PREDICTOR AIDED TRACKING IN A SYSTEM WITH TIME DELAY:

PERFORMANCE INVOLVING FLAT SURFACE, ROLL, AND PITCH CONDITIONS

by John M. Leslie, Lawrence A. Bennigson,

and Michael E. Kahn

Prepared under Grant No. NsG 111-61 by

STANFORD UNIVERSITY
Stanford, California

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

March 1966

ABSTRACT

This report describes a study of a human operator's ability to pursuit track a course under conditions where his control commands are delayed 2.6 seconds. The purpose was to prove the effectiveness of a predictor as an aiding device to an operator who has the task of driving a vehicle through such a transmission delay. Thirty subjects were tested under combinations of four speeds (2, 3, 4, 5 mph), four terrain conditions (flat, roll, pitch, roll and pitch), and three control modes (no-delay, delay without predictor, delay with predictor). Tracking performance with the predictor proved to be an improvement over performance without predictor to a confidence level of at least 99% for all conditions tested.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

A. General

This report covers one phase of the total work performed by Stanford University under Grant NsG 111-61; the other phases are covered by References 7, 8, and 9. This report describes a study of a human operator's ability to pursuit track a course under conditions where his control commands are delayed 2.6 seconds. This delay is typical for the case of an operator who has the task of steering a lunar vehicle, by remote control, from earth. In this situation, his control signal would require approximately 1.3 seconds to travel from earth to the moon, and a television picture of the resultant action would require an additional 1.3 seconds to return to earth. This study was for the purpose of proving the effectiveness of a predictor in aiding an operator subjected to such delay while driving a course that may involve flat surface, roll, pitch, or roll and pitch conditions.

B. Background

Man possesses a unique combination of characteristics which make his inclusion in certain control situations highly desirable and, in some cases mandatory. No other control system element is capable of the quality of performance which man exhibits in his ability to (1) adapt to changing conditions, (2) make decisions based on incomplete or low quality data, and (3) predict future performance based on both data received in the recent past and his knowledge of the system behavior. Systems in which man is included in some capacity within the control loop customarily are called man-machine systems.

For reasons of safety, economy, and convenience, the human operator often is remotely located from the controlled element in the system. Until recent years, the distance involved in these situations has been no more than a few thousand miles on the earth's surface, so the resulting time required for signal transmission has been relatively short. For example, a signal traveling at the speed of light is delayed approximately 5 milliseconds in going 1000 miles, and this is short in comparison to an operator's reaction-time delay which may be on the order of a few hundred milliseconds. But with the advent of exploration of outer space, the distances between the controller and the controlled element are being extended so that the time delay due to signal transmission may be a significant deterrent to good system control and stability. The character of tracking performance degradation due to transmission delay has been the subject of study by only a limited number of researchers.

Warrick[1*] (1949) reported on a series of compensatory tracking experiments with transmission delay of 0 to 320 milliseconds. He concluded

* Superscripts refer to numbers in Reference Section.

that any amount of transmission delay in the control loop affected tracking accuracy. He hypothesized an inverse linear relationship between the delay and the logarithm of time-on-target.

Adams[2, 3, 4] (1961-62) reported the first experiments on vehicles controlled through transmission delay. He studied operator tracking performance as a function of target complexity and delay magnitude. The experiments were performed with a robot vehicle driven at speeds up to 2.7 feet per second (less than 2 mph) and delays up to 3 seconds. Changes in target complexity were made by changing the vehicle speed over the test course. For each experimental run the speed was constant. Both two- and four-wheel steering were used. Two-wheel steering was similar to that used in automobiles. In four-wheel steering, all wheels turned together in response to a steering command. The more maneuverable four-wheel steering vehicle enabled the tests subjects to track effectively a more complex course than was possible with two-wheel steering. Adams found that the percentage of time-on-target for a given course complexity deteriorated rapidly with increases in the transmission-time delay. For example, at a vehicle speed of 2.7 feet per second with four-wheel steering, the following results were obtained:

Transmission Delay	Time-on-Target
0.0 sec.	98%
0.5 sec.	85%
1.0 sec.	55%
2.0 sec.	25%

His results also showed that time-on-target fell rapidly when course complexity was increased for a fixed transmission delay.

Chomet, Freeberg, and Swanson[5] (1962) conducted driving tests on a modeled lunar landscape. The driver was asked to maneuver a small (14 inches long) tractor-like vehicle from a starting point to a distant, but initially visible, goal in as short a time as possible while using a control system having a 3.0 second transmission delay. The path to be taken was not specified but was chosen by the operator. His performance was evaluated on the basis of the total time required to reach the goal and the number of obstacles struck along the way. The results of this program agreed qualitatively with those of Adams.

Fox[6] (1962) in another study reported the effects of 2.5 second transmission delay on human tracking performance. The remotely controlled vehicle was a Jeep. It was driven at average speeds of 1.82, 2.74, and 4.33 mph over courses of three different complexities. The tracking task was to keep the Jeep on a road outlined by uniformly spaced traffic cones. Fox reported that tracking performance deteriorated exponentially with increasing vehicle speed.

