was variable



a. Driver by Lane   b. Driver by Intercept   c. Lane by Intercept

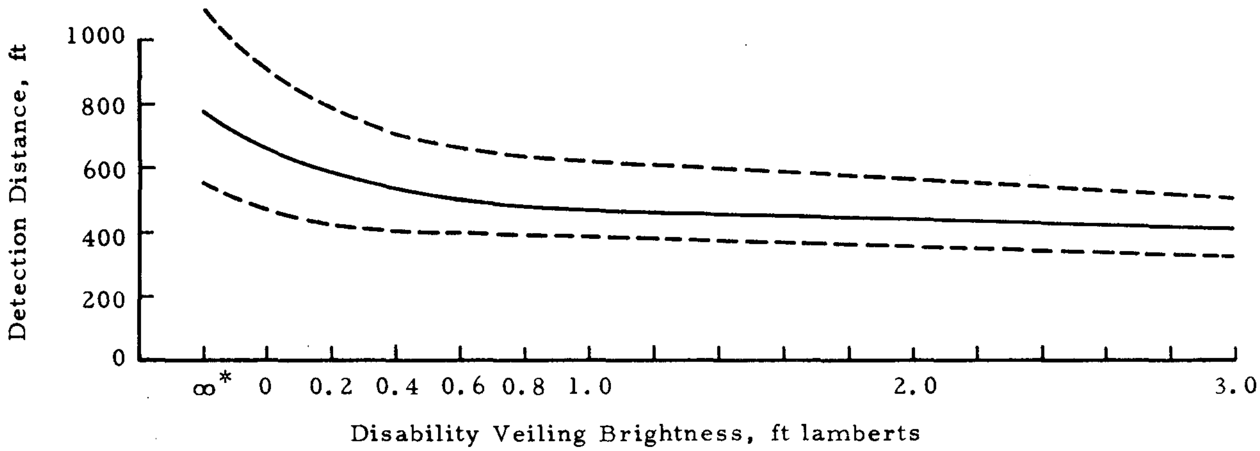
FIGURE 15. EXPERIMENT A1, INTERACTION EFFECTS ON DETECTION DISTANCE

during these tests. Although headlights were accurately aligned and selected for compliance with specifications for beam pattern and intensity, the fact that the subject car driver did not follow a controlled path and was allowed to move laterally at will within the driving lane undoubtedly caused the effective glare intensity received by him to vary from that obtained in the controlled, parallel path, fixed lateral separation situation on which the glare intensity curves, Figures 12 and 13, were so used. More importantly, although every effort was made by means of the guide markers and aiming device to maintain the glare car on as straight a course as possible, some steering errors developed. These were more conducive to variations in the glare intensity received by the subject car driver than were steering errors of the subject car itself, particularly at the longer separation distances. Although variations in glare intensity did occur, the main effects, it is felt, have been clearly and definitively established.

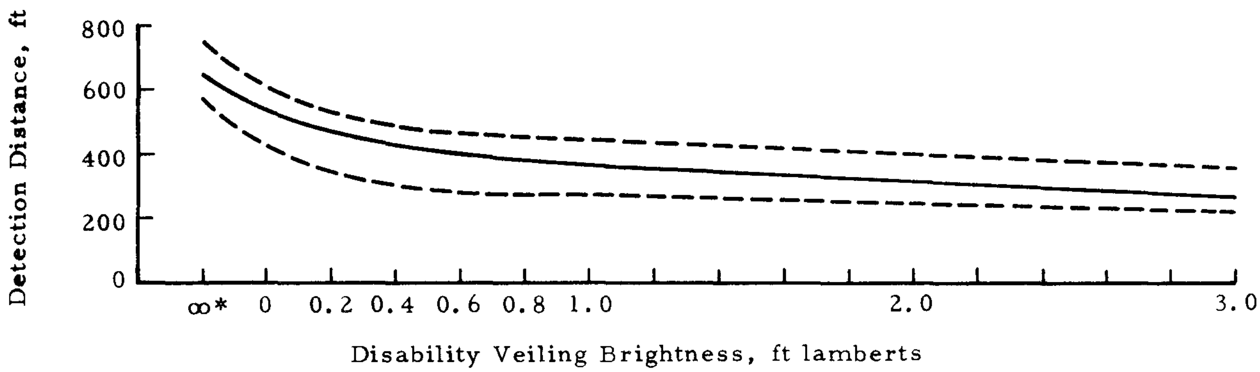
The glare intensities at detection are related to the detection distances in Figures 16 and 17 for the three targets and experiment conditions. Figure 16 covers all of the unpolarized lighting conditions, while Figure 17 shows the three polarized light configurations. It will be noted that **there is an average reduction in detection distance of about 250 feet for the two, right side of the road, vertical targets, and about a 100-foot reduction for the line target from no-glare to maximum glare conditions, with a fairly consistent decrease of detection distance with increasing glare intensity.** There is also a markedly greater effect on detection distance change with the more readily detected vertical targets than with the line target.

In the case of the polarized lighting systems of Experiment A6, it must be recognized that, in all cases, glare levels, overall, are far below those encountered with the unpolarized headlights. It should therefore be expected that the detection distance/glare intensity curves for Experiment A6 would be essentially flat and comparable to the no-glare values of the unpolarized headlight systems, except for the decreased light intensity available for illuminating the targets. The first effect to be noted is that, although there is a lower detection distance with unopposed, polarized standard lighting than with unopposed, normal lighting, when opposed lighting is considered, detection distance for the polarized system is lower only for the sign target. Detection distances are almost the same for the pedestrian and line targets, even though the polarized lighting with standard headlights provides only about 40% as much illumination on the target. When 100-watt headlamps are used in the polarized system (Experiment A6C), detection distances are equal to or better than those obtained with the standard, unpolarized headlamps for all conditions.

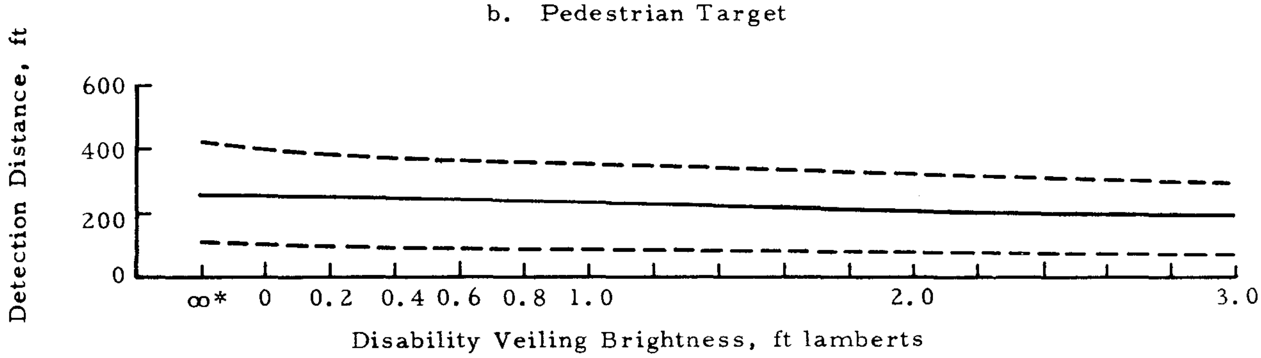
Although it is perhaps a moot point, the practical elimination of headlight glare as a driving hazard and discomfort source will extend by years the period of time that older drivers can continue their nighttime driving with safety and comfort.



a. Sign Target



b. Pedestrian Target



c. Line Target

——— Average, All Drivers
– – – Limits of Detection, All Drivers
* No Opposing Glare Car Present

FIGURE 16. EFFECT OF VEILING GLARE ON DETECTION DISTANCE
(Normal Lighting - Data from Experiments A1, 2, 4 & 5)

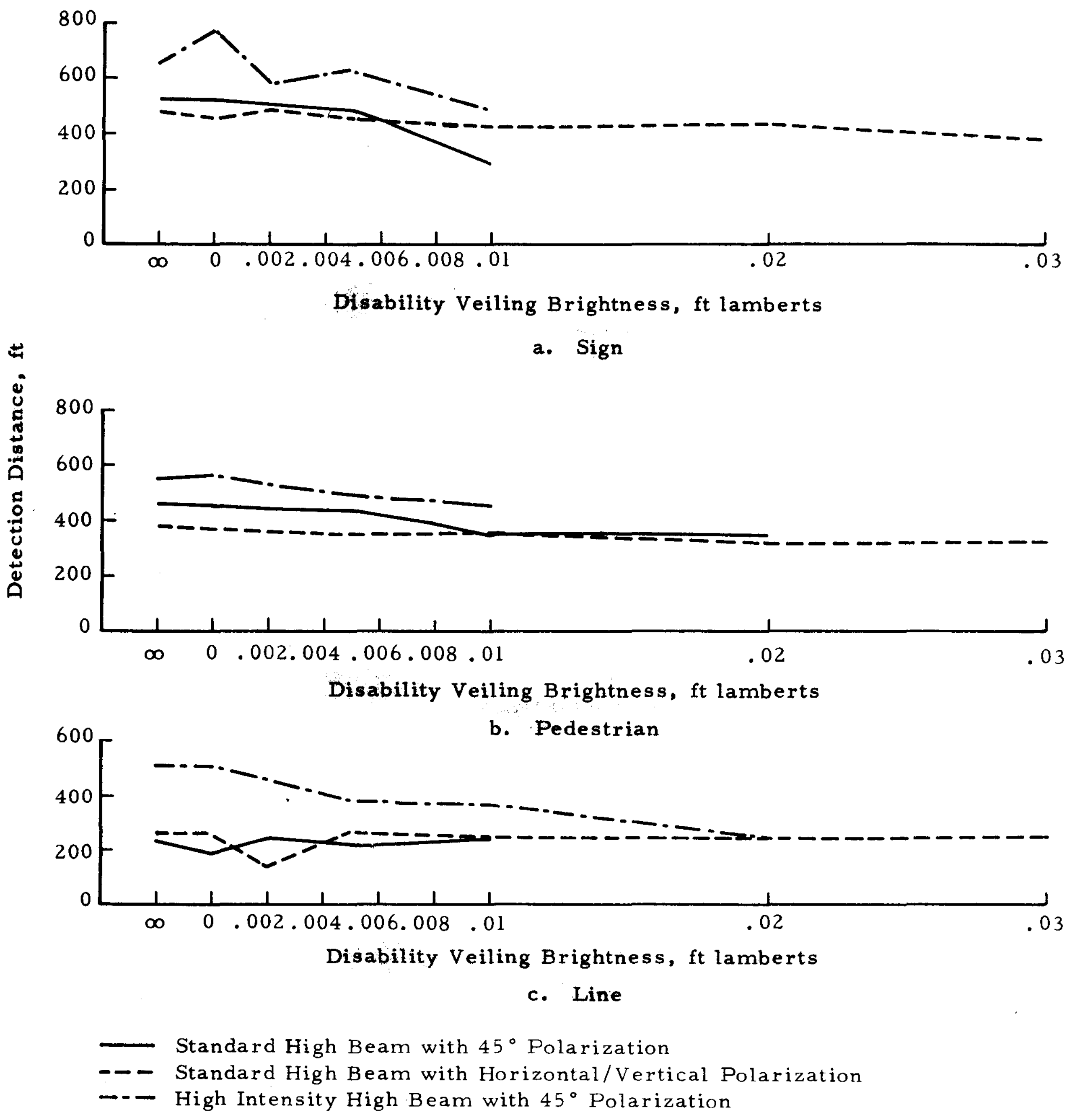


FIGURE 17. EFFECT OF VEILING GLARE ON DETECTION DISTANCE (POLARIZED LIGHTING)

2. Lateral Deviation

Work of previous investigators[1,2] (Michaels and Cozan, and Case, et al., included) has shown that visual targets being approached by a driver will influence the path he selects in the roadway. In these previous studies, the factors studied, in general, related to size, shape, orientation and distance from the road edge of roadside structures, and the differences in deviation associated with these elements as variables.

In this study, steering deviation is also of interest, but the relative influences of the factors of interest are considered to be much more subtle and difficult to differentiate. Questions immediately arose as to the relative influence of the roadside sign or pedestrian as a forcing factor to cause deviation to the left as opposed to the line target on the right, or whether the target influences were completely suppressed by the presence of the oncoming glare car. Early tests indicated that the targets had very little effect on the subject vehicle path, as compared to the glare car. This vehicle presented a real and perhaps the only conscious hazard to the subject car driver. The principal question to be answered then was whether the data provided a sufficient base for differentiation between the various experiment variables.

By the time the subject car reached the beginning of the deviation radiator loop, it had generally reached steady-state conditions of speed and normal steering track. It is apparent from the individual run steering traces that steering is a random but cyclic phenomenon with a characteristic period which varies among the drivers. Harmonic analyses of the vehicle paths, through the section of the course of 1250 feet before to 500 feet after the target for all runs in Experiment A1, showed the dominant frequency to vary among the several drivers from the first to the fifth harmonic over periods ranging from 22 to 4.4 seconds.

All runs for a given set of conditions were averaged to remove the effect of cyclic steering deviation and plotted in Figures 18 to 21. While there is considerable spread of mean deviation from the lane centerline among the drivers, owing to their normal preference for guidance in the roadway, a consistent effect attributable to the approaching glare car is evident with every driver in more or less degree. Averaging all of the runs for all of the drivers for each lane configuration discloses a greater effect for the two-lane meeting engagements with little essential differentiation between the three- and four-lane situations.

A consistent tendency to steer toward the oncoming glare car and a distinct reduction in steering deviation at an intercar separation distance of around 800 feet (5 seconds from meeting point) was observed with most drivers. This is attributed to an anticipatory "steadying" of steering control before the approaching encounter. Prior to this point, the approaching car does not present a hazard; i.e., sufficient time is available to maneuver in the event something unexpected occurs. At this point, the presence of the glare car forces the observer to recognize that he is approaching a potential hazard which he must avoid. After this point, he is forced to make corrections to his vehicle path to avoid collision with the glare car.

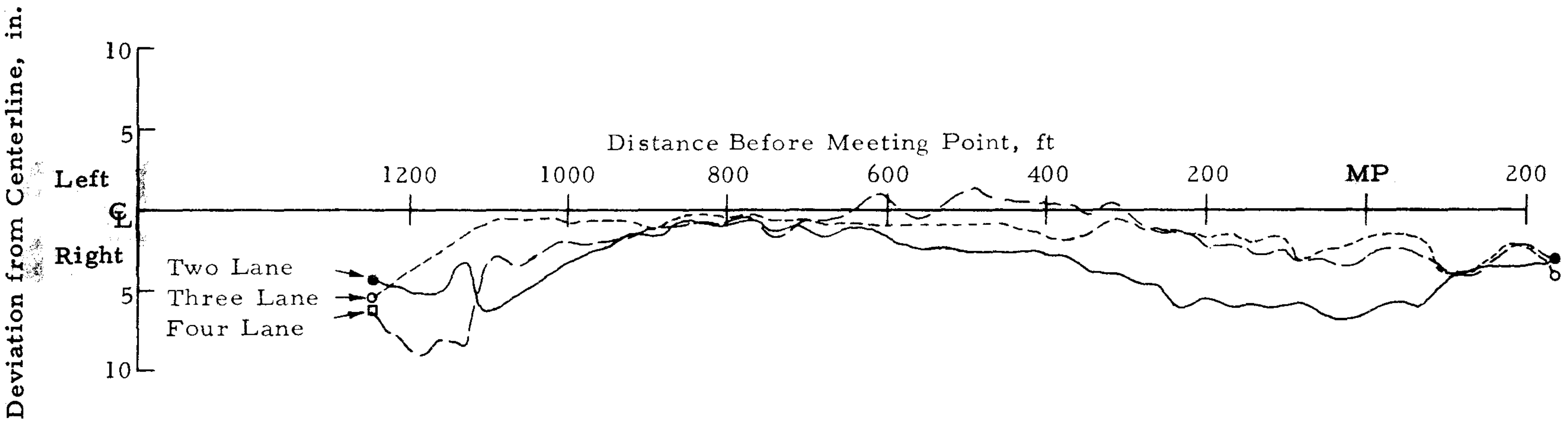
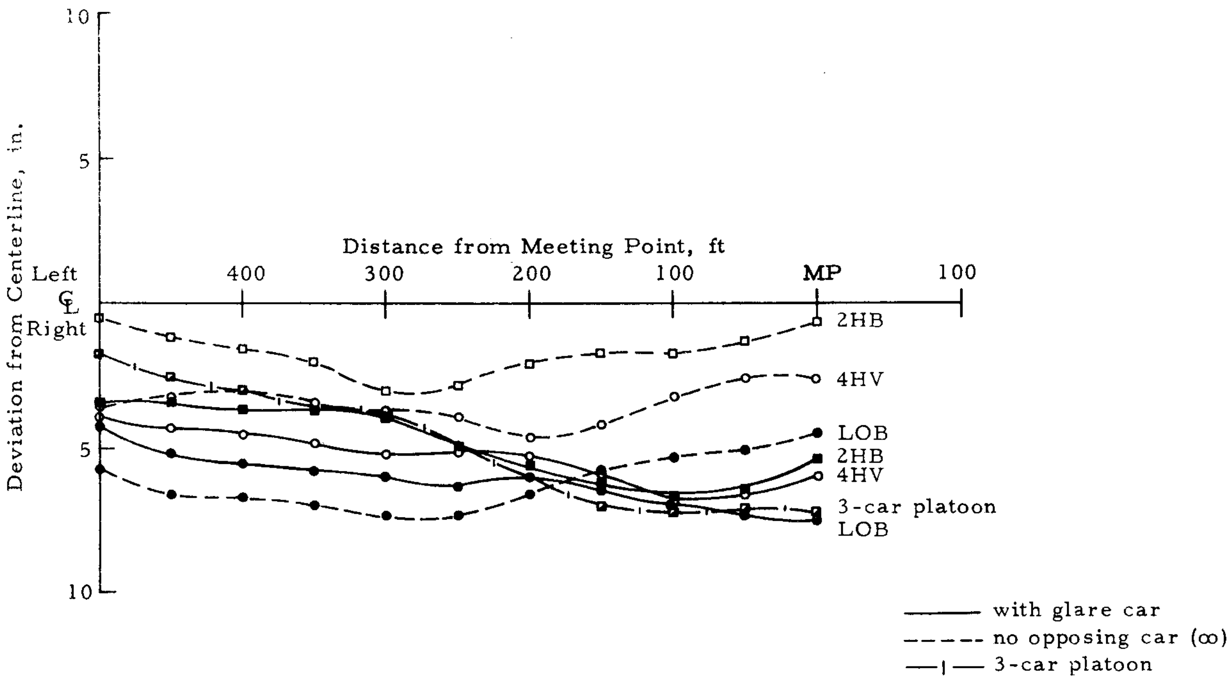
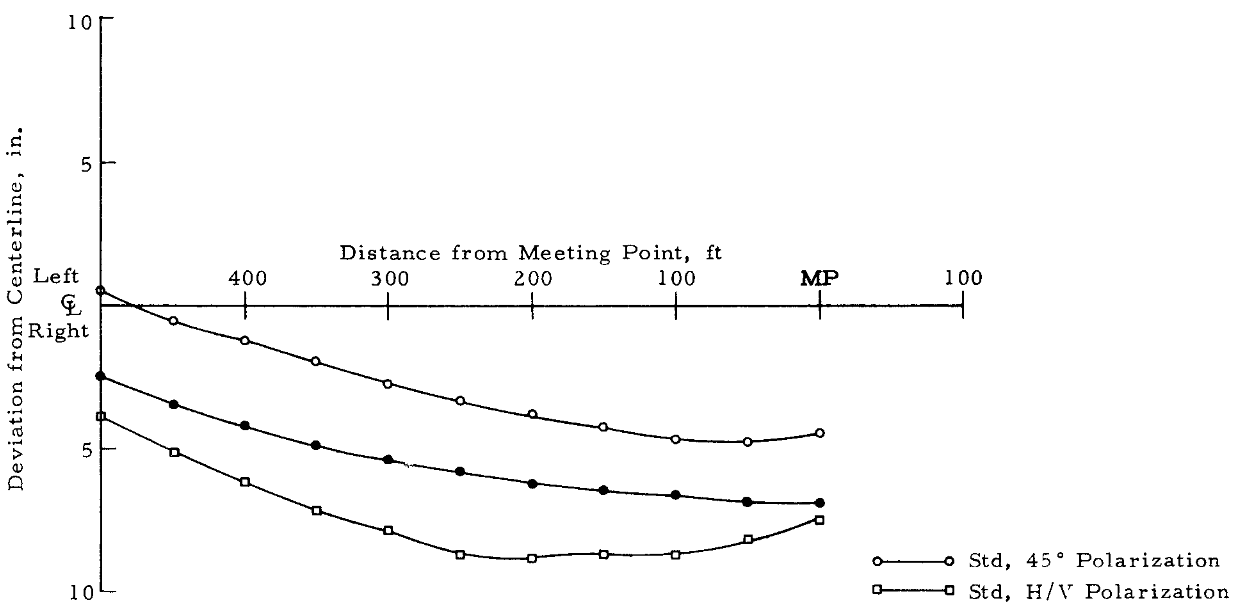


FIGURE 18. SIGN TARGET, EXPERIMENT A1, ALL DRIVERS
MEAN SUBJECT CAR PATH



a. Experiments A2 and A5



b. Experiments A6A, A6B, and A6C

FIGURE 19. MEAN PATHS - ALL DRIVERS, SIGN TARGET

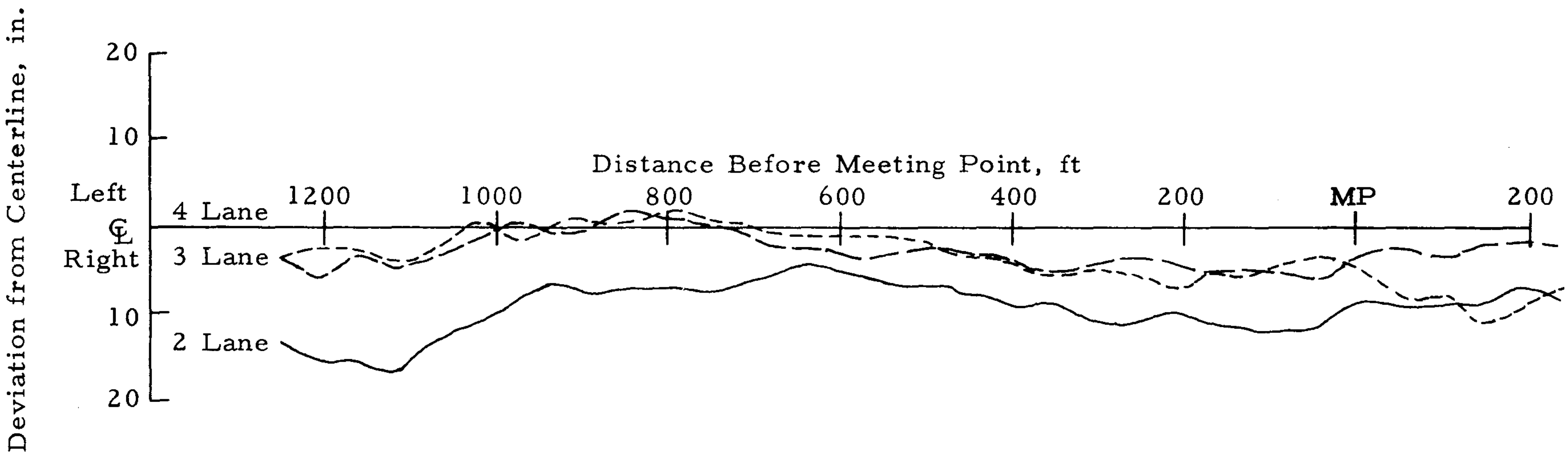


FIGURE 20. **MEAN PATHS, ALL DRIVERS, PEDESTRIAN TARGET, EXPERIMENT A1**

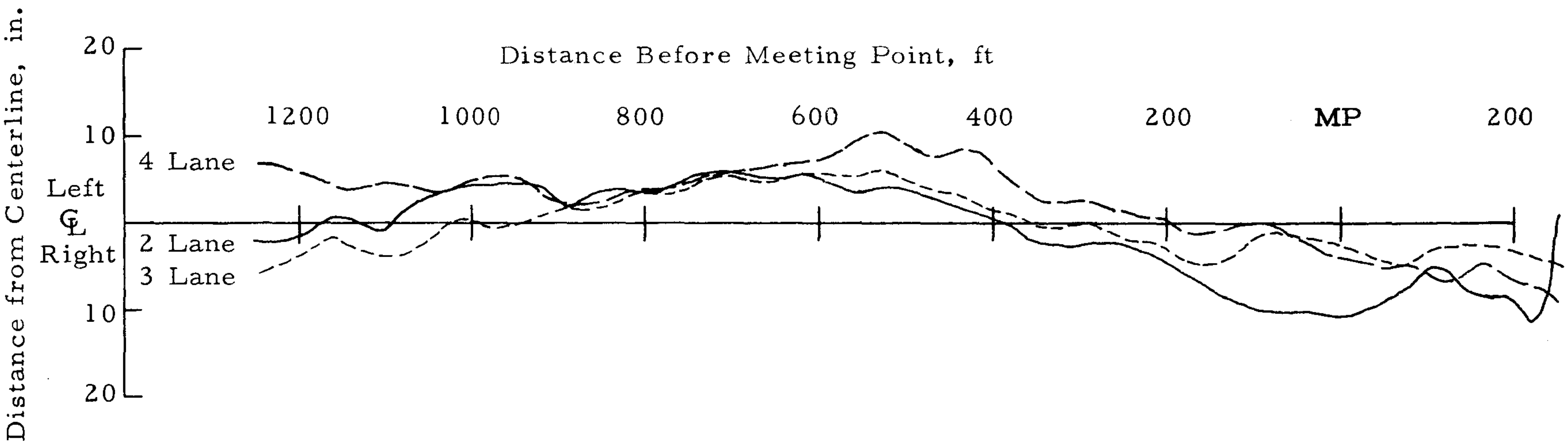


FIGURE 21. MEAN PATHS, ALL DRIVERS, LINE TARGET, EXPERIMENT A1

Analysis of variance of the effects of variation in lighting (Experiment A2), using the maximum deviation amplitude in the steering trajectory immediately preceding the meeting point of the two vehicles as the performance score, did not indicate any significant discrimination between the lighting factors. A second performance score, consisting of the distance at which the effect of the approaching glare car became evident, was likewise unproductive of significant discriminations (Figs. 22 and 23).

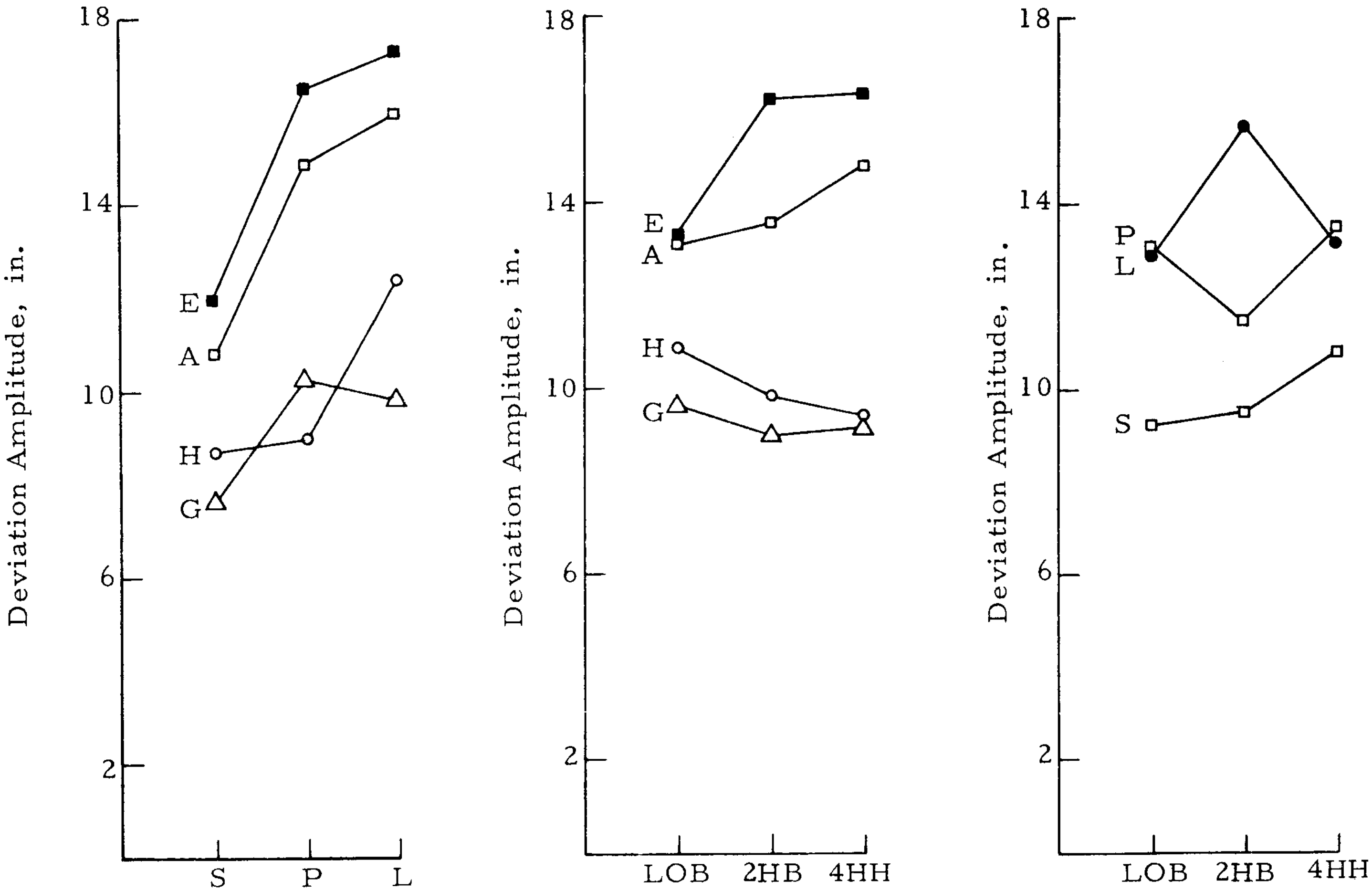
The same technique was utilized to examine these characteristic interactions resulting from the trials with polarized headlights (Experiments A6A, B, C). These show, in Figures 24a, b, c, the characteristic differences between drivers noted before. However, although there is some significance indicated with respect to targets, the deviation encountered is in the same range as that shown in Figure 19 for the various modes of lighting in Experiment A2. It is likewise not possible to discriminate between the three modes of polarized lighting.

Other analyses of variance have been performed utilizing scores of mean slope in the subject car path segment 500 feet before the meeting point, deviation outside bounds of 6 inches right and left of the mean position and variance, skew, mean position, slope, maximum amplitude and deviation out-of-bounds for the full vehicle path from 1250 feet before to 200 feet past the meeting point. With the exception of the above noted lane effect, the only apparent significant variate is the glare car itself. If the glare car is present, most drivers react and move away from it toward the right-hand side of the road. If it is not present, the driver maintains his normal steering track.

Considering the extent of steering adjustment by a driver on a straight road at the speed used in these tests, it is not surprising that no significant differences can be detected due to subtle differences in lighting, as compared to the major effect induced by the presence of the glare car itself. Steering corrections seldom resulted in greater than 0.25° change in direction of the vehicle path, and most fluctuations in direction were of the order of 0.1° or less. This corresponds to steering wheel movements of 7° to 3°, or less.

3. Effects of Headlight Configuration

Experiment A2 was concerned with the effects of high and low beam headlight usage, with the high beam separately evaluated for two-lamp (7-inch diameter) and four-lamp (5-3/4-inch diameter) systems with over-and-under and horizontal orientation. In this instance, an analysis of variance of detection distance shows that the intercept distance has a strong effect (Fig. 25d). However, this is the same effect as previously noted, resulting from inclusion of the ∞ (no glare car) detection distances. Insofar as the lighting is concerned, the significance is relatively weaker (Fig. 25f). The reduced glare from the glare car, in the low beam case, is accompanied by lesser detection distance due to simultaneous reduction in illumination from the subject car on the target. The higher intensity, high beam lights of the



a. Drivers × Targets   b. Drivers × Lighting   c. Targets × Lighting

FIGURE 22. EXPERIMENT A2, DEVIATION AMPLITUDE INTERACTION BY LIGHTING (Maximum Deviation Amplitude Before Meeting Glare Car)

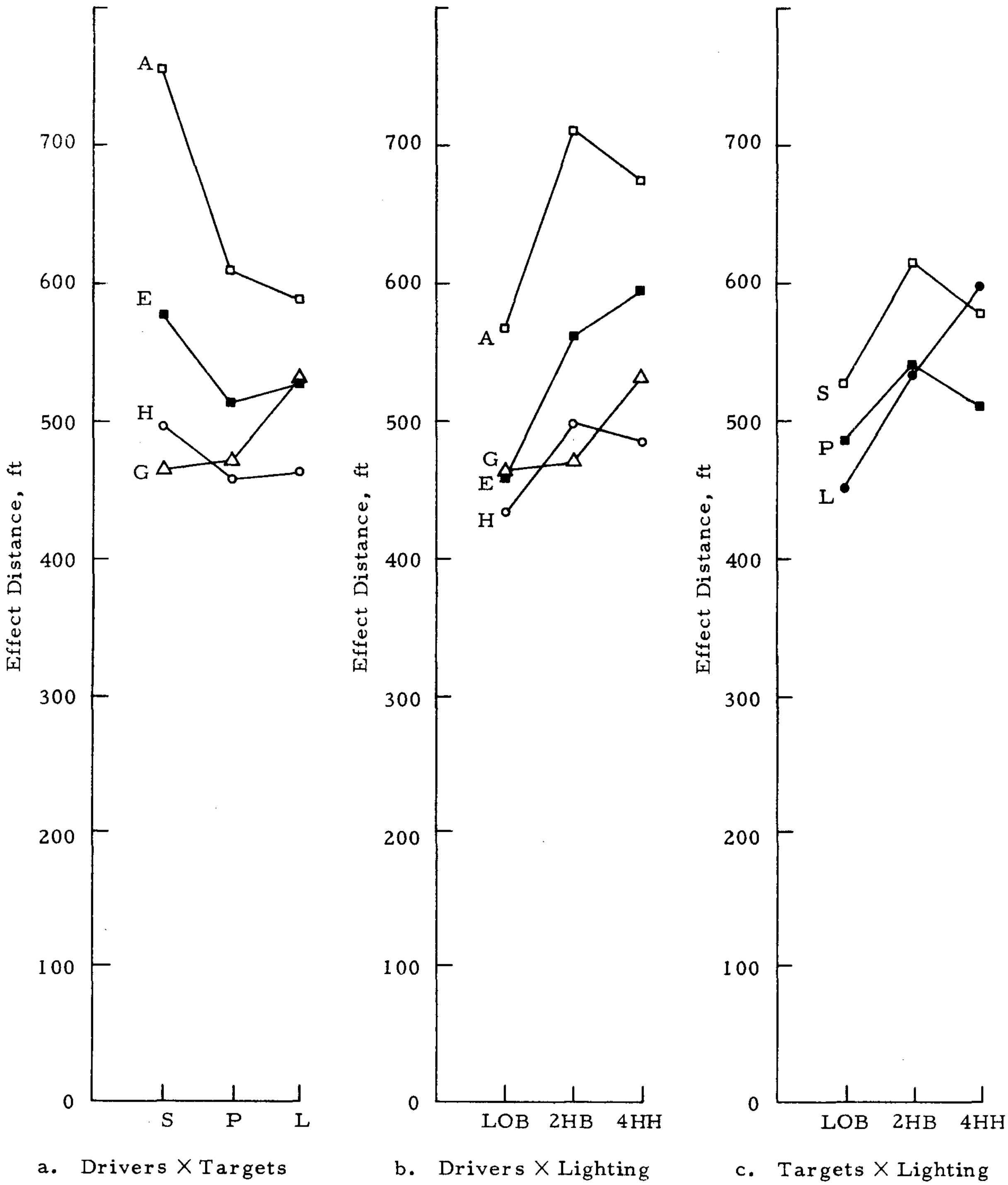
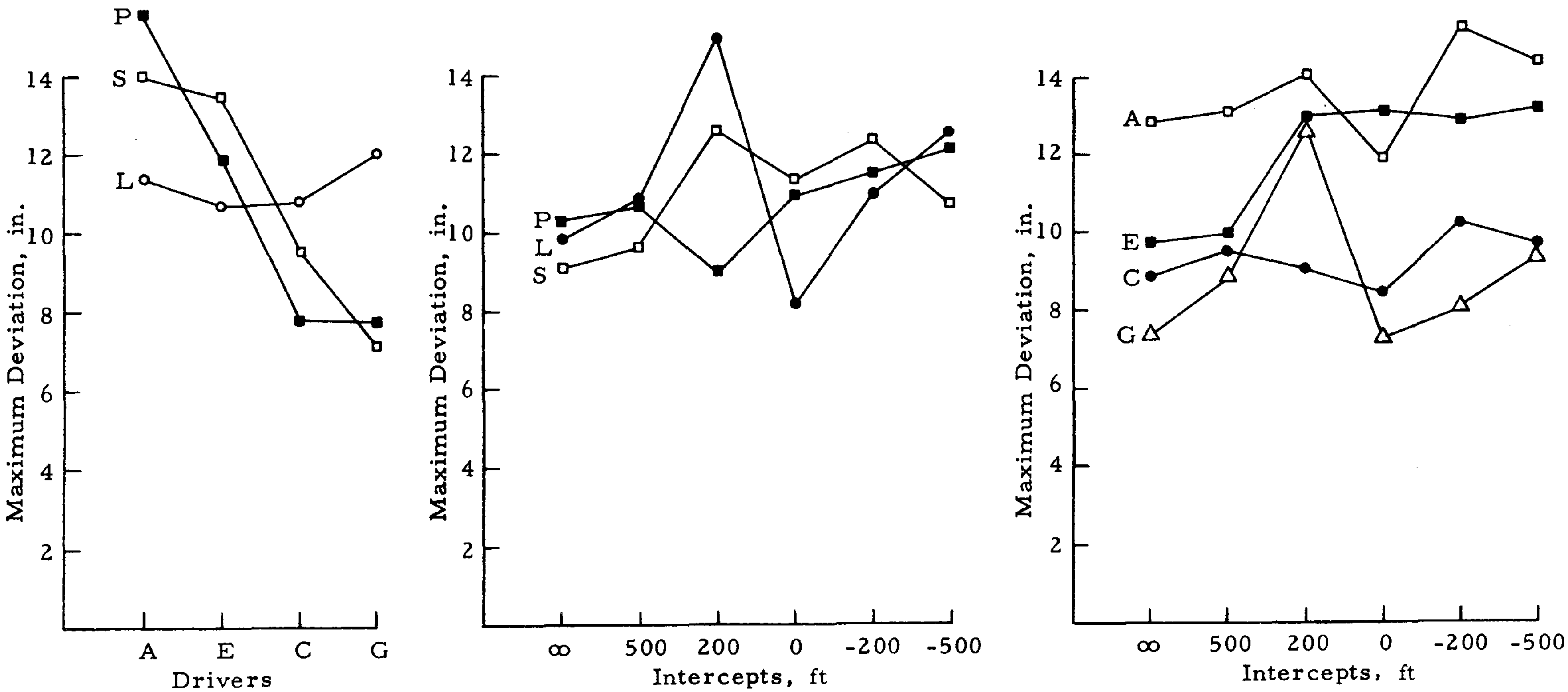
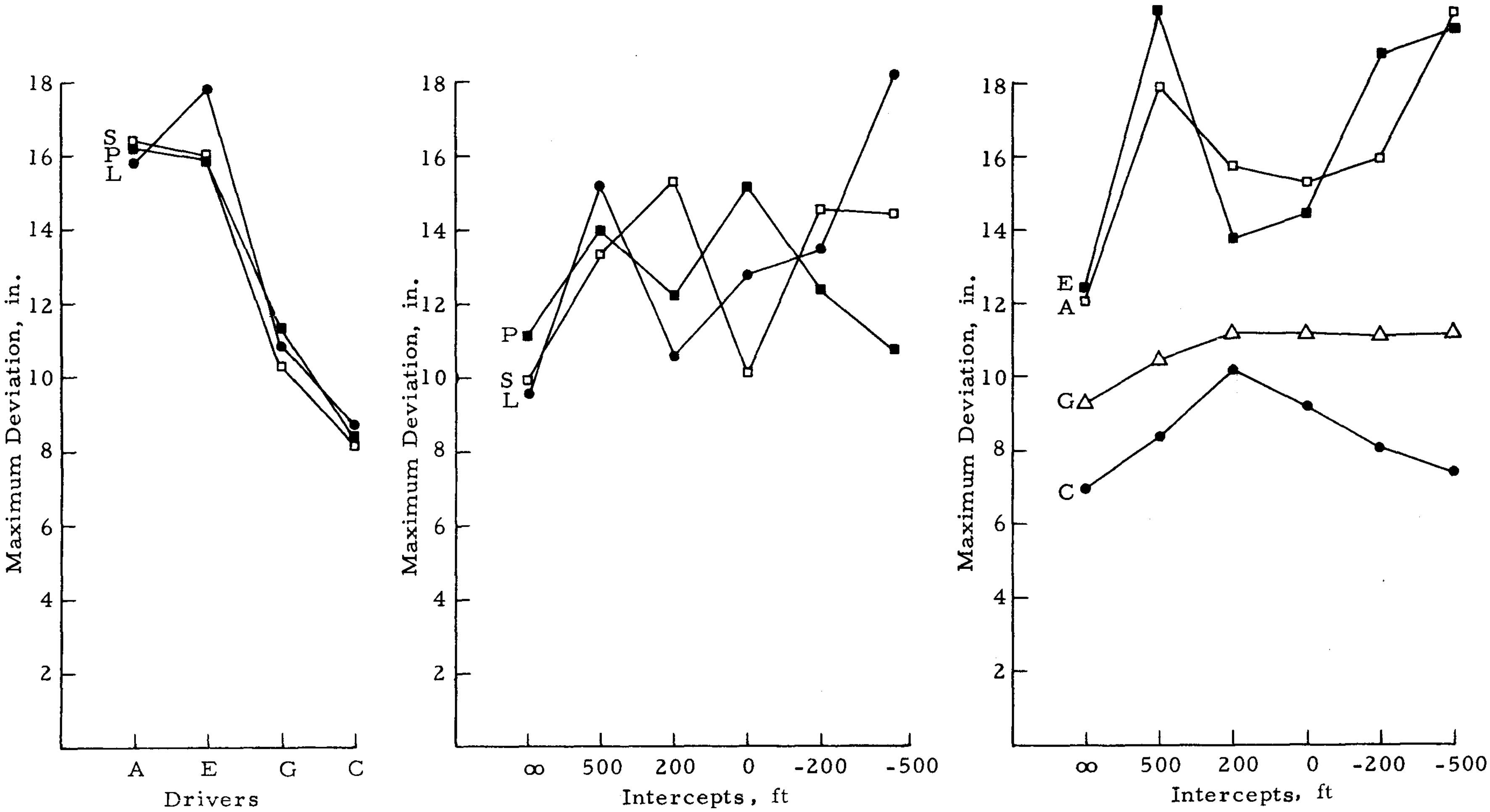