Braisted[7] (1963), and Braisted and Arnold[8] (1963), in an extension of Adams's work, developed an operator aiding device for use in systems with transmission delay. The device, called a predictor, was intended to relieve the operator of the complex mental computations he must perform continuously while carrying out the tracking task. At any given time during the tracking experiment, the operator must appraise his present position, recall his control inputs to the system for the previous delay period, and estimate his position due to these commands before making a decision for his next input. In the case of a continuous tracking task, this calculation process must be done with continuous addition of recent commands and deletion of commands which are no longer relevant. When the tracking task is elementary, these calculations are within a human's capabilities. But as either the task becomes more complex or the transmission delay longer, the operator's performance degrades due to his inability to properly store and process the increased data. Braisted's predictor was intended to minimize this problem in the operation of systems with long transmission delays.

Braisted conducted a series of field tests using a remotely controlled vehicle that had a four-wheel steering configuration. The vehicle was driven over a course marked in chalk on a football field. The driver operated the vehicle from a closed van which was located near the field. His view was by means of a television camera mounted on the vehicle and a display on a TV monitor before him in the van. Both the picture signal and his steering commands were via a two-way radio link between the van and vehicle.

Tests were performed under three different modes of operation: (1) no transmission delay, (2) 2.6 sec. delay without predictor, and (3) 2.6 sec. delay with predictor. Modes 1 and 2 provided opportunity to verify the qualitative results of others[2, 3, 4, 5, 6], and modes 2 and 3 the means to evaluate the aiding effects of the predictor upon tracking performance. In the no-delay mode, the operator's steering commands were transmitted directly to the vehicle; in the other two modes they were delayed 2.6 seconds. In all three cases, the television picture was in real (no-delay) time.

Braisted found that his predictor was an aid to driver performance in his series of flat surface tests. He concluded that the predictor makes it possible for a human operator to drive nearly as well with a signal transmission delay as he can drive at the same speed without such delay.

Leslie[9] (1965) conducted a study with delays of 0.00, 0.27, 0.50, 1.00, 2.60, 5.00 and 10.00 seconds. Operators tracked a step-type input consisting of individually illuminated lights. His operators sat before a console containing two horizontal rows of eleven lights each. The upper row was the "course" and was controlled by pre-programmed magnetic tape record. The lower row was manually controllable by the operator but subject to the delay required for the particular test. The operator's task was to match his light illumination positions as best he could to agree with the "course." Data from 31 test operators showed that their tracking performance had a frequency response, under the conditions of 0.00 seconds delay, that resembled a low pass filter having a cutoff frequency of 0.8 cps and a roll-off beyond cutoff of six decibels per octave. Increased delay both decreased the cutoff frequency and affected the character of the performance at frequencies higher than cutoff. For delays (T) greater than 1.00 seconds, the cutoff frequency can be approximated by the relationship

$$f = \frac{0.14}{T^{0.7}}$$

C. Experimental Objectives

The objectives of this study were aimed primarily at determining the effectiveness of the Braisted-type predictor to conditions other than only flat surfaces. The experiments were designed to test tracking performance under flat surface, roll, pitch, and roll and pitch conditions to obtain a statistically meaningful comparison of performance between the following tests:

1. No transmission delay and no predictor
2. 2.6 second delay and no predictor
3. 2.6 second delay with predictor

FIGURE 1

Figure 1 - Overall View of Simulator

The Driver's Control Booth is at left, Predictor and associated electronics in in center, and Road and Vehicle Simulator to the right. (The IBM RAMAC is not part of this system.)