FIGURE 23. EXPERIMENT A2, DISTANCE FROM MEETING POINT WITH GLARE CAR FOR INITIATION OF DEVIATION CHANGE



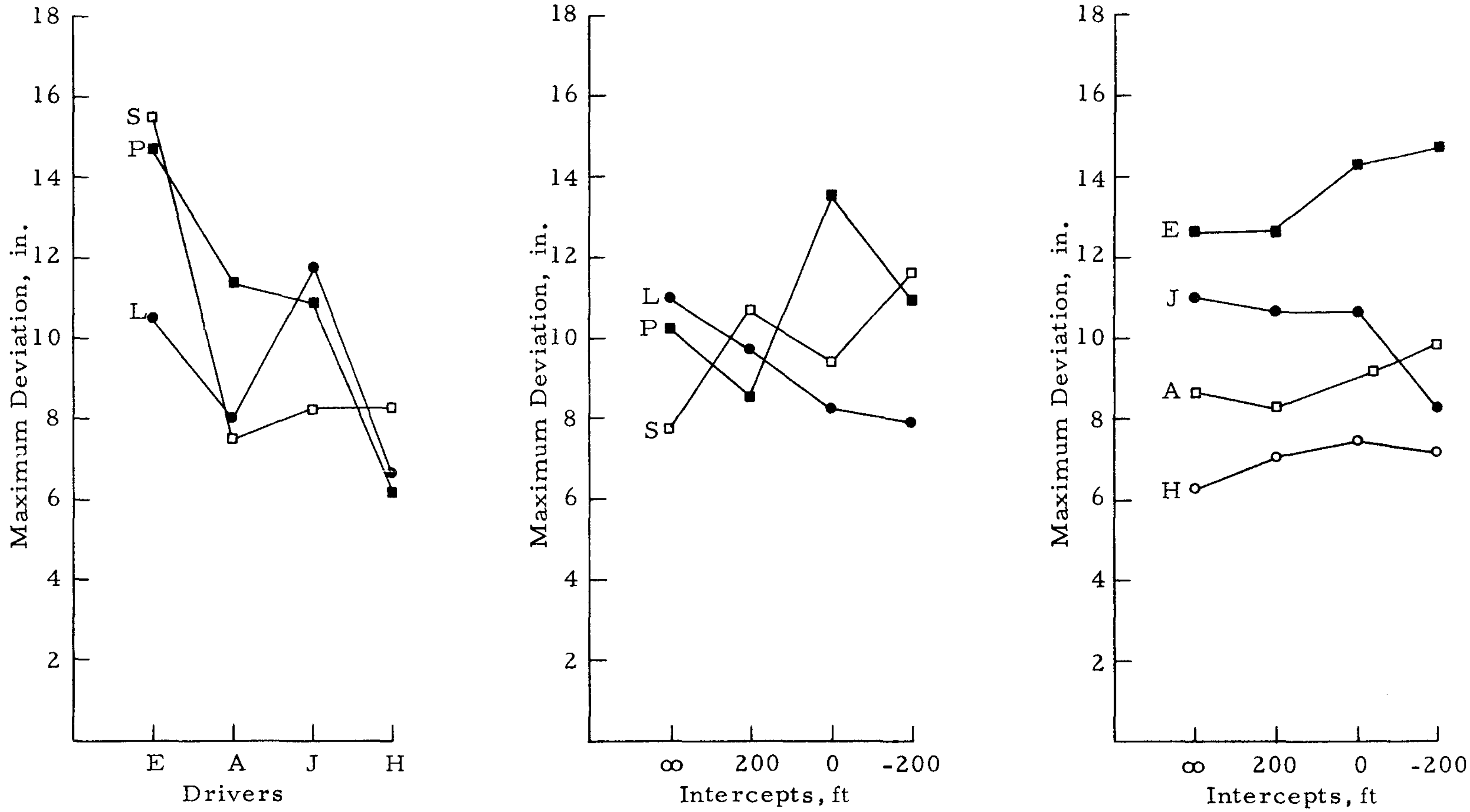
a. Experiment A6A - Standard Headlights, ±45° Polarization

FIGURE 24. MAXIMUM DEVIATION APPROACHING MEETING POINT WITH GLARE CAR



b. Experiment A6B - Standard Headlights, H/V Polarization

FIGURE 24. MAXIMUM DEVIATION APPROACHING MEETING POINT WITH GLARE CAR (Cont'd)



c. Experiment A6C - High Intensity Headlights, ±45° Polarization

FIGURE 24. MAXIMUM DEVIATION APPROACHING MEETING POINT WITH GLARE CAR (Cont'd)

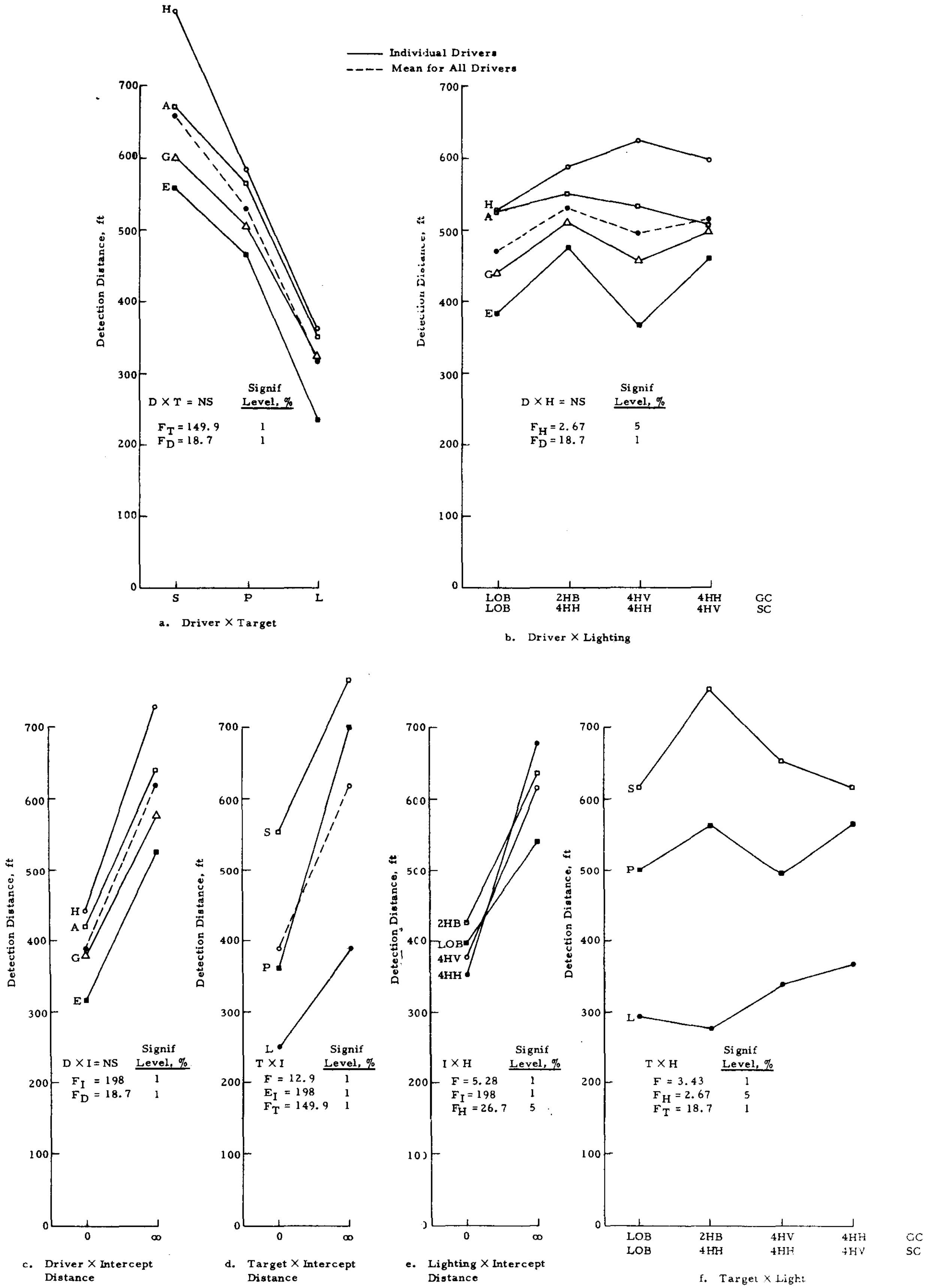


FIGURE 25. EXPERIMENT A2, EFFECT OF LIGHTING VARIATION ON DETECTION DISTANCE

glare car produce greater veiling glare which overcomes the advantage the observer might have had from the increased illumination at the target produced by the high beam subject car headlights. No trials were included utilizing low beam glare car headlights with high beam subject car lights. When only the unopposed lighting situation is considered (∞ intercept), it is readily apparent that there is an average increase in detection distance of approximately 100 feet between the low and high beam conditions for all targets combined (Fig. 25e).

4. Speed

Experiment A4 examined the effect of speed on the detection of the targets. The lower speed selected (30 mph) is generally representative of nighttime speed limits in unlighted urban streets, while the higher speed (55 mph) is the nighttime speed limit for two-lane rural highways in a majority of states.

Analysis of variance of the detection distances show significance at the 1% level for intercept distance and drivers and at the 5% level for the different speeds. However, it is readily seen in Figures 15c and 26a that the intercept distance significance comes from the inclusion of the ∞ intercept condition. It is also apparent that the indication of speed significance is weak and results essentially from only one driver's performance (Fig. 26b). It may therefore be concluded that speed has at best only a minor influence in detection distance in night driving. Previous investigators[14, 23] have concluded that speed does influence detection distance to a greater degree than has been brought out by these studies. However, review of published data indicates that reaction time of the observers was not taken into consideration in establishing the distance at which the targets were seen. The studies reported herein do make such a correction. It is not considered pertinent that there is less time to see a target at higher speeds, nor is there evidence that the target would be apparent to foveal vision at a lesser distance. Rather, the distance covered in reacting to the sighting of the target is greater at the higher speed[23]. If no correction is made for distance travelled during the reaction time, the apparent detection distance will therefore be less at a higher speed and will appear to have a strong relationship to speed.

5. Multiple Glare Cars

A platoon of three vehicles at 50-foot spacing was substituted for the single glare car for Experiment A5. All of the vehicles were passenger cars having four-lamp headlight systems and were run on the two-lane highway at a zero-intercept distance only. Although four subject drivers were utilized and were common to Experiment A2, only two were common to Experiment A1.

Although there were only two drivers whose performance could be compared between Experiments A1 and A5 (platoon of three vehicles as glare source), their detection distances were measurably reduced by the longer

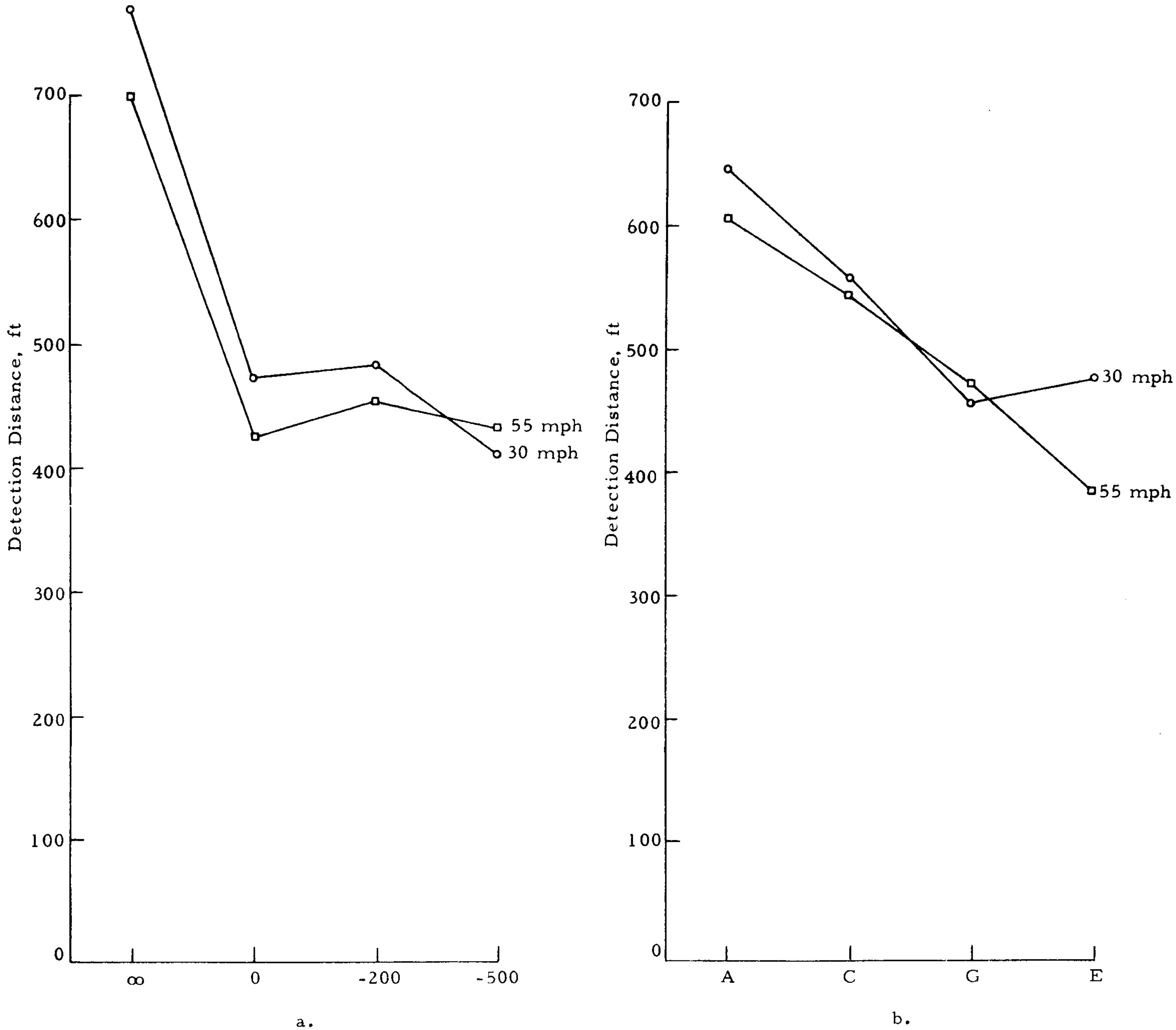


FIGURE 26. EXPERIMENT A4, EFFECT OF SPEED ON DETECTION DISTANCE

exposure conditions encountered in A5 for all targets. It will also be noted that the platoon of vehicles forces detection to occur for the less visible targets (pedestrian and line) in the face of higher glare intensities, again owing to the longer period of exposure encountered. Further, although not directly comparable, the performance of the other drivers is consistent with this (Fig. 27).

6. Polarized Headlights

Many previous investigators in and peripheral to the automotive industry have generally concluded that polarization of headlights offers the only reasonably practical, overall solution to the two- and three-lane night driving problem for unlighted highways. There are serious implementation problems and more or less minor operational problems of concern in the utilization of polarized headlights. Although the problem was quite thoroughly studied during the late 1940's, some of the then considered deficiencies have been overcome by vehicle evolution, and a more receptive climate for its use may now exist. It was considered that the present study offered a particularly advantageous opportunity to make a thorough comparison of polarized with standard lighting. This is also considered to be a modernization of previous work since little has been done in comparative studies of polarized lighting since the advent of the new headlighting systems in 1957.

Discussion of the basic phenomena and application of polarizing screens and analyzers to automotive use will not be made here since this is well covered in the literature. As previously indicated, three polarizing configurations have been studied under certain highway/vehicle conditions. These relate to straight road and dry pavement and vehicles with clean and dirty windshields. With standard 4001 and 4002 type lamps, dichroic polarizers of 45° and 0° (horizontal) orientation were employed, together with a third configuration utilizing 45° orientation with 100-watt 4001 lamps. The analyzers were mounted on the normal sun visor in front of the driver and oriented, respectively, at 45° (parallel to the vehicle's own headlights and normal to the opposing vehicle's headlight rays) and at 90° (normal to both vehicles' headlights). The analyzers were adjusted prior to test runs to obtain maximum extinction of the opposing, glare car's headlights.

Although it is recognized that specular reflection of the polarized beam from the vehicle's own headlights, in the case of the horizontal/vertical orientation, would result in extinction of the reflected rays, the more or less diffuse reflection of natural roadside targets results in some depolarization of the incident rays, with consequent partial transmission of this reflected, depolarized light through the analyzer. This has been reported as a disadvantage in seeing specular reflections or "glinting" surfaces of parked vehicles at night but an advantage in reducing "back scatter" reflection when driving in fog. This same analyzer would also be useful in daytime driving, without the necessity for reorientation, to reduce the glare produced on the highway by polarization of sky light. Under some night driving conditions, particularly with wet road surfaces and wet windshields, the differences in effectiveness

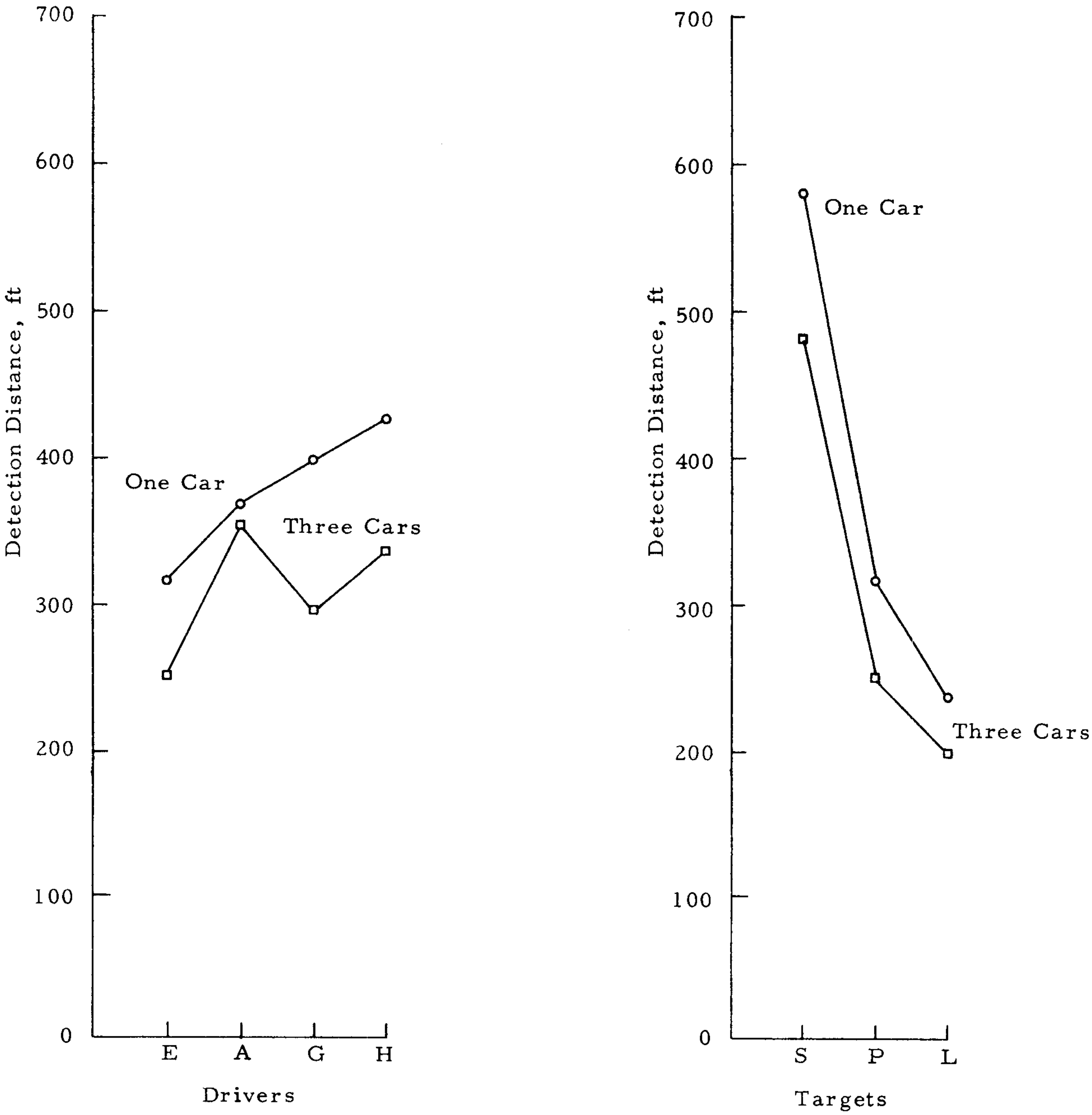


FIGURE 27. EXPERIMENT A5, DETECTION DISTANCES WITH MULTIPLE GLARE VEHICLES

between the two modes of polarization orientation do not appear to have been previously studied. It was, therefore, decided to include both orientations in the study to determine whether there were practical differences, deficiencies or advantages in one system over the other. Those tests involving wet roads, wet windshields and fog are still to be conducted.

In the overall analysis of the three polarization systems, in Experiments A1, A6A, B, and C, only two drivers were common to all three conditions, although four drivers were used in each case. An analysis of variance on detection distances indicates the previously noted strong influence of drivers and targets and a relatively weaker significance of intercept distance. There is strong significance in respect to the polarization modes. Plots of the interaction means in relation to the polarization modes, however, show this significance to be largely resulting from the high-intensity lamp system with very little, if any, distinction between the two different orientations of polarization used with the standard headlamps (see D $\times$ P, T $\times$ P, Figs. 28a, c).

Considering the two orientation modes used with the standard headlamps only, there appears to be an advantage, in the case of the sign and pedestrian targets, of the ±45° system over the horizontal/vertical system, although there does not appear to be any difference in the case of the line target (Fig. 28h). This advantage is also shown consistently in respect to the intercept $\times$ polarization interaction analysis and plot (Fig. 28b, i).

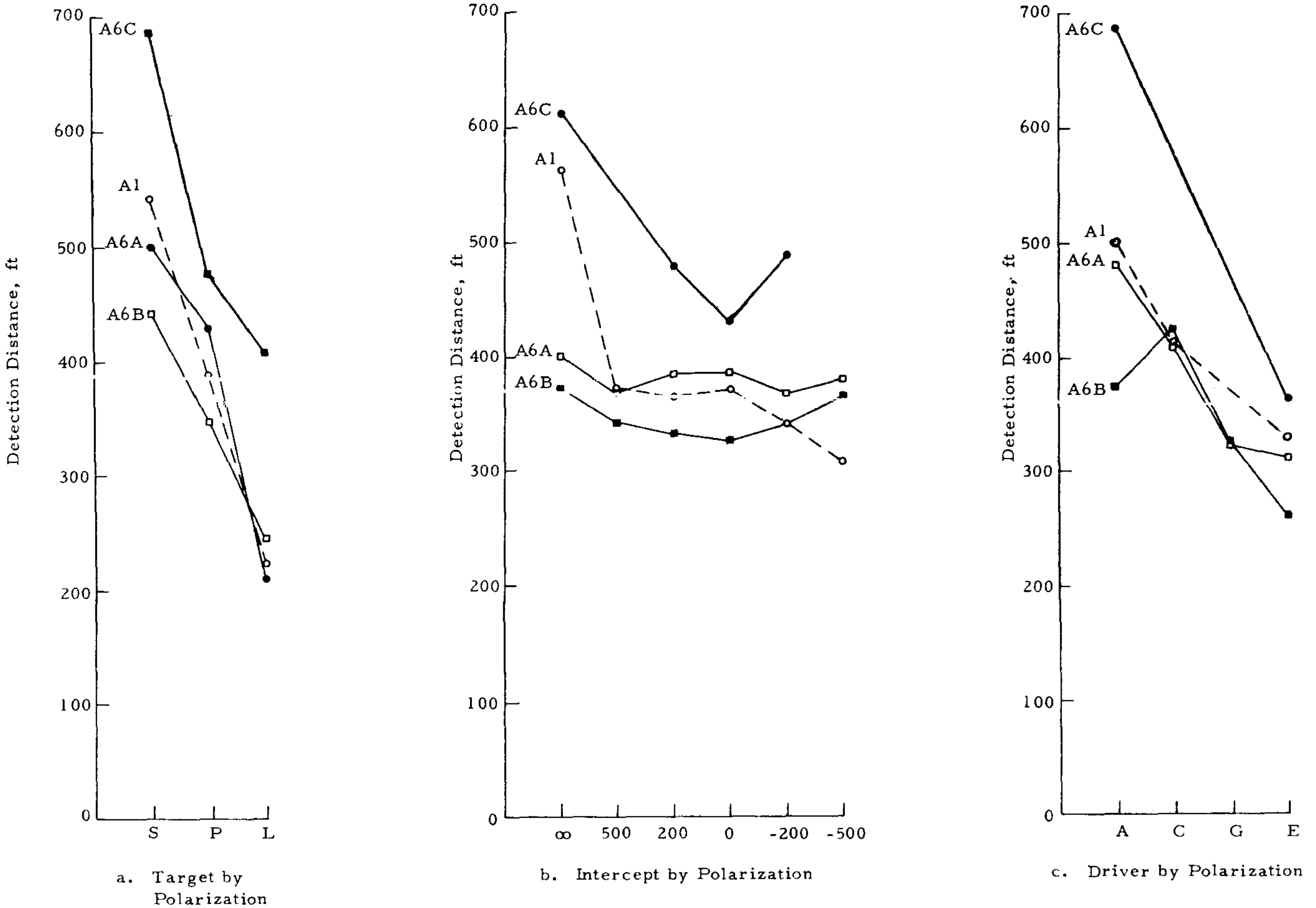
7. Dirty Windshield--Experiments A3 and A8

Road grime and dust on the windshield form a diffusing, light scattering layer or illuminated screen before the driver's eyes which become more or less difficult to see through, depending on the intensity of light illuminating it from an opposing vehicle.

A standardized, dirty windshield was prepared by a light, "dust" spraying of white paint on a 0.035-inch thick, acrylic plastic sheet which was then taped over the normal windshield with the painted side inward. Figures 29 and 30 show an opposing vehicle as it appears when viewed through this windshield, with and without opposing headlights.

Normal high beam headlights and polarized headlights were studied in the experiments involving the dirty windshield.

Unlike the other experiments, the only significant factor here was the intercept distance. The illumination of the dirty windshield was at a maximum during negative intercepts and resulted in maximum reductions in target detection distances because of the interposed glare on the windshield. The use of high-intensity polarized headlights shows the same changes in detection distances over standard high beam headlights as in experiment A6C. While reductions in detection distances were apparently due to the dirty windshield, both Figures 31 and 32 show there was no appreciable effect related to



A1 - Standard 4 Lamp Headlights, High Beam
A6A - Standard 4 Lamp Headlights, High Beam, with ±45° Polarization
A6B - Standard 4 Lamp Headlights, High Beam, with H/V Polarization
A6C - High Intensity 4 Lamp Headlights, High Beam, with ±45° Polarization

FIGURE 28. EFFECTS OF POLARIZED HEADLIGHTS ON DETECTION DISTANCES

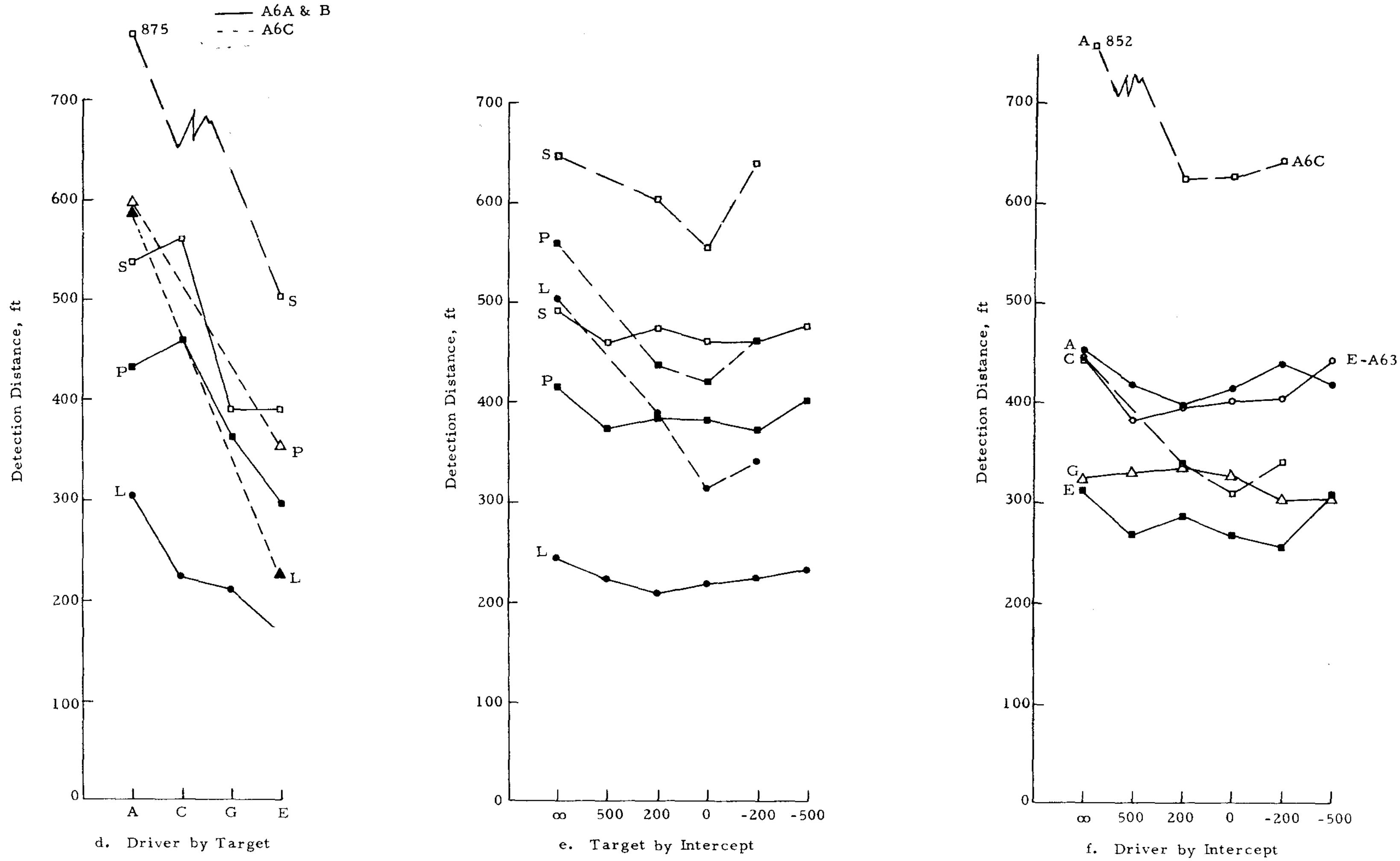
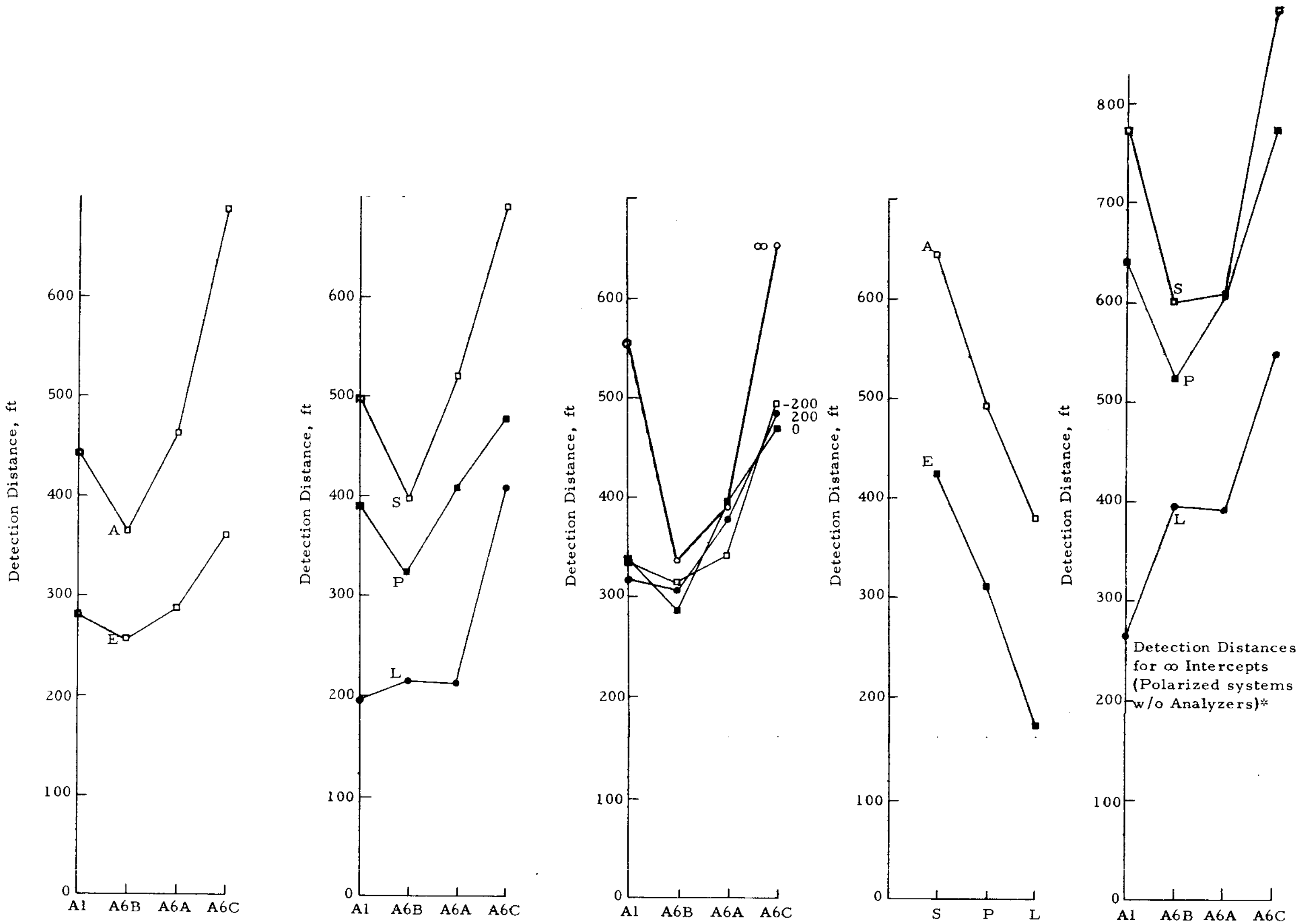


FIGURE 28. EFFECTS OF POLARIZED HEADLIGHTS ON DETECTION DISTANCES (Cont'd)



g. Driver by Polarization

h. Target by Polarization

i. Intercept by Polarization

j. Driver by Target

k. Target by Polarization

*All other ∞ data obtained with analyzer.

FIGURE 28. EFFECTS OF POLARIZED HEADLIGHTS ON DETECTION DISTANCES (Cont'd)

FIGURE 29. DIRTY WINDSHIELD WITHOUT OPPOSING ILLUMINATION

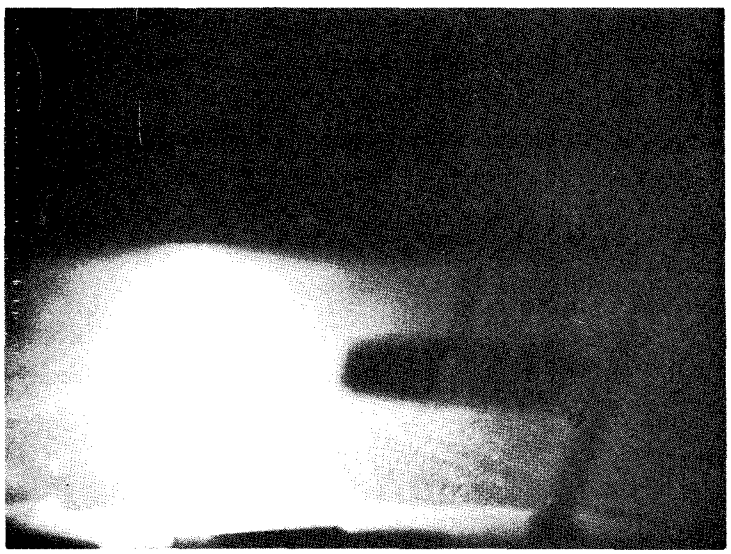


FIGURE 30. DIRTY WINDSHIELD WITH OPPOSING HEADLIGHTS

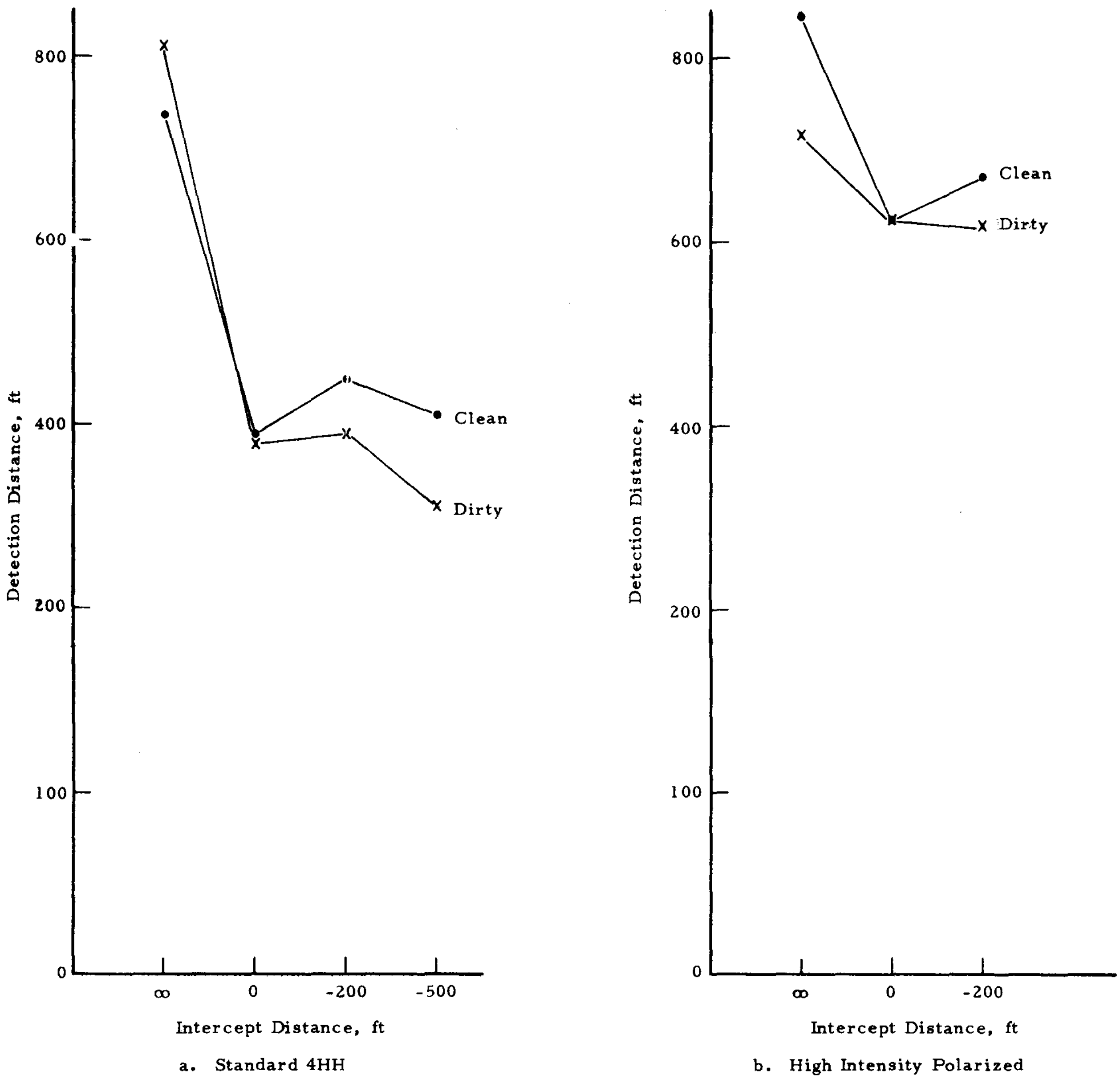


FIGURE 31. EXPERIMENT A3/A8, EFFECT OF DIRTY WINDSHIELD ON DETECTION DISTANCE

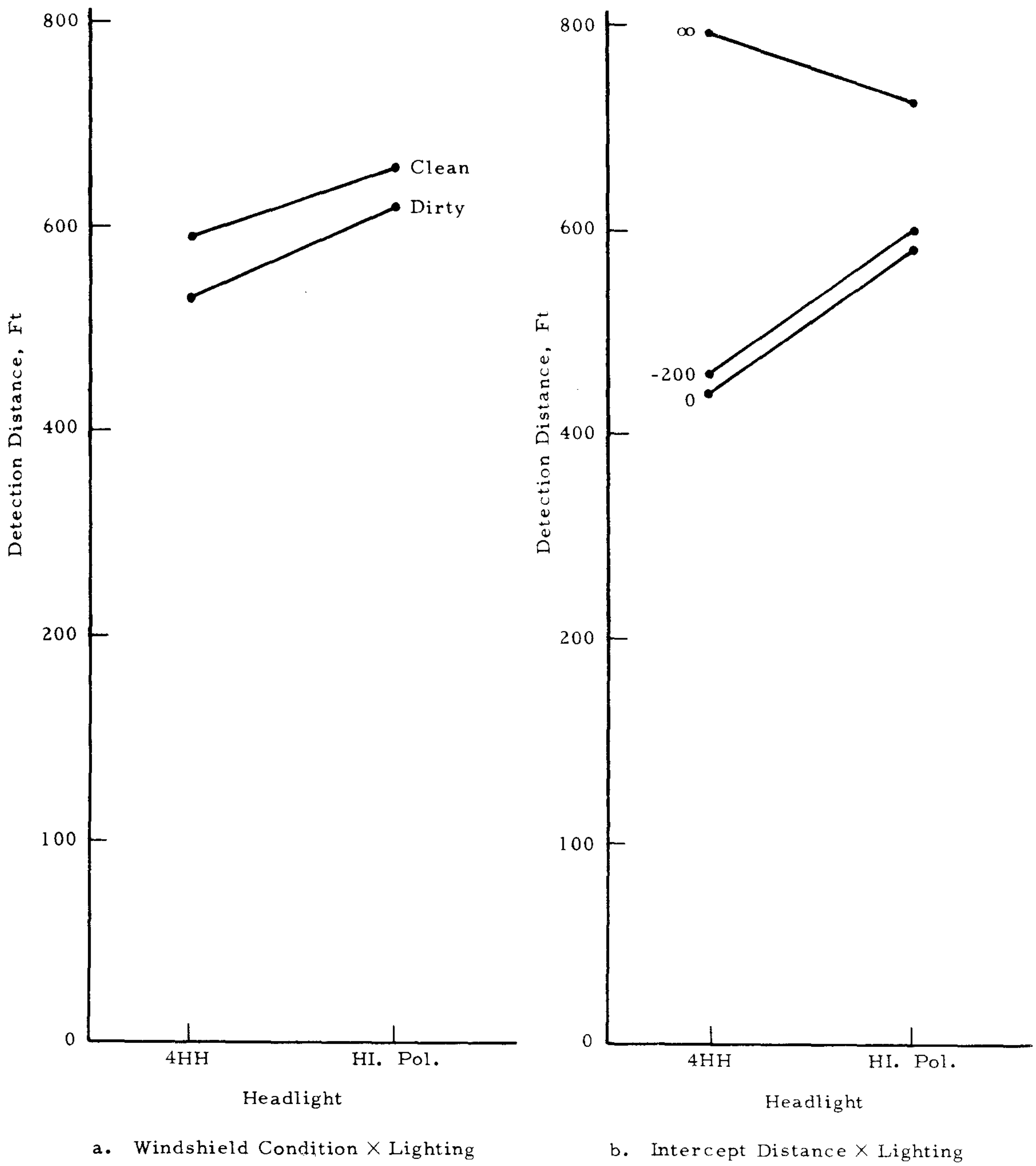


FIGURE 32. EXPERIMENT A3/A8, EFFECT OF DIRTY WINDSHIELD ON DETECTION DISTANCE

polarization. Since only one driver was common to these experiments, the data for all drivers in each experiment concerned (A1, A3, A6C, and A8) were averaged for the last analysis of variance summarized in Table 3 and presented graphically in Figure 32.

8. Glare Adaptation Response

Inasmuch as no standard methodology is available for determining glare adaptation, the equipment and procedures used herein may be considered to provide only relatively comparative ratings of individual responses. Subjects having target detection times of less than 3.0 seconds were arbitrarily considered as good and those greater than 5.0 seconds as poor. On this basis in the preliminary experiments A1 through A6 and A8, Drivers E and G would be rated poor, while A, B and F would be good, with C and H falling in the zone between 3.0 and 5.0 seconds. Examination of those interaction plots in which drivers are delineated shows reasonable agreement between these scores and resulting detection distances, although it will be noted that the performance of H is the best (Figs. 25a, b), and F is one of the poorest performers (Figs. 14c, 15a). In Experiment A7, five drivers had response times over 5.0 seconds and eight were below 3.0 seconds. Table 4 shows the relationship between glare adaptation response time and detection distances for various combinations of lighting and targets.

This tabulation shows, in most instances, a marked increase in detection distances for those drivers whose response times are below 3.0 seconds with little difference for those over 3.0 seconds.