Figure 2 - General System Block Diagram

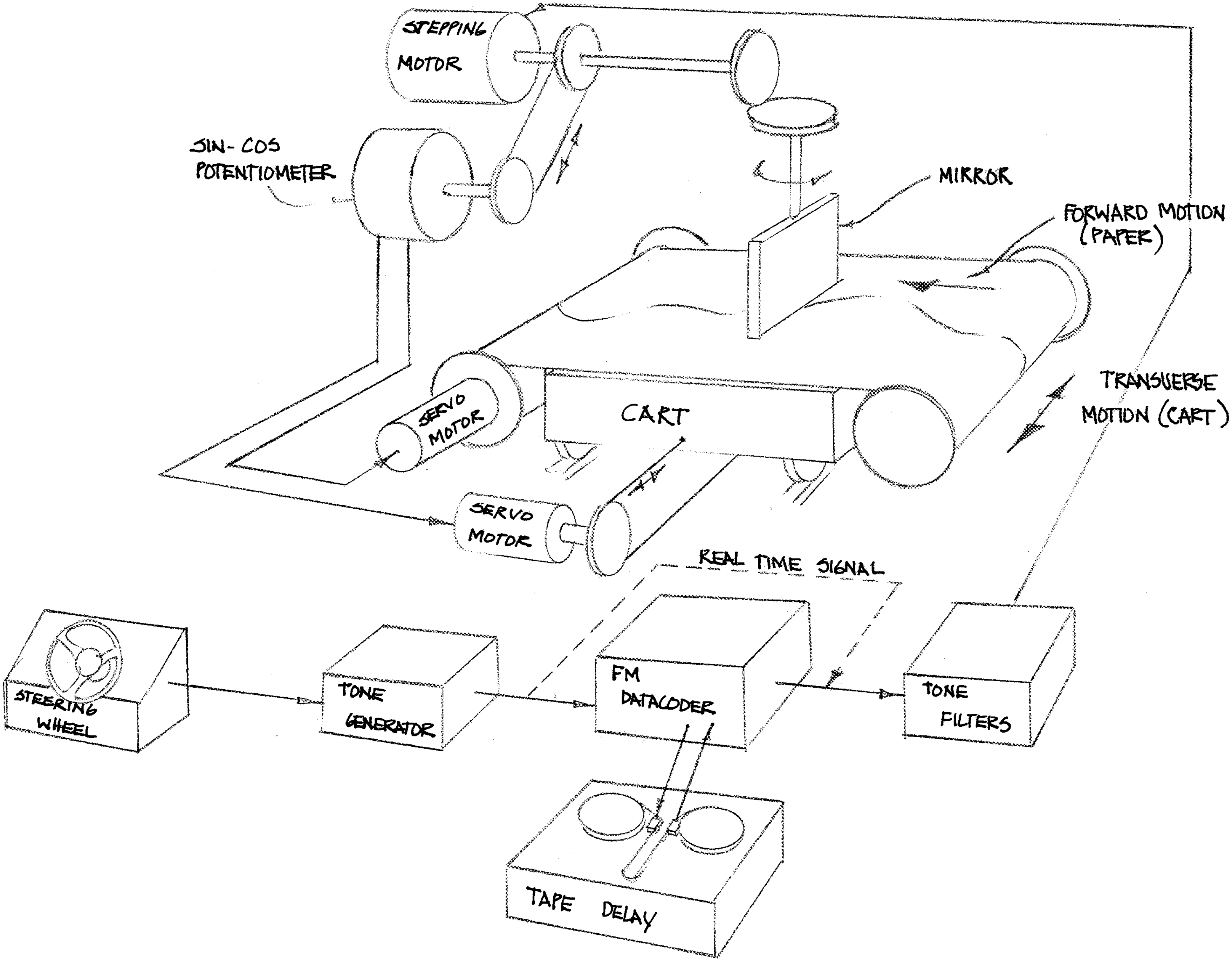

STEPPING MOTOR
SIN-COS POTENTIOMETER
MIRROR
FORWARD MOTION (PAPER)
TRANSVERSE MOTION (CART)
CART
SERVO MOTOR
SERVO MOTOR
REAL TIME SIGNAL
STEERING WHEEL
TONE GENERATOR
FM DATACODER
TONE FILTERS
TAPE DELAY

FIGURE 2

II. EXPERIMENTAL APPARATUS

A. General

Earlier research at Stanford (Adams[2, 3, 4], and Braisted[7, 8]) was limited to flat surface terrain conditions. Therefore, it was practical to perform the tests on the University's athletic fields. The present study required certain sections of road to have roll, pitch, or roll and pitch conditions; obviously, it was no longer practical to consider using these same fields.

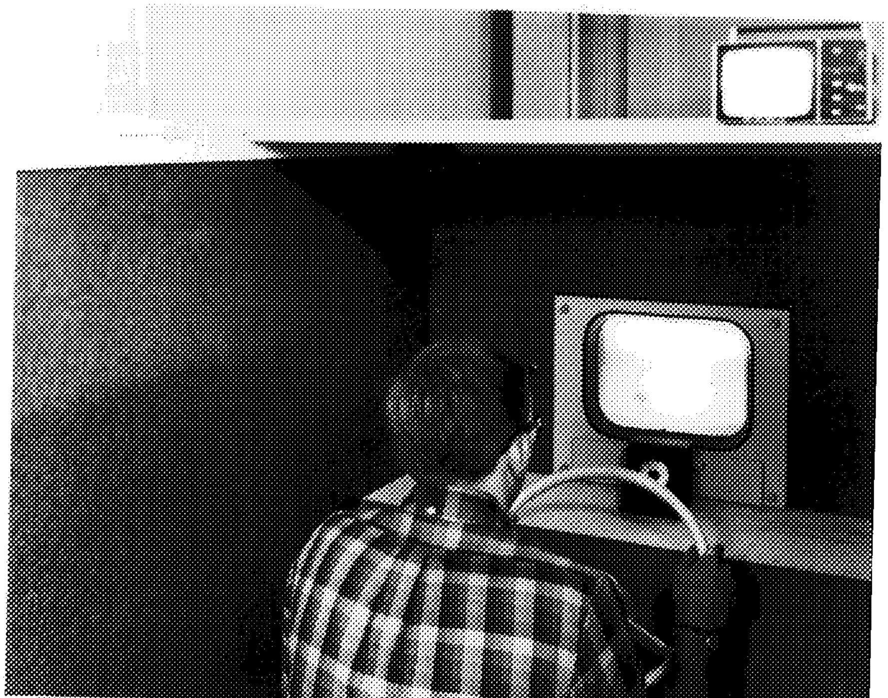
The solution chosen to the problem was to design a laboratory-type simulator. It provides means of introducing any of the conditions at will. A system photograph is shown in Figure 1 and a block diagram in Figure 2. The simulator can be divided into three sections: driver's control booth, road and vehicle simulator, and predictor.