TABLE 4. EXPERIMENT 7, AVERAGE DETECTION DISTANCE RELATED TO GLARE ADAPTATION RESPONSE

Lighting/Target Condition	Detection Distances for Glare Adaptation Response Time		
	<3.0 Seconds	3.0 - 5.0 Seconds	>5.0 Seconds
With Glare Car			
Low Beam	273	249	235
4 lamp High Beam	322	280	311
Standard Lamp - Polarized	416	377	391
High Intensity - Polarized	485	458	459
No Glare Car (∞)			
Low Beam	393	305	329
4 lamp High Beam	581	632	588
Standard Lamp - Polarized	514	424	407
High Intensity - Polarized	628	565	566

V. RESULTS--PRINCIPAL EXPERIMENT A7

The principal experiment of the series of studies was conducted primarily to obtain a substantial cross section of typical driver performance. Twenty drivers were employed, of both sexes, ranging from 17 to 54 years of age. As previously stated, page 16, the only criteria for selection for the program were that the drivers/observers be currently licensed and have at least 3 years of driving experience. Physiological characteristics of these drivers are shown in Table 2, page 20.

The experiment consisted of a series of fifty-two separate runs, for each driver, preceded by a series of seven preliminary runs for orientation. Headlight configuration was the principal factor of concern and four variations were employed:

a. Standard low beam;

b. Standard four-lamp, high beam;

c. Standard four-lamp, high beam, polarized 45°;

d. High intensity (100 watt) four-lamp, high beam, polarized 45°.

All three targets were used with intercept distances of ∞, 200, 0, -200 feet. Vehicle speeds were 55 mph, and only the two-lane road pattern was employed. The glare car was driven at all times by one of the drivers who had been in the preliminary experiments.

Considerable care was taken to insure that the observer drivers were not cognizant of either the purpose of the experiment or the measurements being made. None of these drivers were regular employees nor did any of them have daytime jobs of engineering or technical nature. Answers to any questions raised concerning the experiment were specifically deferred until the driver had finished his complete series of tests. Only sufficient information was given before and during a test to enable the driver to properly carry out the tasks of driving and to signal detection of a target.

As in the preliminary experiments, the criteria of performance were target detection distance and lateral deviation in driving the subject car. Additionally, the observers were asked to make two subjective evaluations upon completion of each run. These were six point numerical estimates or ratings of the visibility of the target and discomfort glare.

	Rating No.	Discomfort Glare	Target Visibility
a.	0	No problem	Couldn't see
	1		
b.	2	Bothersome	Hard to see
	3		
c.	4	Quite uncomfortable	Some difficulty
	5		
d.	6	Practically blinding	Easily seen

The sequence of headlight configurations used, after each driver completed his orientation runs, was randomized among the drivers in four patterns but arranged so that five drivers were assigned to each pattern. The sequence of intercept distances and targets was also randomized in each pattern, additionally, blind runs with no target were employed to prevent drivers "anticipating" the target position.

Experiment A7--Results. As in the preliminary experiments, analyses of variance on detection distance and lateral deviation have been conducted. In most respects, the preliminary findings have been positively confirmed and strengthened. The supplementary information of discomfort glare and target visibility is of interest.

Figure 33 shows the detection distance relationships with lighting, target and intercept distance variations. Figure 33a, which relates intercept distance and lighting, has been plotted in terms of intercar distance at the time the target was detected ($ICD_{det.}$). This relationship may be somewhat more readily visualized than that involving the intercept distance concept. The relationship is:

$$ICD_{det.} = \text{Intercept Dist.} + 2 \times \text{Detection Dist.}$$

This clearly delineates the advantage of polarized headlights in all vehicle meeting engagements but shows that in the unopposed highway situation the 100-watt polarized system is still not comparable to normal high beam lighting when the driver is looking through the analyzer. If the analyzer is not being used, the detection distances will exceed those of the normal high beam system (see Figure 28k--this lighting configuration was not included in Experiment 7).

Figure 33 shows the relationships of targets to lighting at detection with similar positive results.

Figures 34 through 36 illustrate the distribution of detection distances for each target and lighting configuration among the twenty drivers. In almost all cases where the glare car is present, the polarized lighting configurations provide greater detection distances. An exception appears in the case of the

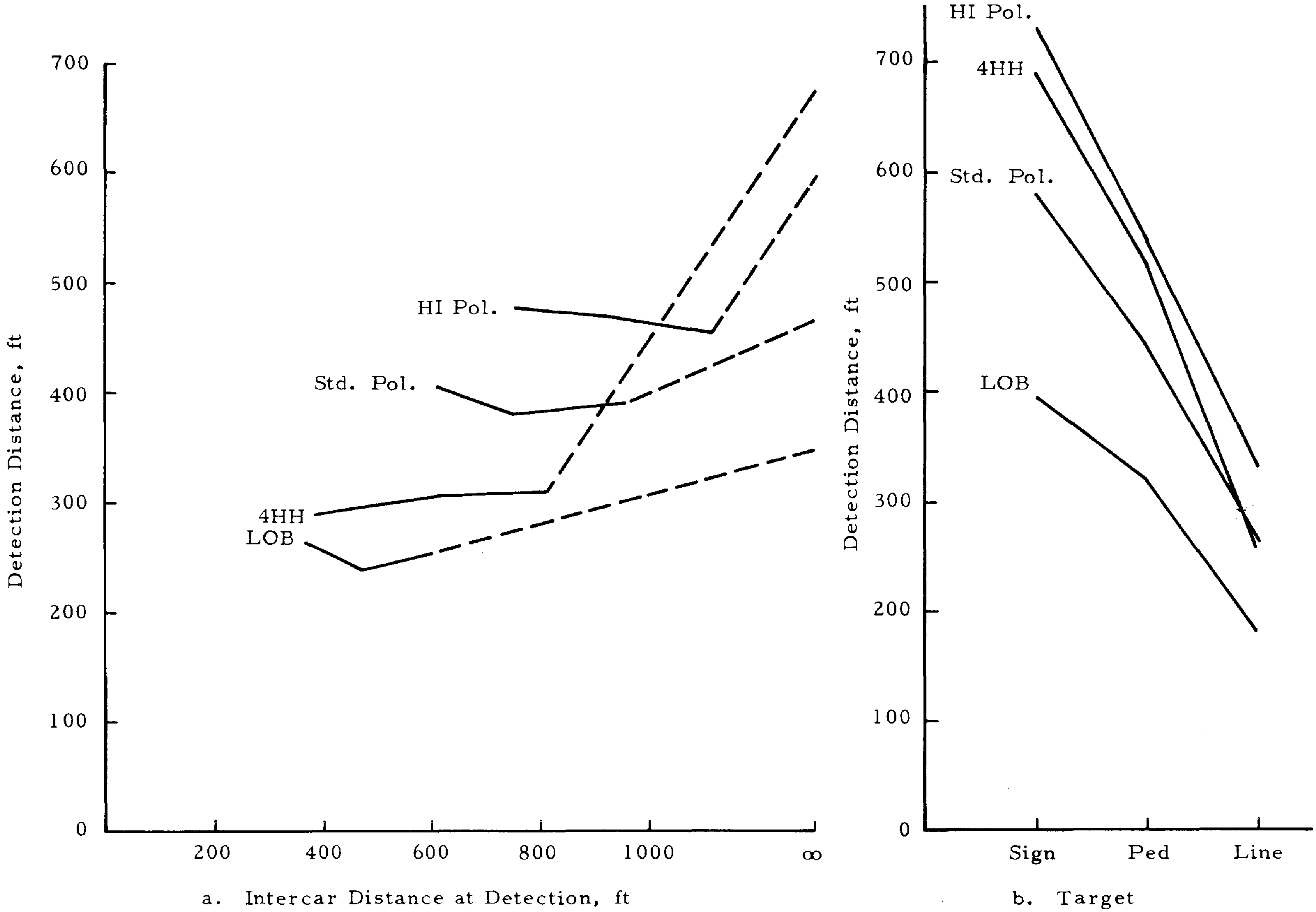
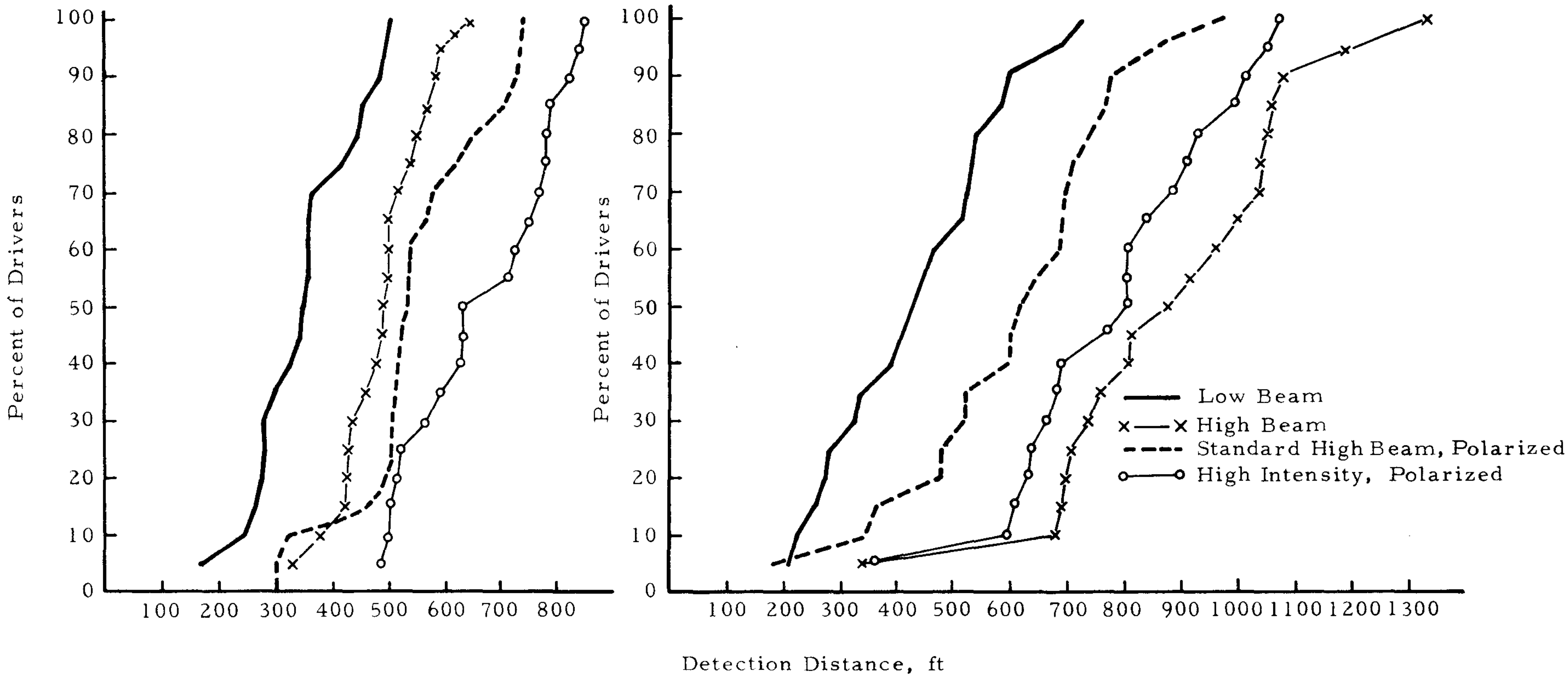


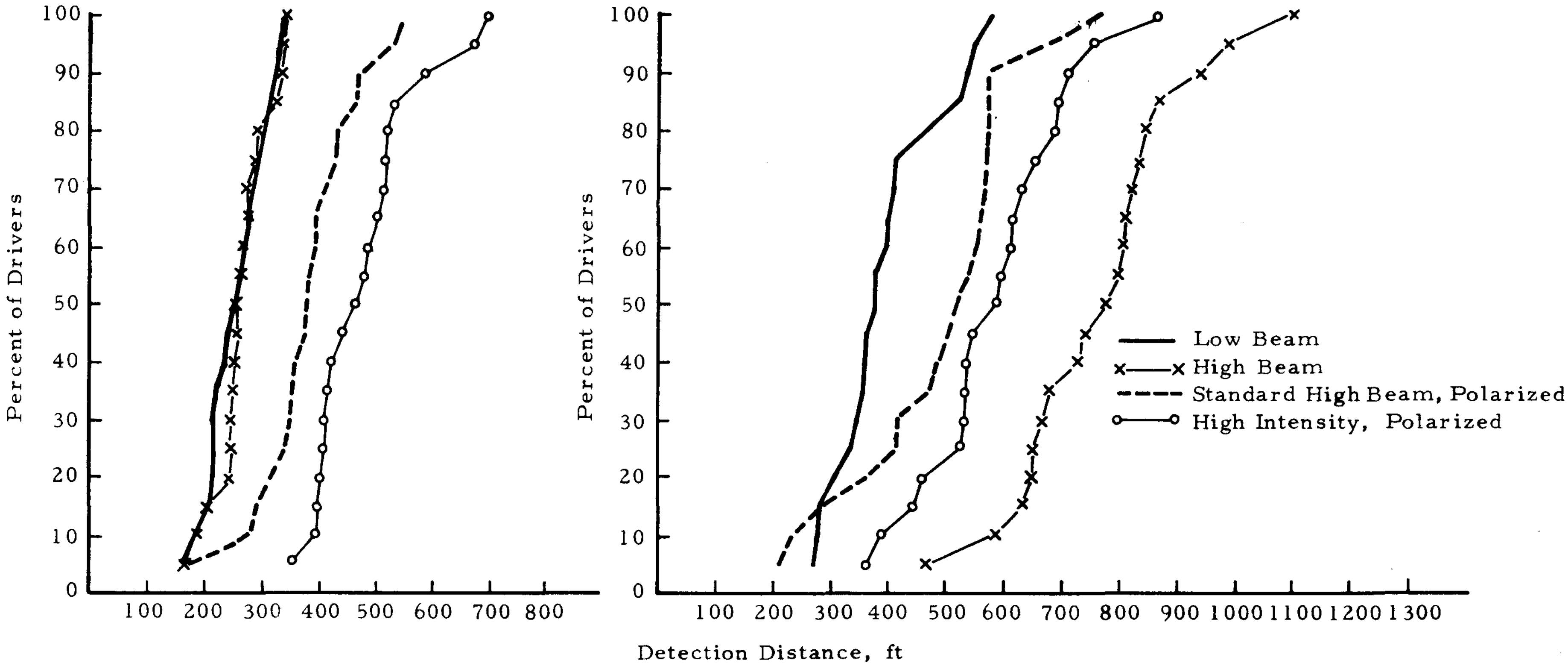
FIGURE 33. DETECTION DISTANCES FOR DIFFERENT TARGETS AND HEADLIGHT CONFIGURATIONS



a. With Opposing Glare Car

b. Without Opposing Glare Car

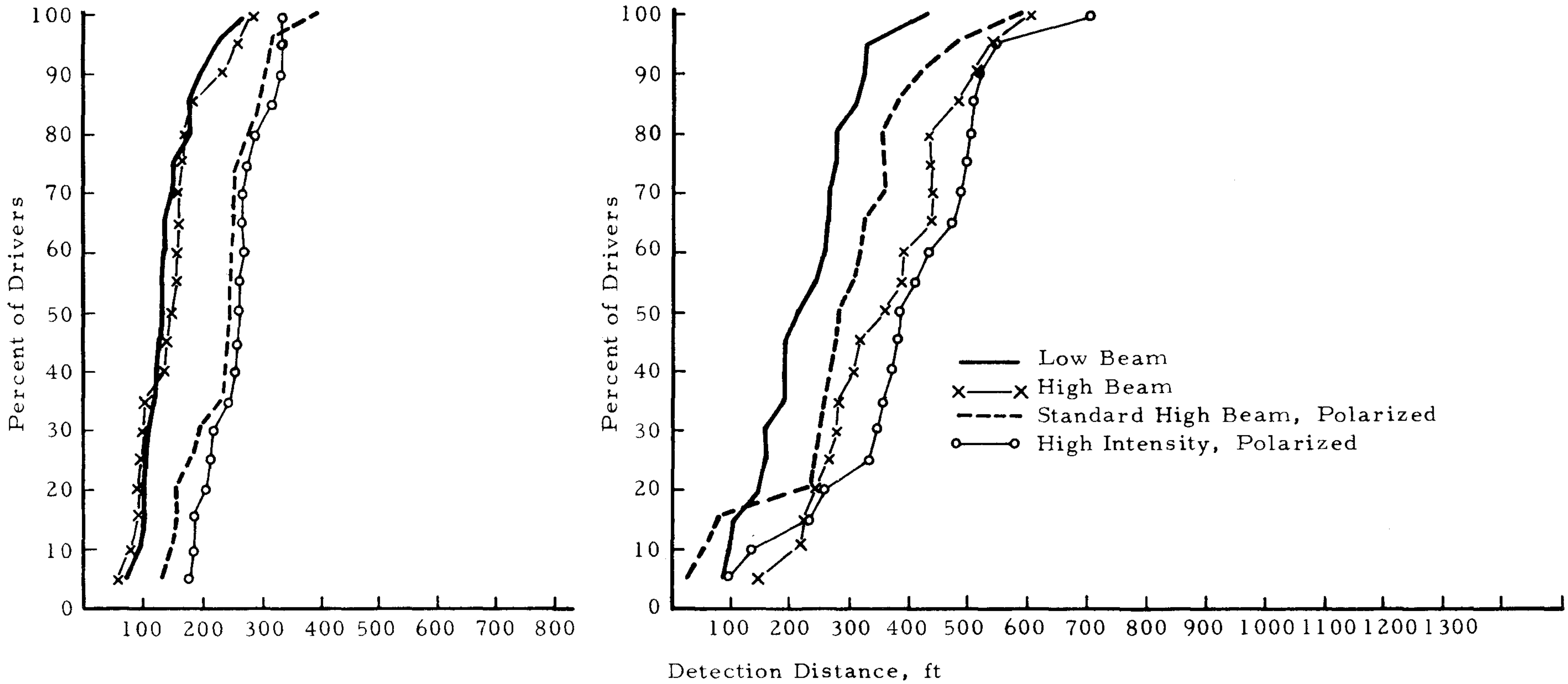
FIGURE 34. DISTRIBUTION OF DETECTION DISTANCES FOR ALL DRIVERS AND HEADLIGHT CONFIGURATIONS - SIGN TARGET



a. With Opposing Glare Car

b. Without Opposing Glare Car

FIGURE 35. DISTRIBUTION OF DETECTION DISTANCES FOR ALL DRIVERS AND HEADLIGHT CONFIGURATIONS - PEDESTRIAN TARGET



a. With Opposing Glare Car

b. Without Opposing Glare Car

FIGURE 36 DISTRIBUTION OF DETECTION DISTANCES FOR ALL DRIVERS AND HEADLIGHT CONFIGURATIONS - LINE TARGET sign target with two drivers with standard high beam, polarized headlights. In the unopposed, no glare car present, (∞) case however, the maximum detection distances are obtained, for the sign and pedestrian targets with standard, high beam, unpolarized headlights. In the case of the line target, the polarized high intensity headlights provide maximum detection.

Similar results relating to Discomfort Glare and Target Visibility are shown graphically in Figures 37 and 38. The major reduction in glare inherent in polarization is evident in all of the relationships plotted in Figure 37. Likewise, the improvement in target visibility with reduced sensation of glare is evident in Figure 38.

The tabulation of results of the analyses of variance in Experiment A7 is given in Table 5. In general, interactions are found to be significant when the ∞ runs are included, as previously noted. When the ∞ runs are deleted from the analysis, those interactions involving intercept distance become essentially nonsignificant.

The influence of lighting configuration on lateral deviation in steering of the subject car is plotted in Figure 39. In this analysis, as before, the most successful approach to date uses as a definitive score the total deviation in the sector of the subject car path immediately prior to the meeting point between the two cars. Minimum deviation occurs in the ∞ runs, when no glare car is present, as should be expected. There is a definite indication also that greater deviation occurs when the headlight glare becomes greater or visibility is reduced. This is more evident when the vehicles are closer together near the point of target detection; i.e., negative intercept distances (see Fig. 39).

It is evident that some modification of performance occurs during these experiments even with the limited exposure of the drivers in Experiment A7. In Figure 39c, the average deviation distances from the seven preliminary orientation runs for all of the drivers are shown with the mean values obtained for the three targets during the test runs. Although there is little difference in the ∞ results between the orientation and test runs, there is considerable reduction in deviation with experience in the case of the opposed glare runs.

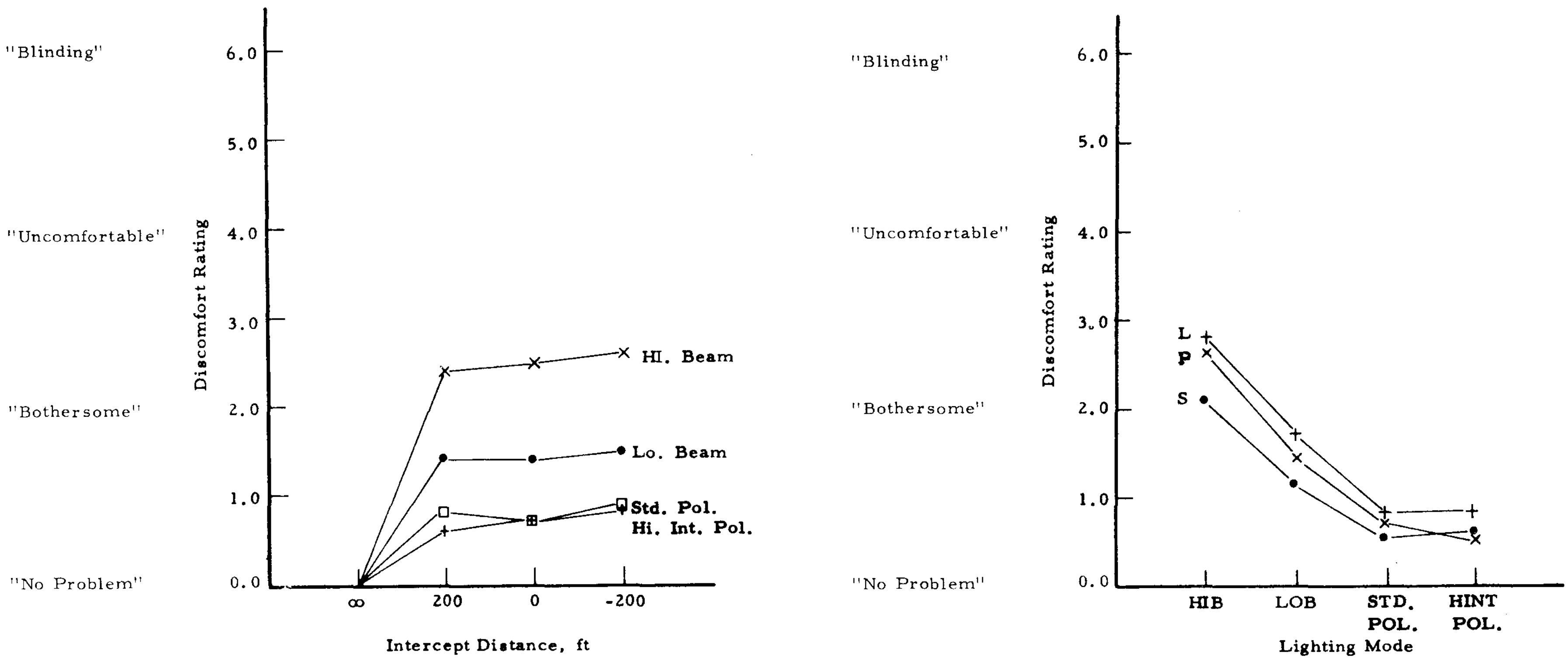


FIGURE 37. EXPERIMENT A7, DISCOMFORT GLARE RATING OF VARIOUS LIGHTING MODES

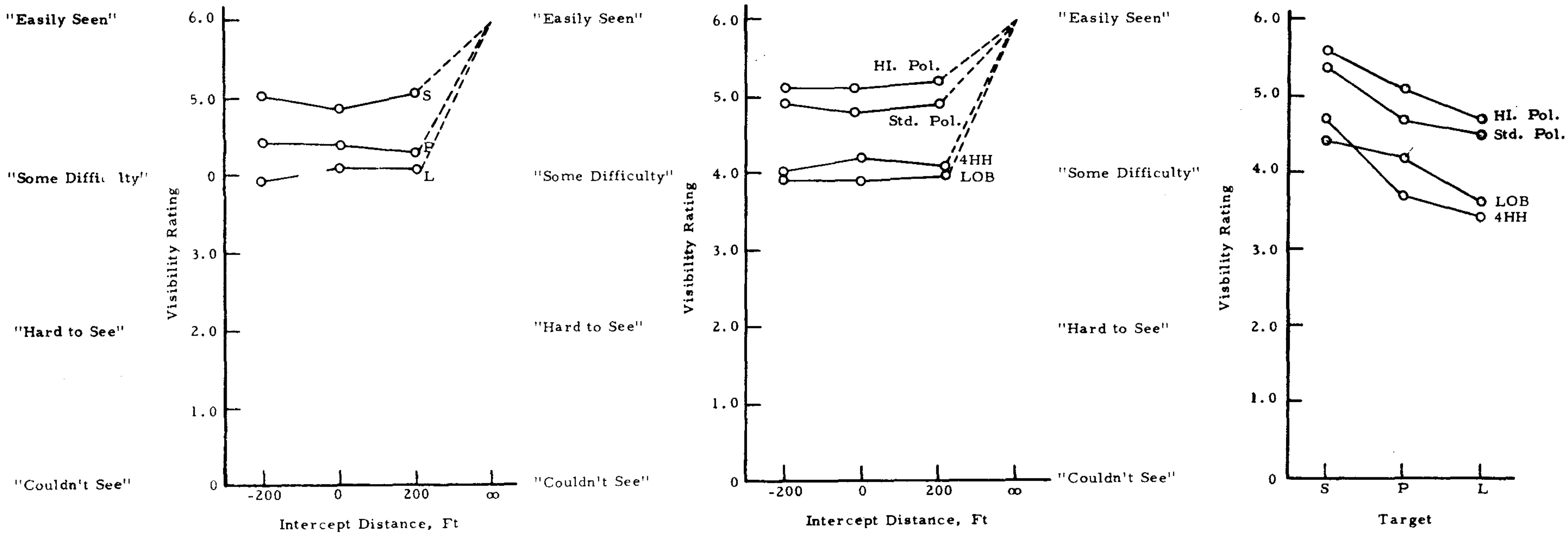


FIGURE 38. **EXPERIMENT A7, VISIBILITY RATING OF TARGETS WITH VARIOUS LIGHTING MODES**

TABLE 5. SUMMARY OF ANALYSIS OF VARIANCE OF EXPERIMENT A7

	Drivers (D)	Targets (T)	Lighting (L)	Intercepts (I)	D × T	D × L	D × I	T × L	T × I	L × I	D × T × L	D × T × I	D × L × I	T × L × I
Detection (With ∞ Runs)														
F-Ratio	17.0	906	230	140	3.17	3.15	1.81	17.1	6.34	19.7	1.37	1.26	--	2.87
Significance Level	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	5%	>5%	NS	1%
(Less ∞ Runs)														
F-Ratio	14.0	1119	308	1.17	4.07	3.68	--	26.3	1.36	1.52	2.22	1.14	1.20	1.61
Significance Level	1%	1%	1%	>5%	1%	1%	NS	1%	>5%	>5%	1%	>5%	>5%	>5%
Glare Rating														
F-Ratio	20.7	28.4	301	2.52	1.90	9.40	--	3.20	--	--	1.45	1.73	1.28	1.36
Significance Level	1%	1%	1%	>5%	1%	1%	NS	1%	NS	NS	1%	1%	>5%	>5%
Target Visibility														
F-Ratio	22.2	96.3	103.0	--	3.24	4.17	--	3.11	--	--	1.35	--	--	--
Significance Level	1%	1%	1%	NS	1%	1%	NS	1%	NS	NS	5%	NS	NS	NS
Total Deviation (With ∞ Runs)														
F-Ratio	11.7	21.6	8.33	27.3	1.99	1.44	--	--	--	--	--	--	--	--
Significance Level	1%	1%	1%	1%	1%	5%	>5%	>5%	>5%	NS	>5%	>5%	NS	NS
Total Deviation (Less ∞ Runs)														
F-Ratio	9.11	15.4	5.21	--	1.79	1.67	--	--	--	--	--	--	--	--
Significance Level	1%	1%	1%	NS	1%	1%	NS	NS	NS	NS	NS	NS	NS	NS

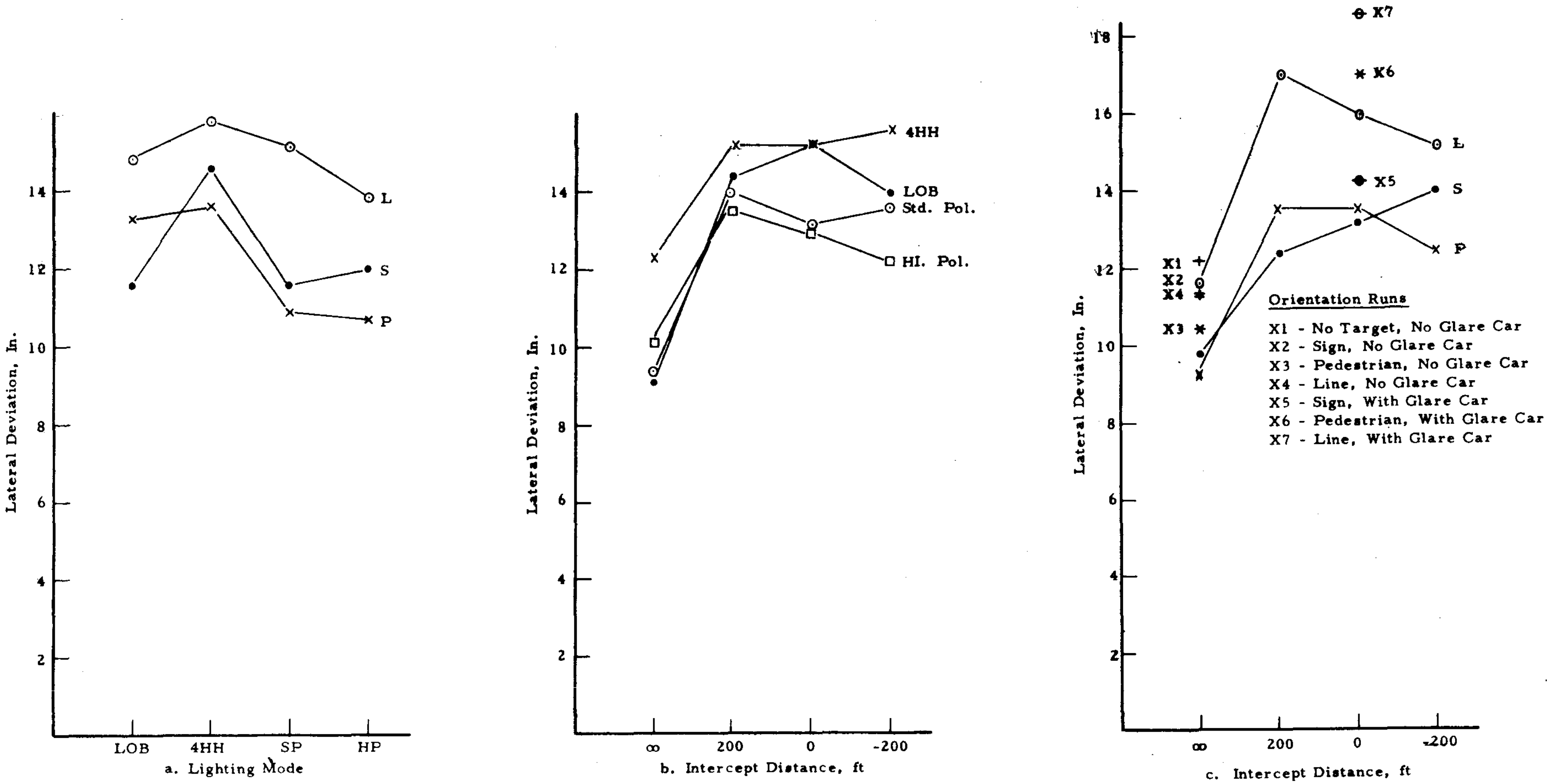


FIGURE 39. EXPERIMENT A7, MAXIMUM DEVIATION AMPLITUDE

VI. SUMMARY OF FINDINGS

Although there is a wide variation in performance among drivers in their responses to opposing headlight glare, a number of conclusions have been confirmed by these studies. **For the most part, the findings reaffirm those determined by other investigators in situations involving less realistic simulation of highway nighttime meeting encounters.**

Specifically:

(1) Detection distances, with normal headlighting, were greater when both vehicles were on high beam than when both were on low beam, even though discomfort and disability glare were greater in the high beam case. It is of interest that the accepted vehicle stopping distance of 291 feet at 55 mph exceeds by 22 feet, the mean detection distance determined for the pedestrian target and the stopping distance of 532 feet at 70 mph exceeds by 41 feet the mean detection distance for the unreflectorized, white on black, sign target in high beam, opposing traffic.

(2) Detection distances for side-of-the-road objects such as signs or pedestrians are reduced, on average, 53.2%, from mean distances of 830 feet to 380 feet, when opposing high beam headlights are encountered by both drivers within 1000 feet of the object.

(3) Detection distances for center-of-the-road "no-passing" lines are reduced 59%, from 365 feet to 150 feet, by the presence of opposing high beam headlights.

(4) Detection distance was not significantly changed by the relative position of the glare car within a range of 1000 feet or more at the instant the target was detected.

(5) Lateral separation of opposing vehicles on the highway will reduce disability glare of the opposing high beam headlights by 74.9% on a three-lane road and 90.7% on the outside lanes of a four-lane road over that encountered on two-lane roads (12-foot lane width). Furthermore, the peak glare will occur at greater distances between the vehicles as lateral separation is increased with a reduction in glare as the vehicles approach more closely.

(6) When approaching a roadside object, at least within the range of 30 to 55 mph, vehicle speeds do not appreciably affect the distance at which it is initially detected. However, distance travelled in initiating a vehicle maneuver, engendered by the driver's sighting of an object, is a function of vehicle speed because of his characteristic reaction time.

(7) The presence of an opposing vehicle on the highway causes a driver to steer toward the road edge to provide an optimum balance between the psychological pressures for maximum clearance between the two vehicles as they pass and running off the edge of the road. This tension begins to develop at 5 to 7 seconds before the meeting point and increases until the vehicles pass. The amount of lateral displacement occurring during the meeting encounter increases with increasing glare intensity, particularly in the two-lane road case.

(8) Meeting a queue of closely following vehicles will reduce detection distances of roadside objects more than a single vehicle because of the greater length of time that glare is present as well as an increase of 20% in glare intensity. Under certain vehicle/road/target conditions, silhouette lighting of an object may occur more frequently with vehicles in a queue than with single vehicles, with consequent greater target detection distances.

(9) Detection distances are reduced by the presence of road film, dust, insect debris, or other dirt on the windshield interposing an illuminated screen between the driver and the vision target. Although some depolarization occurs when opposing polarized light strikes such windshield dirt, the deterioration in detection distance is less than that observed with normal headlights.

(10) Polarization of standard headlights on both vehicles increased detection distances over those observed with unpolarized headlighting for all meeting encounters. When polarized, high-intensity (100 watt) headlights were fitted, detection distances for all targets were increased over those obtained with unpolarized, standard headlights, in the unopposed driving environment when no analyzer was employed.

(11) The polarizing analyzer is an effective (60%) filter of light from opposing, unpolarized headlights, which may effectively reduce disability glare from such a source and still allow improved detection distance when the observer's vehicle is equipped with polarized headlights. Further investigation of this lighting configuration will be conducted.

(12) Headlamp current requirement, in the four lamp, 5-3/4-inch-diameter headlight system is increased from 12.56 to 22.60 amperes when the present standard system is replaced by the high-intensity system utilizing 100-watt lamps in the No. 1 (#4001 type) positions. No difficulty was experienced in maintaining voltage at the standard 12.8 volts at the headlamps utilizing the standard 40-ampere alternators with which the test vehicles were equipped.

VII. CONCLUSIONS

It is concluded from the above that virtually all of the major technical and operational objections, formerly raised, to the adoption of polarized headlights for motor vehicles have been largely overcome by headlamp and vehicle evolution. Moreover, the benefits of such polarized headlights in single vehicle encounters on rural highways is clearly demonstrated. Further research is needed on multiple vehicle encounters, fatigue problems, side effects in urban areas and other problems which may be encountered by the general public under actual conditions of use. Of most importance, it now appears that the need for nationwide simultaneous conversion of all vehicles to polarized lighting may not be essential to its adoption. Further research in this area is to be conducted. It may be possible to initiate the conversion on a mandatory basis for newly manufactured vehicles only and to permit those already in the hands of the public to be modified on a voluntary basis. Even the fitting of the analyzer alone on a vehicle will allow its driver to obtain the advantage of eliminating the glare from opposing vehicles equipped with polarized headlights and reducing the glare from opposing, unpolarized headlights although with some reduction in detection distance in the latter instance. Ultimately, when the majority of vehicles are equipped with polarized headlights, consideration can be given to elimination of low beam lamps and dimmer switches and modification of the headlights to obtain broader beam coverage and the higher illumination intensities required for safe seeing at increased highway speeds.

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APPENDIX A

INSTRUMENT SYSTEM

The purpose of the instrumentation system was to provide measurement of:

(1) The distances between the subject car and the glare car and between the subject car and the visibility test target,

(2) The lateral displacement of the subject car from the desired straight-line path,

(3) The onset and termination of the target invisibility region, and

(4) Light intensity at the subject car from the glare car.

The system uses a combination of mechanical and electronic techniques to obtain an optimum combination of the following characteristics:

(1) Accuracy,

(2) Ease of data reduction,

(3) Simplicity of installation and use,

(4) Minimum track preparation both initially and prior to each series of tests,

(5) Reliability, and

(6) Low system cost.

Basic System

Figure A. 1 shows a basic layout of the test track and the distance involved in the required measurements. The desired measurements are the distances d_2, d_5, and d_7. In this system, the desired measurements are determined indirectly (except for the lateral displacement, d_7) through prior knowledge of the geometry and measurement of the distance traveled from the starting points by each of the two cars. From these measurements and information on the track distances, d_3 and d_6, the required distances can be determined from the following simple relations:

$$d_2 = d_3 - d_1 \tag{1}$$

$$d_5 = d_6 - (d_1 + d_4) \tag{2}$$

The distances d_1 and d_4 are measured by the use of an odometer wheel with a pickup to generate an electrical pulse once for each foot of travel. By counting the pulses, the distance traveled is determined. Figure A. 2 shows the basic system which provides the measurements and performs the

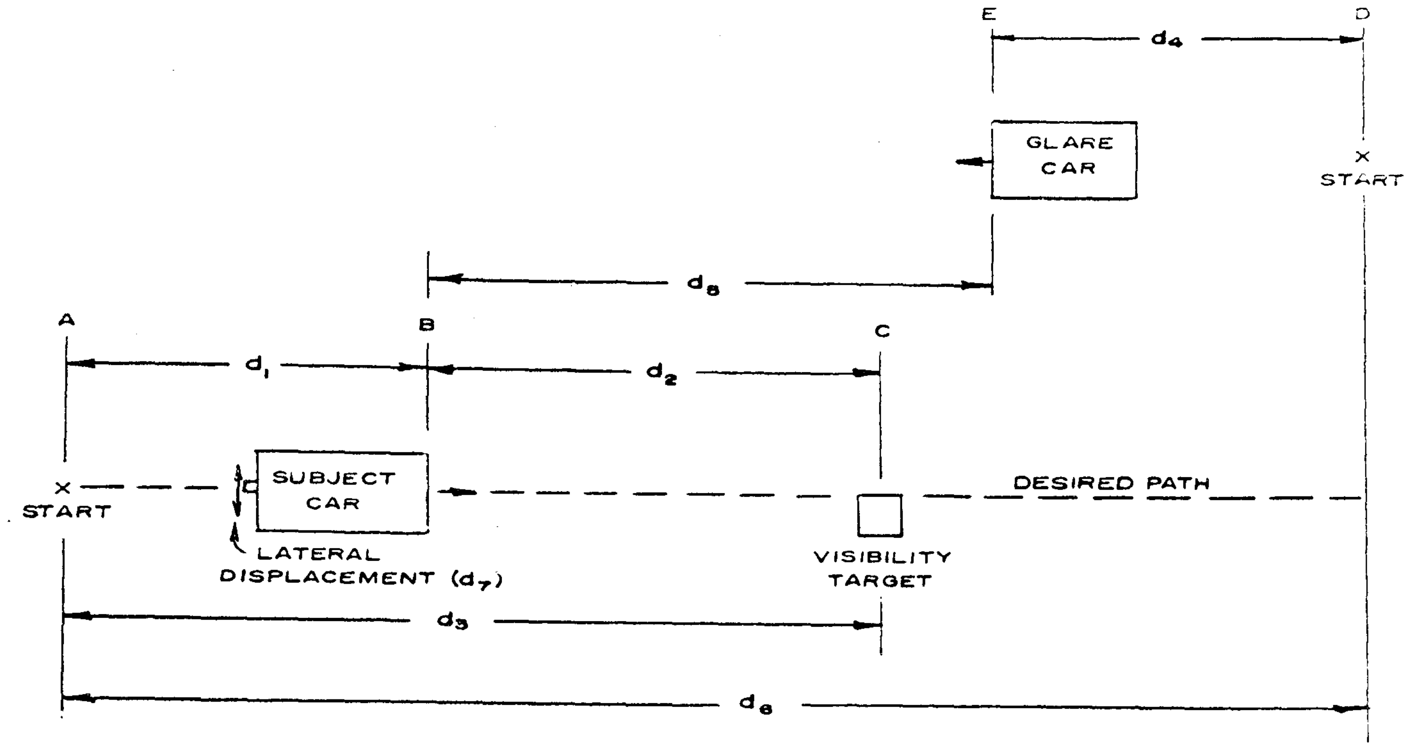


FIGURE A.1. DISTANCE RELATIONS

necessary mathematical operations to produce a digital printout of the desired distances, as well as an indication of the target visibility of the driver.

The system uses a radio frequency transmitter in both the glare car and the subject car to telemeter the pulses from the odometer wheel to a data recording station. The output from the transmitter in the subject car is picked up by a receiver which produces an output in the form of a pulse for each foot of travel of the odometer wheel. These pulses go to a backward counter (number 1) which, at the start of the test, is preset with the distance between the starting point and the visibility test target. Each odometer pulse reduces the counter reading by 1 foot. Thus, the counter reading at any instant is a measure of the distance from the subject car to the target. Similarly, the output from the transmitter in the glare car is picked up and demodulated by receiver 1. The odometer pulse outputs from both receivers 1 and 2 are connected to an anticoincidence circuit (which prevents the loss of a pulse when both odometer pulses occur simultaneously) in backward counter 2 which is preset at the start of each test run with the distance between the starting points for the two cars. Each odometer pulse from both cars reduces the reading of this counter by 1 foot with the result that the counter reading is a continuous indication of the distance between the two cars. The outputs of both counters are connected to a digital printer.