B. Driver's Control Booth

Figure 3 shows the control booth in which the driver viewed a simulated road (tracking target) on a television monitor. His task was to steer so as to keep the road centered on a black dot that can be seen at the lower edge of the screen. This situation is analogous to keeping the hood ornament of an automobile lined up with some imaginary track on the highway. The driver view was always a real time image of the relative position of the road and vehicle. When he was operating in a "no delay" mode, the results of his control commands appeared on the screen immediately, but when he was in a "delay" mode the results did not appear until 2.6 seconds later.

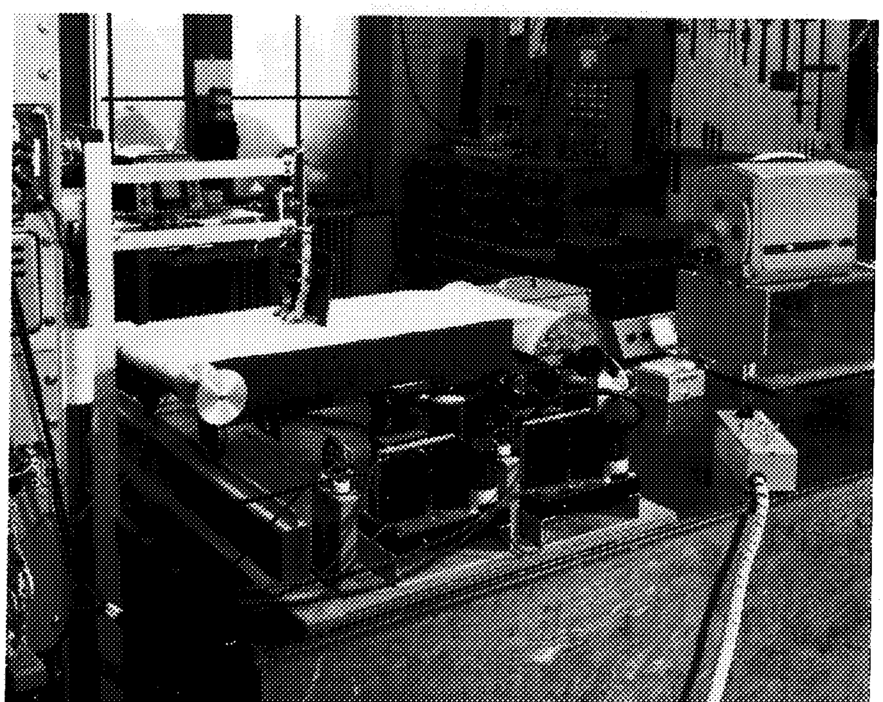
Rotation of the steering wheel produced pulses in proportion to the angle through which it was rotated. These pulses were used to control the road and vehicle simulation and predictor systems. Physically, it was possible for the driver to turn the wheel continuously in either direction, but technical limitations of the simulator made it necessary for him to stay within limits of plus or minus ninety degrees of a straight-ahead position. As he approached either ninety degree limit, he was warned automatically by the auditory sound of a buzzer and the visual signal of a red light. The latter signal also indicated which limit, right or left, he was approaching.

The driver was also aided by a device called a wheel angle indicator; it can be seen in Figure 4 in front of the television monitor. This device furnished an approximate measure of the angle through which the steering wheel had been rotated from center. This information was useful primarily in the delayed mode. It permitted the driver to determine (in real time) the approximate position of the wheel. This he found helpful when he was in the midst of performing a series of rapid steering motions.



FIGURE

Figure 3 - Driver's Booth



FIGURE

Figure 4 - Road and Vehicle Simulator

C. Road and Vehicle Simulator

Figure 4 is a photograph of the road and vehicle simulator. The system was composed of a television camera, a movable mirror, a wheeled cart mounted on tracks perpendicular to the axis of the camera, two servo motors, a roll motor, and a pitch motor. The road was printed on a large roll of paper mounted on the cart.

The picture seen on the driver's monitor was televised by the vehicle camera shown in Figure 4. It was the image of the reflection in the mirror of the road on the paper roll. Motion of the road in the monitor was obtained by (1) motion of the paper along the cart, (2) rolling of the cart along the tracks, and (3) rotation of the mirror about a vertical axis. In addition, apparent rolling of the road was the result of rolling of the vehicle camera about its optical axis; apparent pitching of the road was obtained by rotation of the mirror about an axis through its lower edge. Rolling and pitching motions were independently controlled and could be actuated alone or together. For these tests, roll frequency was 0.20 cps with a peak to peak amplitude of 15°. Pitch frequency was 2.2 cps with a peak to peak amplitude of 8°.