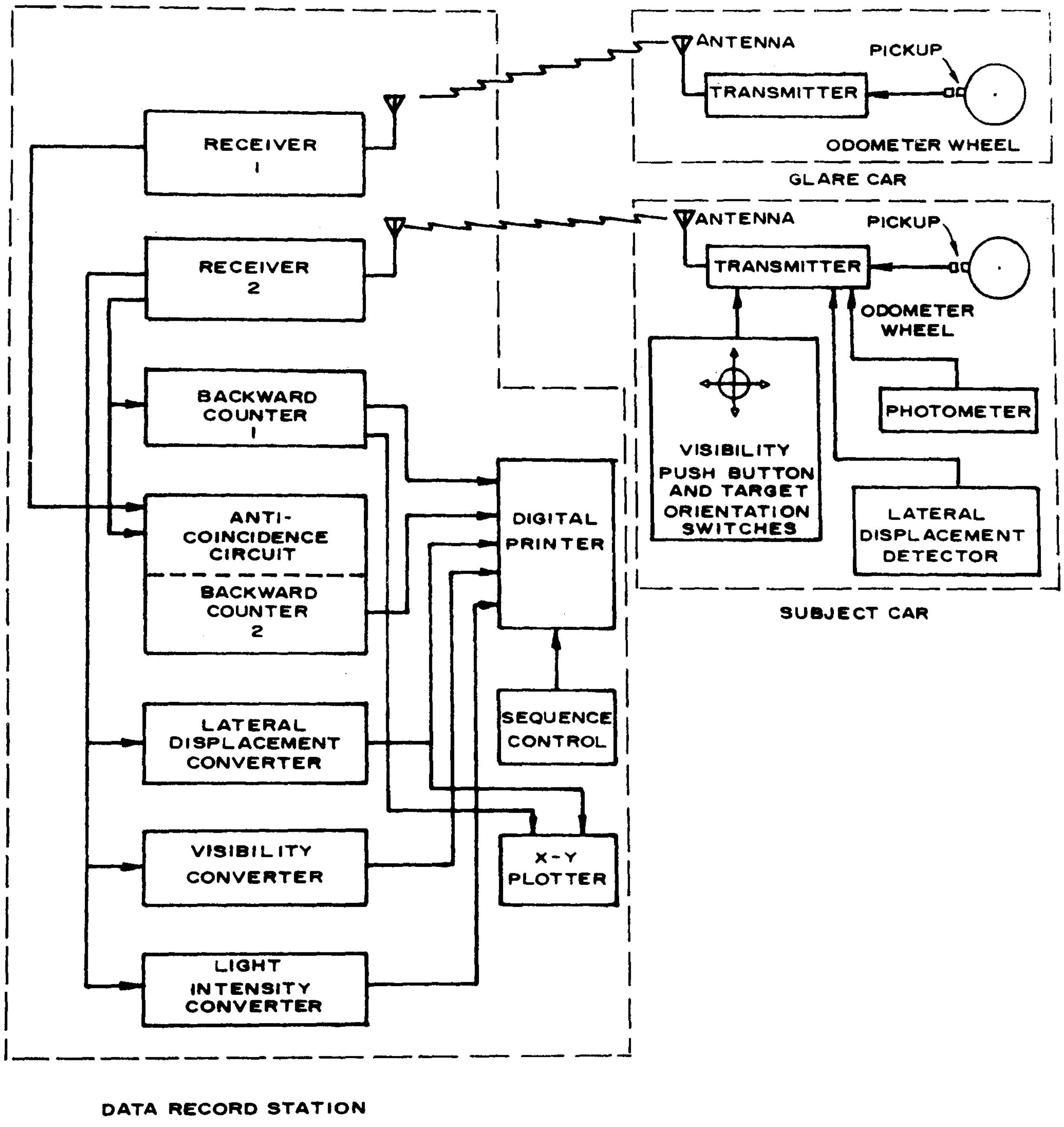


FIGURE A.2. INSTRUMENTATION SYSTEM

The transmitter in the subject car also telemeters the lateral displacement of the subject car from the desired straight-line path, the relative light intensity from the glare car as measured by a photometer, and through a push button and four-way switch actuated by the driver, information as to the visibility of the target. The lateral displacement detector senses the deviation from a straight-line path by use of a probe mounted on the subject car, 71 inches long, supported 15 inches above roadway surface. This probe detects an electromagnetic field produced by a current flowing through a wire laid on the roadway. The wire is small and of such a color and installation that it is not visible to the driver. This is considered to be a desirable feature since previous experience with an optical system using a series of photoelectric cells to sense a painted line caused a bias in the data by unintentionally providing the driver a marked course. A resolution on the order of 1 inch is possible with this approach.

A Pritchard photometer is installed in the subject vehicle at eye level of the driver and as close to him as possible without interfering with his driving. This photometer can be set up to measure various light levels, both absolute and through filters approximating the sensitivity of the eye. In addition, polarizing filters are available, and other filters and lens configurations may be utilized for specific tests. The photometer is adjusted to a range suitable for the light intensity of a particular series of runs, and the output is telemetered back as a percentage of full scale. The accuracy of the telemetry and data system is within 1%, which is comparable with the accuracy of the photometer operated in a test vehicle. The telemetered information on the lateral displacement, light intensity, and the target visibility appear at the output of receiver 2 and are connected to electronic converter circuits, to drive the digital printer, and an x-y plotter.

Several data recording methods could be used, but the digital printer approach has the advantage of producing a record which greatly reduces the time required for data analysis. The printer prints out the input information at a rate of five times per second. An eleven-column printer is used, with three columns for each of the distances d_2 and d_5 (resolution 1 foot), two for the lateral displacements (resolution 1 inch), two for light intensity, and one for an indication of target visibility and orientation. The record thus produced may be readily scanned and the distances read off directly in feet at the points where the target becomes invisible, and again when it becomes visible. With the highest vehicle speeds and the five lines per second printout speed, the resolution is better than 20 feet for the subject car to the target distance and better than 40 feet for the distance between the two cars. The exact distances at the onset and termination of the target invisibility region can be quickly demonstrated from a typical printout record tape as shown in Figure A. 3.

In addition to the digital printout, the path of the subject car is traced on calibrated graph paper. The digital distance signal generated by the subject car is converted to an equivalent analog signal and applied to the

(1) Subject car to target distance

(2) Intercar distance

(5) Subject car passes target

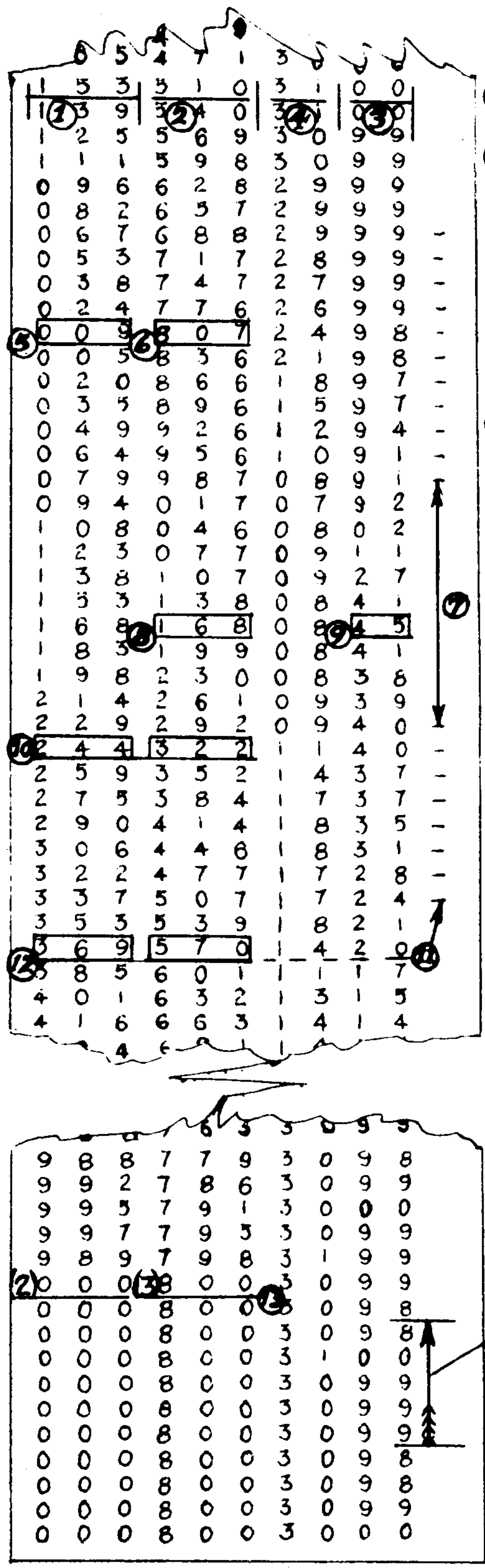
(6) Intercar distance

(8) Distance at maximum glare (9)

(10) Distances at identification of target

(12) Distances at detection time (11) (Reaction time of 0.4 sec; 2 lines; included)

(13) Initial Starting Points 2000 ft from target and 3800-ft intercar distance (Thousands digit is not recorded)



(3) Photometer Reading % full scale

(4) Lateral deviation 0 to 60 in., 30 in. = center

(7) Number of target marks skipped controlled by actuation of target orientation switch

2 or 3 = left
4 or 5 = down
6 or 7 = right
8 or 9 = up

(11) Start of target mark indicates detection of target

Time 1 sec

FIGURE A. 3. DATA TAPE

x-input of an x-y plotter, while the lateral deviation signal is applied to the y-input. A plot of the path of the vehicle is produced in real time, allowing the engineer to immediately evaluate the effects of the test on the steering accuracy of the driver of the subject car, and also determine if the subject car stayed within the desired limits of lateral motion to produce valid test data. Several runs can be traced on each chart by moving the y-reference each time and limiting the width of the total lateral movement to a reasonable fraction of the chart width.

The readout instrumentation is located in a small control trailer located near the target intercept point for the subject car. The use of a control trailer serves a number of purposes, but mainly it will remove the data processing and printout equipment from the deteriorating effect of the vehicle vibration and will place the recorded data directly under the surveillance of the engineer. The engineer is able to make slight corrections in dispatching times to insure obtaining the correct intercept distances by viewing the printout of the exact intercept distance obtained on the last run.

The control trailer is equipped with a portable generator set to provide the necessary power for lights, hearing, and instrumentation.

Radio control to the drivers is established on two separate channels. The use of two channels prevents the "cueing" of the subject driver as to the intercept distance to be used and permits dispatching of the glare car driver to change the target location and/or orientation on his return to the starting position.

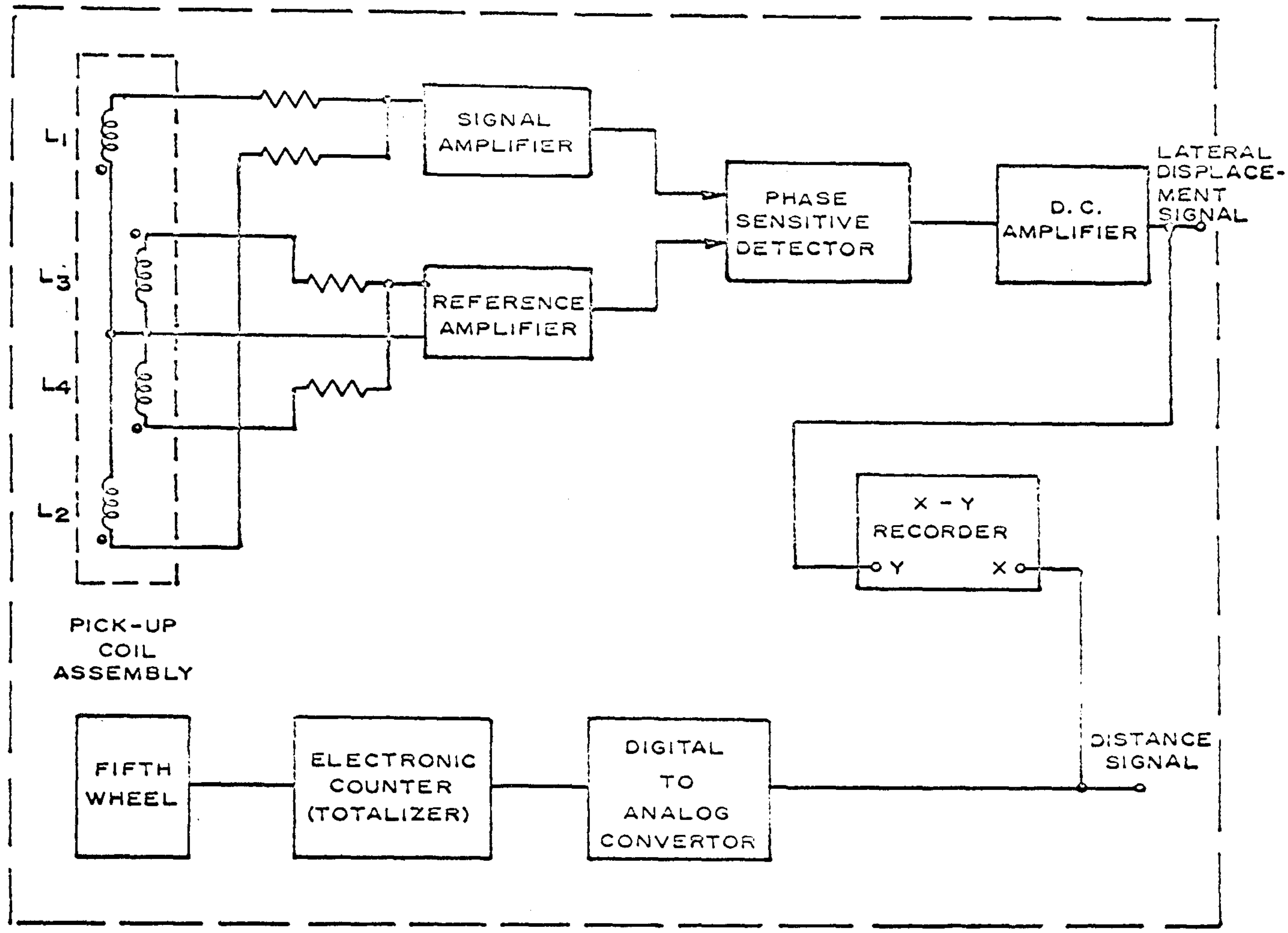
APPENDIX B

LATERAL DISPLACEMENT DETECTION SYSTEM

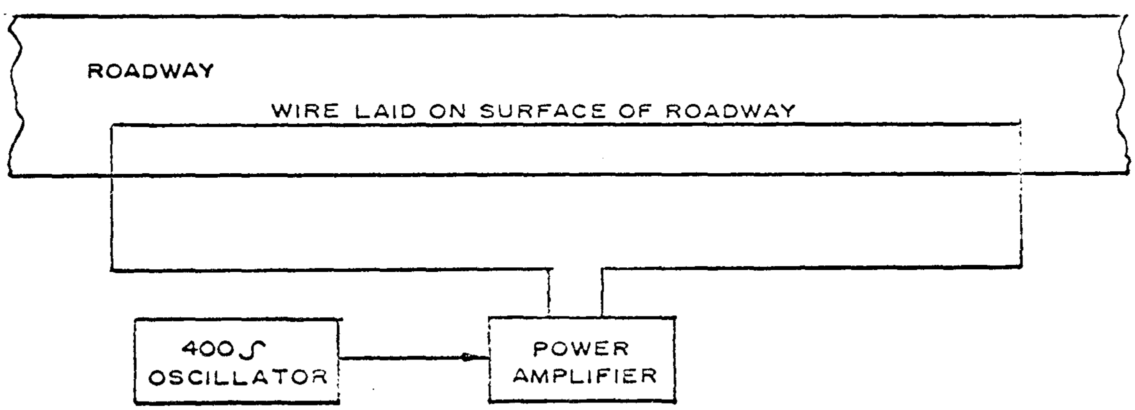
The lateral displacement detection system provided a signal which indicated the position of an automobile relative to a reference line along a roadway. The reference line for this system was a wire laid along the surface of the roadway which was sufficiently small and of such a color that it was not visible to the driver of the vehicle. An AC current flowing through the wire provided a signal which was detected by vehicle mounted equipment and used to provide lateral displacement information. The distance travelled by the vehicle was detected by counting the pulses produced by a fifth wheel. By making use of both the distance and lateral displacement information, an x-y plot of the vehicle position was produced.

Figure B.1 shows a block diagram of the system adapted for producing a recording in the automobile. The wire laid on the roadway surface along the desired path carried a current of 1.5 amperes produced by an audio power amplifier which was driven by a 400-Hz oscillator. The audio power required depends on the wire resistance and is determined by the length of the wire loop and the size of the wire. In this system, the 18-gauge wire used on the roadway was 2000 feet long. The nominal resistance of this wire plus the 16-gauge wire used to complete the return path (off the roadway) totaled 16 ohms. The power required from the audio amplifier to furnish the desired current through this resistance was thus 36 watts and the voltage across the ends of the loop under these conditions was 24 volts.

A block diagram of the system mounted on the vehicle is shown in Figure B.1a. The heart of the lateral displacement detection system is the pickup coil assembly composed of a number of coils (Potter and Brumfield 10,000-ohm relay coils) mounted in a plastic tube approximately six feet long and 2-1/2 inches in diameter. This assembly was attached to the front bumper of the vehicle to place it parallel to and 15 inches above the roadway. It was also spaced approximately 15 inches in front of the bumper to minimize the effect of the metal of the vehicle on the linearity and sensitivity of the system. The simplified diagram of the pickup coil assembly shown in Figure B.1a shows four coils which were connected to provide two output signals. Coils L_1 and L_2 were mounted about 30 inches equidistant from the center of the assembly and connected through summing resistors to the signal amplifier. These coils were oriented parallel to the axis of the tube and connected to the amplifier in such a manner that the signal induced in L_1 from the current through the wire on the roadway is of the opposite phase as that in L_2. The voltage across each coil is maximum when the coil is located directly above the roadway wire and the sum of the two is such that a null is produced when the coils are located equidistant on each side of the wire. Figure B.2a shows the magnitude and shape of the sum of L_1 and L_2 (the "Signal" curve) voltages. The phase of the voltage in region A of this curve is opposite that in region B which, when phase sensitive detection is used, results in a lateral displacement signal of the form shown in Figure B.2b. This curve shows the output voltage to be a linear function of displacement over a range of nearly ±30 inches each side of the reference wire. With the simple two coil system it was not possible to achieve perfect linearity over this large a range and an

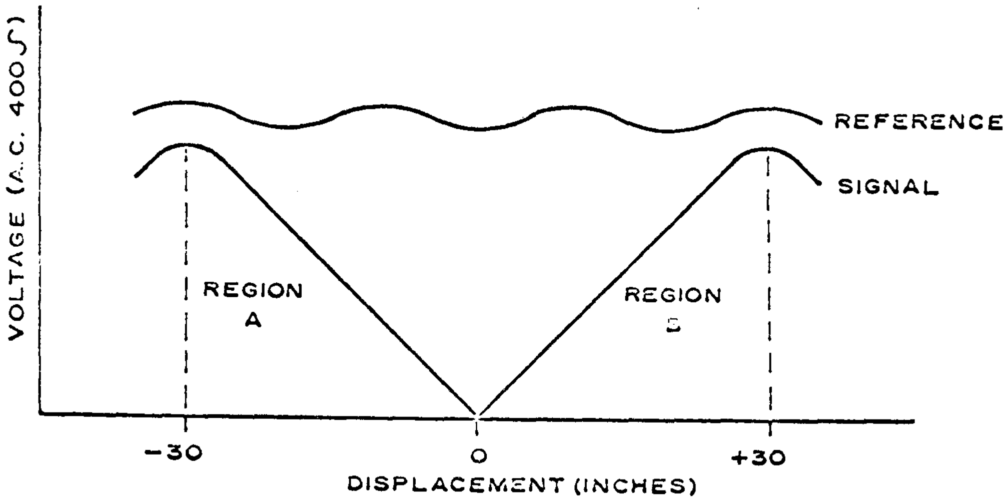


(a) AUTOMOBILE EQUIPMENT

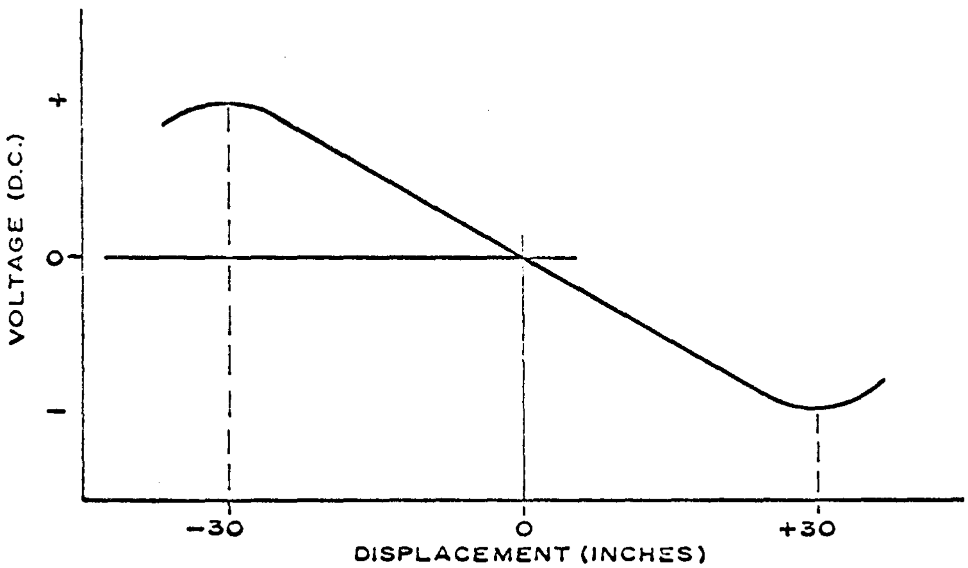


(b) FIXED EQUIPMENT

FIGURE B.1. LATERAL DISPLACEMENT DETECTION SYSTEM



(a) COIL SIGNALS



(b) LATERAL DISPLACEMENT SIGNALS

FIGURE B.2. SYSTEM SIGNALS

additional set of coils (not shown) were located approximately 12 inches each side of the center line to furnish small correcting voltages which were summed with the outputs of L_1 and L_2 to obtain the desired curve.

In order that phase sensitive detection can be used,it is necessary that a phase coherent reference signal be available. This was obtained by using an additional set of coils (represented by L_3 and L_4) in the pickup coil assembly. These coils were oriented in a similar manner to L_1 and L_2 and connected to be additive to produce a relatively uniform output voltage of constant phase for a range of at least ±30 inches each side of the center line as shown by the "reference" curve of Figure B.2a.

The output from the coil assemblies is of the order of a few tens of millivolts and must be amplified prior to the phase sensitive detection. This was accomplished by the transistorized signal and reference amplifiers. The solid state phase sensitive detector produces a DC output which is a function of the vehicle lateral position relative to the wire on the roadway as shown in Figure B.2b. A solid state DC operational amplifier increased the level of this signal. The output of the DC amplifier was connected to a voltage controlled oscillator which modulates the telemetry transmitter; but, for recording in the vehicle, this output may be directly connected to the "Y" input of an x-y recorder.

The distance travelled by the vehicle was detected by the fifth wheel which produced one contact closure for each foot of distance. These contact closures frequency modulate the telemetry transmitter. The trailer mounted receiver detects this modulation and generates a pulse for each contact closure. These pulses are totalized on an electronic counter and the result printed out at a rate of five times per second on the numerical printer. The counter output also goes through a digital-to-analog convertor to provide a voltage proportional to distance travelled. This voltage can be used to provide the "X" input to an x-y recorder. For use with direct recording in the vehicle, the fifth wheel can be directly connected to the electronic counter and the counter output can go through the digital to analog convertor to the recorder "X" axis.

Power to operate the vehicle mounted equipment must be furnished. The most versatile arrangement is to provide 115 v 60-Hz power to allow normal laboratory recorders, counters and other equipment to be utilized. This installation used a solid state 12-vDC to 115-vAC invertor for this purpose.

APPENDIX C

DATA ANALYSES

A. Analyses of Variance on Detection Distance

1. Experiment A1--Overall

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	4	1657584.0	414396.0	213.2	1
Targets	(T)	2	5810239.8	2905119.9	1495.0	1
Lanes	(S)	2	302015.7	151007.8	77.5	1
Intercept	(I)	5	959778.1	191955.6	98.8	1
D × T		8	347783.7	43472.9	22.4	1
D × S		8	28416.3	3552.0	1.82	-
D × I		20	177881.1	8894.0	4.57	1
T × S		4	58625.7	14656.4	7.53	1
T × I		10	394985.7	39498.6	20.3	1
S × I		10	125853.6	12585.4	6.47	1
D × T × S		16	57567.1	3597.9	1.80	5
D × T × I		40	160207.9	4005.2	2.06	-
D × S × I		40	89016.9	2225.4	-	-
T × S × I		20	55924.1	2796.2	-	-
Residual		80	155601.3	1945.0		
Total		269	10381481.0			

2. Experiment A1--Less ∞ Cases

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	4	2214329.6	553582.4	129.0	1
Targets	(T)	2	8004797.8	4002398.9	938.0	1
Lanes	(S)	2	724765.0	362382.5	84.3	1
Intercepts	(I)	4	14595.1	3648.8	-	NS
D × T		8	437997.7	54749.7	12.8	1
D × S		8	68212.1	8526.5	1.99	-
D × I		16	139943.0	8746.4	2.04	5
T × S		4	140758.1	35189.5	8.21	1
T × I		8	102427.7	12803.5	2.99	1
S × I		8	130537.3	16317.2	3.81	1
D × T × S		16	138178.2	8636.1	2.01	5
D × T × I		32	146210.5	4569.0	-	-
D × S × I		32	166693.1	5209.2	-	-
T × S × I		16	88279.7	5517.5	-	-
D × T × S × I		64	287927.9	4498.9	-	-
Within Repl		225	965168.0	4289.6		
Total		449	13770820.9			

3. Experiment A1--Identification Distance (Sign Target Only)

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	4	1824477.8	456119.5	77.2	1
Lanes	(S)	2	108086.3	54043.1	9.14	1
Intercepts	(I)	4	3384.5	846.1	-	-
D × S		8	63895.6	7987.0	1.35	-
D × I		16	77624.4	4851.5	-	-
S × I		8	72499.7	9062.5	1.53	-
D × S × I		32	140826.7	4400.8	-	-
Within Repl		75	443242.0	5909.9		
Total		149	2734037.0			

4. Experiment A2--Headlight Variation

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	3	711380.3	237126.8	18.7	1
Targets	(T)	2	3806557.6	1903278.8	149.9	1
Intercepts	(I)	1	2519000.3	2519000.3	198.3	1
Headlights	(H)	3	101576.4	33858.8	2.67	5
D × T		6	150023.0	25003.8	-	-
D × I		3	57604.5	19201.5	-	-
D × H		9	118472.9	13163.6	-	-
T × I		2	327794.0	163897.0	12.9	1
T × H		6	261521.6	43586.9	3.43	1
H × I		3	200727.8	66909.2	5.27	1
D × T × I		6	56182.6	9363.8	-	-
D × T × H		18	239905.6	13328.1	-	-
D × I × H		9	299899.0	33322.1	2.62	1
T × H × I		6	97827.3	16304.5	-	-
D × T × H × I		18	169510.9	9417.3	-	-
Within Repl		96	1219225.0	12700.3		
Total		191	10337209.0			

5. Experiment A1/A3--Dirty Windshield--Variable Is Detection Distance

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Windshield	(W)	1	5176	5176	1.16	NS
Driver	(D)	1	186507	186507	41.6	1
Intercept	(I)	3	923110	307703	68.7	1
W × D		1	32832	32832	7.3	1
W × I		3	32500	10833	2.42	NS
D × I		3	43124	14374	3.21	5
W × D × I		3	4600	1533	-	NS
Within Repl		16	71692	4480		
Total		31	1299543			

6. Experiment A6C/A8--Dirty Windshield--Variable Is Detection Distance

Source of Variation		Deg of Free.	Deg of Squares	Mean Squares	F Ratio	Signif Level < %
Windshield	(W)	1	32640	32640	-	NS
Driver	(D)	2	535046	267523	7.11	5
Intercept	(I)	2	181086	90543	2.41	NS
W × D		2	115267	57633	1.53	NS
W × I		2	23025	11512	-	NS
D × I		4	222827	55706	1.48	NS
W × L × I		4	84399	21099	-	NS
Within Repl		18	676635	37590		
Total		35	1870928			

7. Experiment A1/A3 and A6C/A8--Dirty Windshield--Variable Is Detection Distance

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Windshield	(W)	1	6165	6165	1.51	NS
Lighting	(L)	1	16576	16576	4.07	NS
Intercept	(I)	2	153326	76663	18.83	5
W × L		1	192	192	-	NS
W × I		2	2444	1222	-	NS
L × I		2	30012	15006	3.69	NS
Within Repl		2	8138	4069		
Total		11	216855			

8. Experiment A4--Speed Variation

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Speed	(M)	1	16512.3	16512.3	6.08	5
Drivers	(D)	3	364048.8	121349.6	44.6	1
Intercepts	(I)	3	1015127.3	338375.8	124.6	1
M × D		3	24064.6	8021.5	2.95	5
M × I		3	17986.1	5995.4	-	-
D × I		9	58960.8	6551.2	2.41	5
M × D × I		9	41912.0	4656.9	1.71	-
Within Repl		32	86901.0	2715.7		
Total		63	1625512.9			

9. Experiment A6--Overall Polarized Headlights

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	1	1479466.8	1479466.8	109.6	1
Targets	(T)	2	1626014.7	813007.3	60.0	1
Intercepts	(I)	3	147605.4	49201.8	3.64	5
Polarization	(L)	2	1141082.0	570541.0	42.2	1
D × T		2	9392.1	4696.0	-	-
D × I		3	25774.0	8591.3	-	-
D × L		2	301568.2	150784.1	11.1	1
T × I		6	25030.1	4171.7	-	-
T × L		4	160931.0	40232.8	2.96	5
I × L		6	148725.0	24787.5	-	-
D × T × I		6	57980.4	9663.4	-	-
D × T × L		4	39660.3	9915.1	-	-
D × I × L		6	61465.0	10244.2	-	-
T × I × L		12	114253.5	9521.1	-	-
D × T × I × L		12	208786.2	17398.8	-	-
Within Repl		72	976386.0	13560.9		
Total		143				

10. Experiment A6--Polarized Standard Headlights

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	3	1555230.1	518410.0	78.3	1
Targets	(T)	2	4445449.9	2222725.0	337.0	1
Intercepts	(I)	5	60926.3	12185.3	-	-
Polarization	(L)	1	131217.2	131217.2	19.9	1
D × T		6	305283.0	50880.5	7.69	1
D × I		15	87088.5	5805.9	-	-
D × L		3	257974.6	85991.5	13.0	1
T × I		10	13072.8	1307.3	-	-
T × L		2	212794.2	136397.1	20.6	1
I × L		5	26429.3	5285.9	-	-
D × T × I		30	119434.5	3981.1	-	-
D × T × L		6	78082.0	13013.7	-	-
D × I × L		15	88755.3	5917.0	-	-
T × I × L		10	39629.6	3962.9	-	-
D × T × I × L		30	109450.1	3648.3	-	-
Within Repl		288	1904123.3	6611.5		
Total		431	9494941.0			

11. Experiment A1/A6 A & B--Combined

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	2	1253340.2	626670.1	105.5	1
Targets	(T)	2	4497831.4	2248915.7	379.4	1
Intercepts	(I)	5	523764.0	104752.8	17.7	1
Lighting	(L)	2	32275.0	16137.5	-	-
D × T		4	138818.3	34704.6	5.85	1
D × I		10	4436.7	4433.7	-	-
D × L		4	195535.3	48883.8	8.23	1
T × I		10	72282.8	7228.3	-	-
T × L		4	259165.5	64791.4	10.9	1
I × L		10	553879.8	55387.9	9.33	1
D × T × I		20	62349.4	3117.5	-	-
D × T × L		8	128161.0	16020.1	2.70	1
D × I × L		20	120480.5	6024.0	-	-
T × I × L		20	146658.6	7332.9	-	-
D × T × I × L		40	182294.6	4557.4	-	-
Within Repl		162	961704.5	5936.4		
Total		323	9172877.7			

12. Experiment A5--Platoon of Glare Vehicles

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	3	97633.6	32544.5	8.53	1
Targets	(T)	2	1298113.4	649056.7	170.3	1
Vehicles	(V)	1	82080.0	82080.0	21.5	1
D × T		6	41667.4	6944.6	-	NS
D × V		3	20689.0	6896.3	-	NS
T × V		2	11168.4	5584.2	-	NS
D × T × V		6	13350.7	2225.1	-	NS
Within Repl		48	182818.7	3808.7		
Total		71	1747521.3			

13. Experiment A7--20 Drivers Study (∞ Runs Included)

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	19	2800995	147421	17.0	1
Lighting	(L)	3	6002673	2000891	230.0	1
Targets	(T)	2	15731819	7865910	906.0	1
Intercept	(I)	3	3662335	1220778	140.6	1
D × L		57	1557093	27317	3.15	1
D × T		38	1046200	27532	3.17	1
D × I		57	893903	15683	1.81	1
L × T		6	892348	148725	17.1	1
L × I		9	1539022	171002	19.7	1
T × I		6	330210	55035	6.34	1
D × L × T		114	1356584	11900	1.37	1
D × L × I		171	1700465	9944	-	-
D × T × I		114	1251215	10976	1.26	5
L × T × I		18	449479	24971	2.87	1
Residual		342	2967899	8678		
Total		959	42182241			

14. Experiment A7--20 Drivers Study (Less ∞ Runs)

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	19	1399709	73669	14.0	1
Lighting	(L)	3	4856860	1618953	308.0	1
Targets	(T)	2	11783139	5891569	1119.0	1
Intercept	(I)	2	12338	6169	1.17	NS
D × L		57	1103099	19353	3.68	1
D × T		38	812386	21379	4.07	1
D × L		38	132694	3492	-	NS
L × T		6	828422	138070	26.3	1
L × I		6	48184	8031	1.52	NS
T × I		4	28541	.7135	1.35	NS
D × L × T		114	1330197	11668	2.22	1
D × L × I		114	720785	6323	1.20	NS
D × T × I		76	454051	5974	1.13	NS
L × T × I		12	101580	8465	1.61	NS
Residual		228	1199150	5259		
Total		719	24811137			

15. Experiment A7--20 Drivers Study--Variable Is Target Visibility Rating

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	19	253.7	13.45	22.2	1
Lighting	(L)	3	186.0	62.02	103.0	1
Targets	(T)	2	116.1	58.07	96.3	1
Intercept	(I)	2	0.5	0.24	-	NS
D × L		57	143.2	2.51	4.17	1
D × T		38	74.0	1.95	3.24	1
D × I		38	16.5	0.43	-	NS
L × T		6	11.2	1.87	3.11	1
L × I		6	3.2	0.53	-	NS
T × I		4	2.8	0.71	1.18	NS
D × L × T		114	92.8	0.81	1.35	5
D × L × I		114	69.4	0.61	1.01	NS
D × T × I		76	51.7	0.68	1.13	NS
L × T × I		12	5.3	0.44	-	NS
Residual		228	137.4	0.60		
Total		719				

16. Experiment A7--20 Drivers Study--Variable Is Glare Rating

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level < %
Drivers	(D)	19	172.1	9.06	20.7	1
Lighting	(L)	3	395.1	131.68	301.0	1
Targets	(T)	2	24.8	12.40	28.4	1
Intercept	(I)	2	2.2	1.12	2.52	NS
D × L		57	234.4	4.11	9.40	1
D × T		38	31.6	0.83	1.90	1
D × I		38	16.2	0.43	-	NS
L × T		6	8.4	1.40	3.20	1
L × I		6	1.4	0.23	-	NS
T × I		4	1.0	0.26	-	NS
D × L × T		114	72.3	0.63	1.45	1
D × L × I		114	64.0	0.56	1.28	NS
D × T × I		76	57.6	0.76	1.73	1
L × T × I		12	7.2	0.60	1.36	NS
Residual		228	99.8	0.44		
Total		719	1188.0			

17. Experiment A7--Mean Detection Distance and Standard Deviation (∞ Runs Included)

Source of Variation	Mean Det Dist	Std Dev, Ft
LO	277.7	134.99
4HH	378.5	233.85
POL STD	409.5	182.96
POL HI	499.1	212.13
S	545.4	195.52
P	396.3	169.29
L	232.0	126.61
-200	361.5	188.77
0	352.7	186.75
200	352.7	182.35
INF	498.0	239.60
LO × S	372.7	124.68
4HH × S	547.2	196.84
POL STD × S	563.0	151.81
POL HI × S	698.7	150.73
LO × P	286.4	87.65
4HH × P	382.1	227.16
POL STD × P	412.2	118.89
POL HI × P	504.4	133.30
LO × L	174.1	108.70
4HH × L	206.3	127.47
POL STD × L	253.2	124.40
POL HI × L	294.2	112.95
LO × -200	264.1	143.06
LO × 0	242.6	107.88
LO × 200	258.2	120.09
LO × INF	345.9	143.98
4HH × -200	294.5	162.42
4HH × 0	311.3	151.80
4HH × 200	308.2	168.16
4HH × INF	600.3	277.51
POL STD × -200	405.2	179.05
POL STD × 0	386.6	178.08
POL STD × 200	390.7	156.85
POL STD × INF	455.4	210.17
POL HI × -200	482.1	185.75
POL HI × 0	470.3	213.51
POL HI × 200	453.5	210.94
POL HI × INF	590.5	214.39
S × -200	512.9	153.65
S × 0	512.9	182.05
S × 200	524.5	155.61
S × INF	631.3	251.71
P × -200	358.1	134.70
P × 0	346.2	127.02
P × 200	334.3	120.20
P × INF	546.5	190.38
L × -200	213.4	143.66
L × 0	199.0	79.24
L × 200	199.1	88.24
L × INF	316.3	142.42

B. Analyses of Variance on Lateral Deviation of Subject Car

1. Experiment A1--Variable Is Mean Path in Segments of Subject Car Path before Meeting Point with Glare Car of 1200 to 1000, 600 to 400, 400 to 200, 200 to 0 and 0 to -200 Feet

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Targets	(T)	2	293.0	146.5	45.5	1
Drivers	(D)	4	10731.0	2682.8	833.0	1
Lanes	(S)	2	305.0	152.5	47.3	1
Segments	(P)	4	269.6	67.4	21.0	1
T × D		8	2459.1	307.4	95.3	1
T × S		4	32.2	8.0	-	-
T × P		8	115.4	14.4	4.47	1
D × S		8	133.2	16.7	5.19	1
D × P		16	86.2	5.4	-	-
S × P		8	39.8	5.0	-	-
T × D × S		16	60.1	3.8	-	-
T × D × P		32	137.1	4.3	-	-
T × S × P		16	104.0	6.5	-	-
D × S × P		32	108.6	3.4	-	-
Residual		64	206.4	3.2	-	-
Total		224	15080.8			

2. Experiment A1--Variable Is Standard Deviation of Subject Car Path in Segments before Meeting Point with Glare Car of 1200 to 1000, 600 to 400, 400 to 200, 200 to 0, 0 to -200 Feet

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Targets	(T)	2	2.16	1.08	-	-
Drivers	(D)	4	15.24	3.81	5.52	1
Lanes	(S)	2	3.17	1.58	-	-
Segments	(P)	4	54.67	13.66	19.8	1
T × D		8	2.06	0.25	-	-
T × S		4	4.45	1.11	-	-
T × P		8	4.12	0.51	-	-
D × S		8	4.25	0.53	-	-
D × P		16	10.19	0.63	-	-
S × P		8	5.28	0.66	-	-
T × D × S		16	16.99	1.06	-	-
T × D × P		32	12.89	0.40	-	-
T × S × P		16	12.28	0.76	-	-
D × S × P		32	28.02	0.87	-	-
Residual		64	44.38	0.69		
Total		224	220.20			

3. Experiment A1--Variable Is Mean Slope (Inches per Foot of Travel) in Subject Car Path in Segments before Meeting Point with Glare Car of 1200 to 1000, 600 to 400, 400 to 200, 200 to 0, 0 to -200 Feet

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Targets	(T)	2	0.00075	0.00037	-	-
Drivers	(D)	4	0.00166	0.00041	-	-
Lanes	(S)	2	0.00143	0.00072	-	-
Segments	(P)	4	0.01372	0.00343	9.03	1
T × D		8	0.00474	0.00059	-	-
T × S		4	0.00124	0.00031	-	-
T × P		8	0.00330	0.00041	-	-
D × S		8	0.00139	0.00017	-	-
D × P		16	0.00821	0.00051	-	-
S × P		8	0.00086	0.00011	-	-
T × D × S		16	0.00586	0.00037	-	-
T × D × P		32	0.01767	0.00055	-	-
T × S × P		16	0.00601	0.00038	-	-
D × S × P		32	0.01652	0.00052	-	-
Residual		64	0.02424	0.00038		
Total		224	0.10760			

4. Experiment A2--Variable Is Mean Slope (Inches per Foot of Travel $\times 10^5$) in Subject Car Path in Segment 600 Feet before Meeting Point with Glare Car

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	5	14909647.2	2981929.4	5.23	1
Targets	(T)	2	24770485.4	12385242.7	21.6	1
Headlights	(H)	5	9084484.6	1816896.9	3.18	1
$D \times T$		10	11324149.4	1132414.9	-	5
$D \times H$		25	12283846.4	491353.8	-	-
$T \times H$		10	4292672.4	429267.2	-	-
Residual		50	28668102.6	573362.0		
Total		107	105333388.3			

5. Experiment A1--Variable Is Mean Slope (Inches per Foot of Travel) in Subject Car Path in Segment 600 Feet before Meeting Point with Glare Car

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	4	0.05259	0.01315	2.8	-
Lanes	(S)	2	0.03374	0.01687	3.6	5
Targets	(T)	2	0.10839	0.05420	11.5	1
		8	0.03780	0.00472	-	-
		8	0.02694	0.00337	-	-
		4	0.00601	0.00150	-	-
Residual		16	0.07519	0.00470		
Total		44	0.34066			

6. Experiment A1--Variable Is Deviation Out-of-Bounds (6 Inches R & L of Roadway Centerline)

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	4	2788260.3	697065.1	21.5	1
Lanes	(S)	2	28058.2	14029.1	-	1
Targets	(T)	2	601106.3	300553.1	9.3	1
D × S		8	201575.2	25196.9	-	1
D × T		8	2698628.4	337328.5	10.4	-
S × T		4	25014.9	6253.7	-	-
Residual		16	516825.8	32301.6	-	-
Total		44	6859469.0			

7. Experiment A6A--Variable Is Maximum Deviation Amplitude in Subject Car Path Approaching Meeting Point with Glare Car with ±45° Polarization

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	3	790.8	263.6	6.60	1
Targets	(T)	2	10.1	5.0	-	-
Intercepts	(I)	5	180.0	36.0	-	-
D × T		6	540.3	90.0	2.26	5
D × I		15	205.5	13.6	-	-
T × I		10	329.8	32.9	-	-
D × T × I		30	1025.2	34.1	-	-
Within Repl		144	5747.3	39.9		
Total		215	8829.0			

8. Experiment A2--Variable Is Maximum Deviation Amplitude in Subject Car Path Approaching Meeting Point with Glare Car with Varied Headlighting

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	3	688.7	229.6	112.4	1
Targets	(T)	2	316.2	158.1	7.73	1
Headlights	(H)	2	9.7	4.8	-	-
D × T		6	76.0	12.7	-	-
D × H		6	68.8	11.5	-	-
T × H		4	88.0	22.0	-	-
D × T × H		12	128.1	10.7	-	-
Within Repl		72	1470.0	20.4		
Total		107	2845.6			

9. Experiment A7--20 Drivers Study--Variable Is Maximum Deviation Amplitude in Subject Car Path Approaching Meeting Point with Glare Car (∞ Runs Included)

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	19	7495	394	11.7	1
Lighting	(L)	3	845	282	8.33	1
Targets	(T)	2	1457	729	21.6	1
Intercept	(I)	3	2769	923	27.3	1
D × L		57	2774	49	1.44	5
D × T		38	2551	67	1.99	1
D × I		57	2547	45	1.32	NS
L × T		6	357	59	1.76	NS
L × I		9	297	33	-	NS
T × I		6	324	54	1.60	NS
D × L × T		114	4821	42	1.25	NS
D × L × I		171	7005	41	1.21	NS
D × T × I		114	4928	43	1.28	NS
L × T × I		18	720	40	1.18	NS
Residual		342	11560	34		
Total		959	50449			

10. Experiment A7--20 Drivers Study (Less ∞ Runs)

Source of Variation		Deg of Free.	Sum of Squares	Mean Squares	F Ratio	Signif Level, < %
Drivers	(D)	19	7436	391	9.11	1
Lighting	(L)	3	617	206	5.21	1
Targets	(T)	2	1217	609	15.4	1
Intercept	(I)	2	38	19	-	NS
D × L		57	3767	66	1.67	1
D × T		38	2678	70	1.79	1
D × I		38	1447	38	-	NS
L × T		6	408	68	1.72	NS
L × I		6	97	16	-	NS
T × I		4	310	77	1.95	NS
D × L × T		114	4740	42	1.06	NS
D × L × I		114	4746	42	1.06	NS
D × T × I		76	3405	45	1.14	NS
L × T × I		12	580	48	1.22	NS
Residual		228	8997	39		
Total		719	40485			