The pulse output from the steering wheel movement was used to actuate a stepping motor in the road and vehicle simulator. In the "no-delay" mode the pulses were transmitted directly to the motor; in the "delay" mode they were delayed for 2.6 seconds by a magnetic tape loop. The stepping motor rotated both the mirror and a potentiometer; the latter, in turn, controlled the cart and paper motion. The rotation of the mirror coupled with the corresponding motion of the paper and cart gave the driver the illusion of motion at a constant speed in the direction he was steering.

The Road and Vehicle Simulation system is described in more detail in Appendix A.

D. Predictor

A block diagram of the predictor is included as a part of Figure 2. It consists of a television monitor, X-Y Plotter (with a small disc connected to the pen holder by a vertical rod), an analog computer, and a television camera. A photo of the predictor system is shown in Figure 5.

Steering wheel pulses were transmitted to the analog computer where prediction calculations were performed. The output of the computer was fed to the X-Y Plotter. The combination of the computer, television camera, and X-Y Plotter converted the plan-view information into a perspective matching that of the vehicle television camera. The television camera viewed the motion of the predictor marker superimposed on a background of the image from the vehicle television camera. The composite picture was displayed on the driver's television monitor.

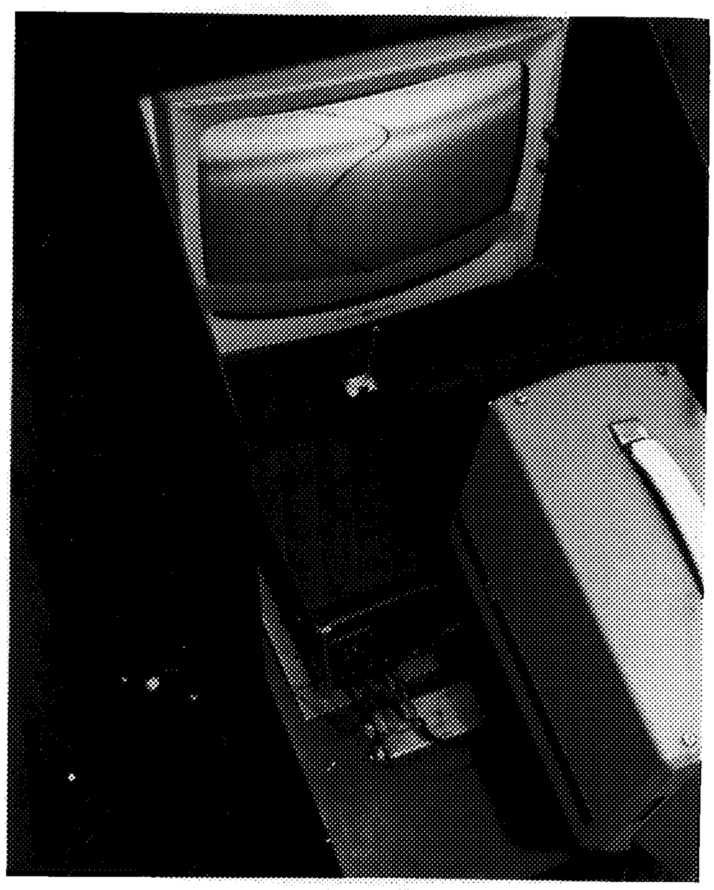


FIGURE 5

Figure 5 - Predictor Superposition System

The analog computer was used in real time in performing calculations of predictor position. Rectangular coordinates (x,y) were used in these calculations. The computer performed an integration of the x and y velocity components for each delay period and converted the results of these calculations to the proper coordinates for use on the X-Y recorder. Thus at any given time T, the position of the predictor as seen by the operator represented the composite effect of all steering commands which the driver had issued during the preceding delay period. The calculations performed are described in more detail in Appendix B.

III. EXPERIMENT DESIGN

A. Test Parameters

The design of this experiment was directed toward evaluation of the effectiveness of the predictor as a steering aid. The test conditions were a function of three independent variables. The first variable was vehicle speed, or in the experimental case, speed of the track. Simulated vehicle speeds of 2, 3, 4, and 5 mph were related to track speed by a scale factor described below. The second variable was simulated terrain condition: flat, rolling, pitching, or rolling and pitching. The third variable was control mode: real time (no transmission delay), 2.6 sec. transmission delay without predictor, or 2.6 sec. transmission delay with predictor.

B. Test Subjects

The series of tests was administered to thirty subjects. The subjects were selected at random from a population of Stanford University students ranging in age from 19 to 47; all subjects but one were right handed. All had routine automobile driving experience; four were licensed aircraft pilots.

C. Simulated Test Course

As mentioned earlier, the simulated test course was printed on a long paper strip which was carried on the vehicle simulation cart. The course was generated from the sum of four sine waves. Values of frequency, amplitude, and relative phase are given in Table 1.

Component No.	Amplitude in.	Frequency rad./sec.	Phase angle rad.
1	0.8	0.454	1.99
2	1.2	0.286	3.80
3	1.2	0.200	0.00
4	1.8	0.100	0.00

Table 1 - Test Course Components

Using these four sine functions, a road segment approximately 20 feet long was calculated on a digital computer and plotted on a Calcomp plotter; with a scale factor of 1" = 6', this represented 1440' of simulated road. For calibration and data reduction purposes, markers were placed on the road at 25' spacings (4.2" on the paper). The road segment was printed repeatedly, end-to-end, on a long strip of paper carried on the cart.

D. Learning

Results of a pilot program indicated that a significant amount of learning took place when a naive subject was first exposed to the simulated driving situation. The learning period was relatively short in the real time condition but longer in the delayed condition. In the delayed mode, even after test periods as long as three hours, subjects reported they were still improving their performance.

Evaluation of learning characteristics was not an objective of this experiment, so it was necessary to reduce the effects of learning as much as possible. This was accomplished in three ways: first, by submitting all subjects to identical learning processes before the test program, second, by including a learning and settling down period immediately preceding every data run, and third, by employing a random ordering of the tests presented to each test subject.

The learning program (see Table 2) was assigned to give the subject an exposure to all combinations of driving situations within reasonably challenging speed ranges. All subjects received identical learning programs administered over similar periods of time.

The results from pilot program tests showed that even after completion of the learning program, a subject continued to learn during the regular driving tests. A major part of this learning took place during the initial part of each run. To compensate for this situation, the first one-third of each test run was allocated for a learning and settling down period and not recorded for data purposes. Observations made during the experimental program on the 30 test subjects support the assumption that performance was relatively consistent during the last two-thirds of each test run.

Run No.	Real Time or Delay (D)	Predictor (PR)	Speed (MPH)	Terrain Roll: (R) Pitch: (P)	Length of run (MINUTES)
1			5		1
2			2		1
3			3		1
4			5		1
5			4	P	2
6			4	R	2
7			2	RP	1
8			4	RP	1
9	D		3		2
10	D		3	P	2
11	D		3	R	2
12	D		3	RP	2
13	D	PR	3		2
14	D	PR	3	P	2
15	D	PR	3	R	2
16	D	PR	3	RP	2

Table 2 - Learning Program

Even though the most significant effects of learning were controlled by the two methods mentioned above, it was still necessary to consider both positive and negative transfer of learning between tests. In a sequence of two real time tests, the subject's performance might improve considerably in the second test as a result of experience gained in the first. However, if the real time test were preceded by a delay test, the subject's performance might suffer from the delayed feedback learning. To minimize this effect, the order in which combinations of test conditions were presented to the test subjects was completely randomized.

The combinations of speed, terrain, and delay mode lend themselves to a 4x4x3 factorial in randomized blocks design. The factors and their levels are shown in Table 3. The order of test conditions for each subject was determined from Table 4 by a sequence of random numbers generated for that test subject.

Speed (mph)	Terrain Condition	Control Mode
2	Flat	Real time
3	Roll	Delayed without predictor
4	Pitch	Delayed with predictor
5	Roll and Pitch	

Table 3 - Test Factors

	Real Time				Delay without predictor				Delay with predictor			
	Speed (mph)				Speed (mph)				Speed (mph)			
Terrain	2	3	4	5	2	3	4	5	2	3	4	5
Flat	1	2	3	4	17	18	19	20	33	34	35	36
Pitch	5	6	7	8	21	22	23	24	27	28	29	40
Roll	9	10	11	12	25	26	27	28	41	42	43	44
Roll and Pitch	13	14	15	16	29	30	31	32	45	56	47	48

Table 4 - Test Numbers for all Combinations of Speed, Terrain Conditions, and Control Modes

E. Test Program

The test program for each subject consisted of the 48 tests in Table 4. Each test had a duration of 90 seconds. The first 30 seconds of the test was allocated for learning and settling down, and the final 60 seconds was recorded as data.

Subject performance was recorded by an inking pen mounted on a bracket behind the mirror. The tip of the pen was located immediately behind the center of the mirror. Since the center of the mirror always corresponded to the dot at the bottom of the driver's television monitor, the pen trace represented a continuous record of the subject's position on the simulated road.

As described previously, the road consisted of 20 foot segments sequentially printed on the paper roll. At a speed of 5 mph, the 90 second test required approximately 8 feet of paper. Test records at lower speeds were correspondingly shorter. The starting point on the road for each test was the termination point of the previous test; this resulted in a random starting point for each of the 48 tests. With 30 subjects, the effect of this random starting point on the results of any given test is considered negligible.

IV. EVALUATION AND CONCLUSIONS

A. Data Extraction

As mentioned previously, a continuous recording was made of each subject's tracking performance relative to the printed road. Measurements of the magnitude of deviation (error) between the two continuous lines was taken at, and at specified locations between, the markers along the road. These measurements were made perpendicular to the road to the nearest 0.05 inches. A record was also logged of the number of times the subject crossed the road during the particular tracking experiment.

B. Performance Criteria

Several variables were considered as possible indicators of performance. These included: central tendency, standard deviation about central tendency, mean error left of track, mean error right of track, standard deviation about mean error left and mean error right of track, and various combinations of these variables. Central tendency, and standard deviation about that central tendency seemed to be the most easily understood and efficient indicators of performance. Central tendency, in the context of this experiment, should be a good indicator of operator or machine bias. Standard deviation about central tendency is a good indicator of the absolute average error in tracking performance.

C. Performance Indicator Calculations

For each test, central tendency (mean position on the track) was computed for each of the thirty subjects. The standard deviation and variance about this central tendency was also computed for each test and each subject. It was assumed that these values of central tendency and values of standard deviation all represent the same population. Mean central tendency for each run was then computed by summing the central tendencies for all thirty subjects on that run and determining the mean value. The mean deviation for each test was similarly computed by summing all the values of deviation on one test for all subjects and determining the mean value. This method of calculation involved thirty subjects and over 400 data points for each test. Ratios of variances were calculated for tests so the resulting "F statistic" could be evaluated for significance. These ratios were calculated for (1) delay conditions over other conditions, (2) terrain conditions over other conditions, and (3) speeds over other conditions.

D. Presentation of Results

1) Standard Deviation vs Speed

The average deviation for each test (set of driving conditions) was plotted against speed as the independent variable. Four plots were produced: one for each set of terrain conditions. These plots are presented in Figures 6 through 9.

Figure 6 - Tracking Deviation versus Speed for Conditions of Flat Terrain

Figure 7 - Tracking Deviation versus Speed for Conditions of Roll Terrain

Figure 8 - Tracking Deviation versus Speed for Conditions of Pitch Terrain

Figure 9 - Tracking Deviation versus Speed for Conditions of Roll and Pitch Terrain

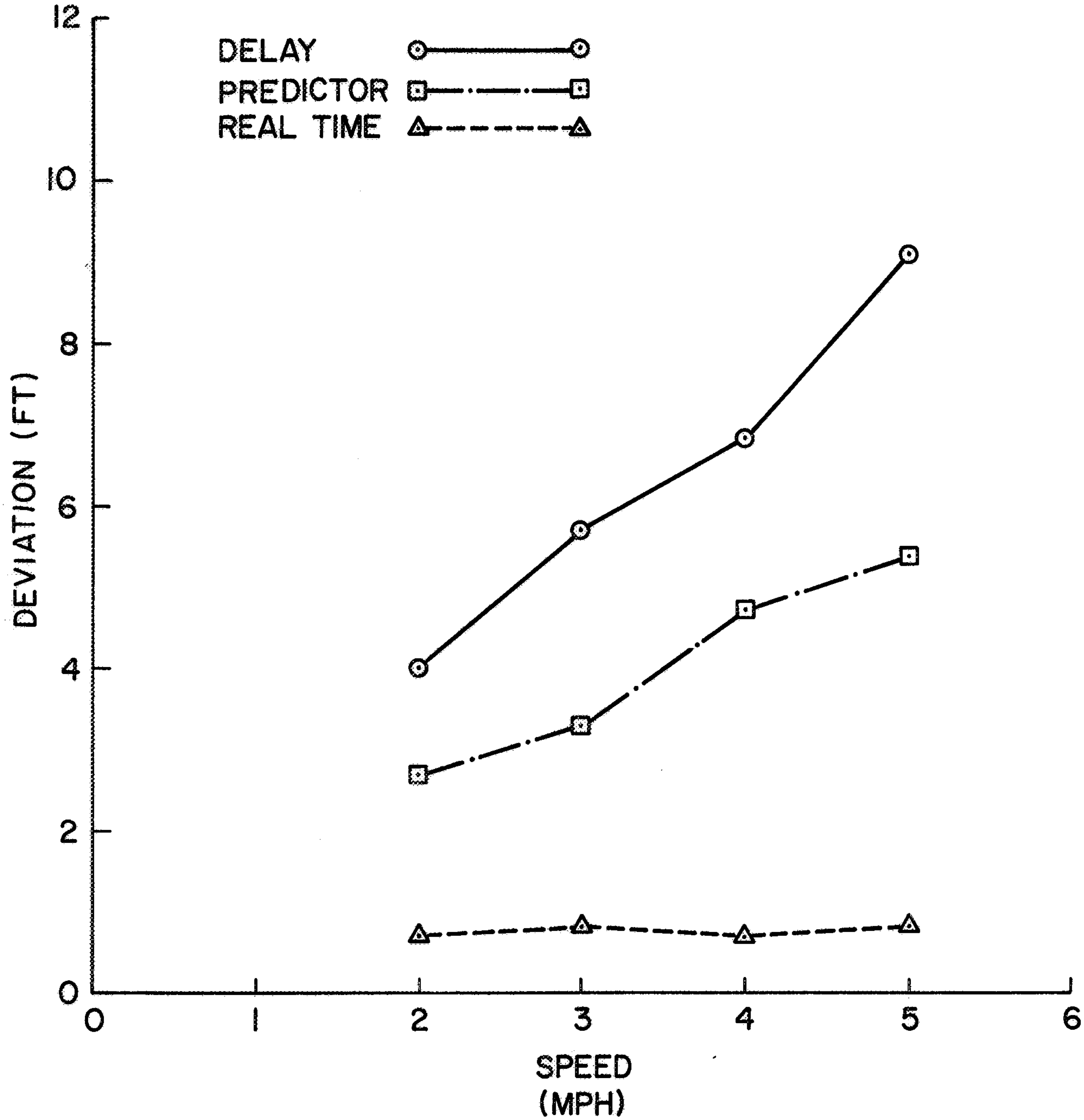
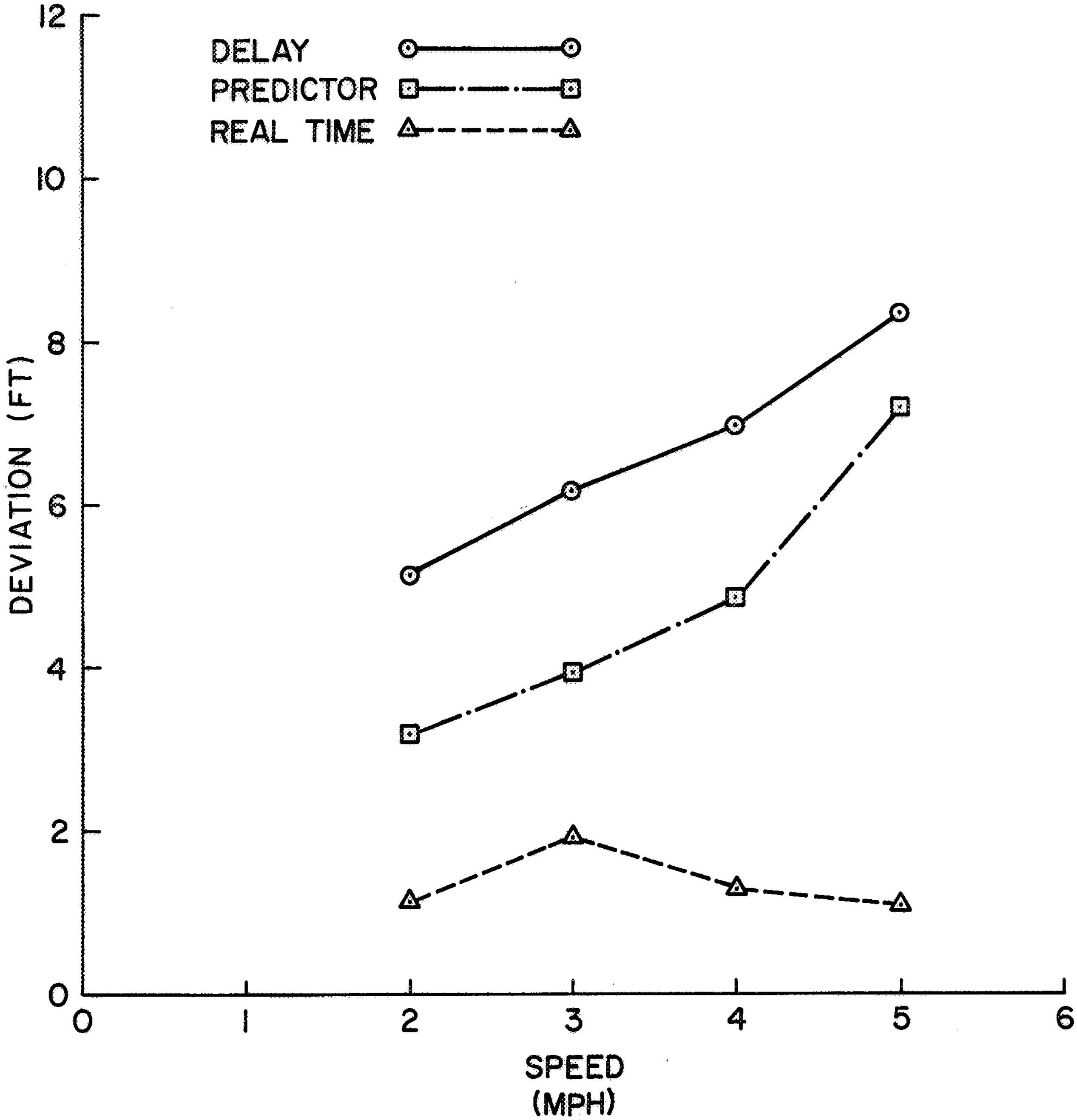
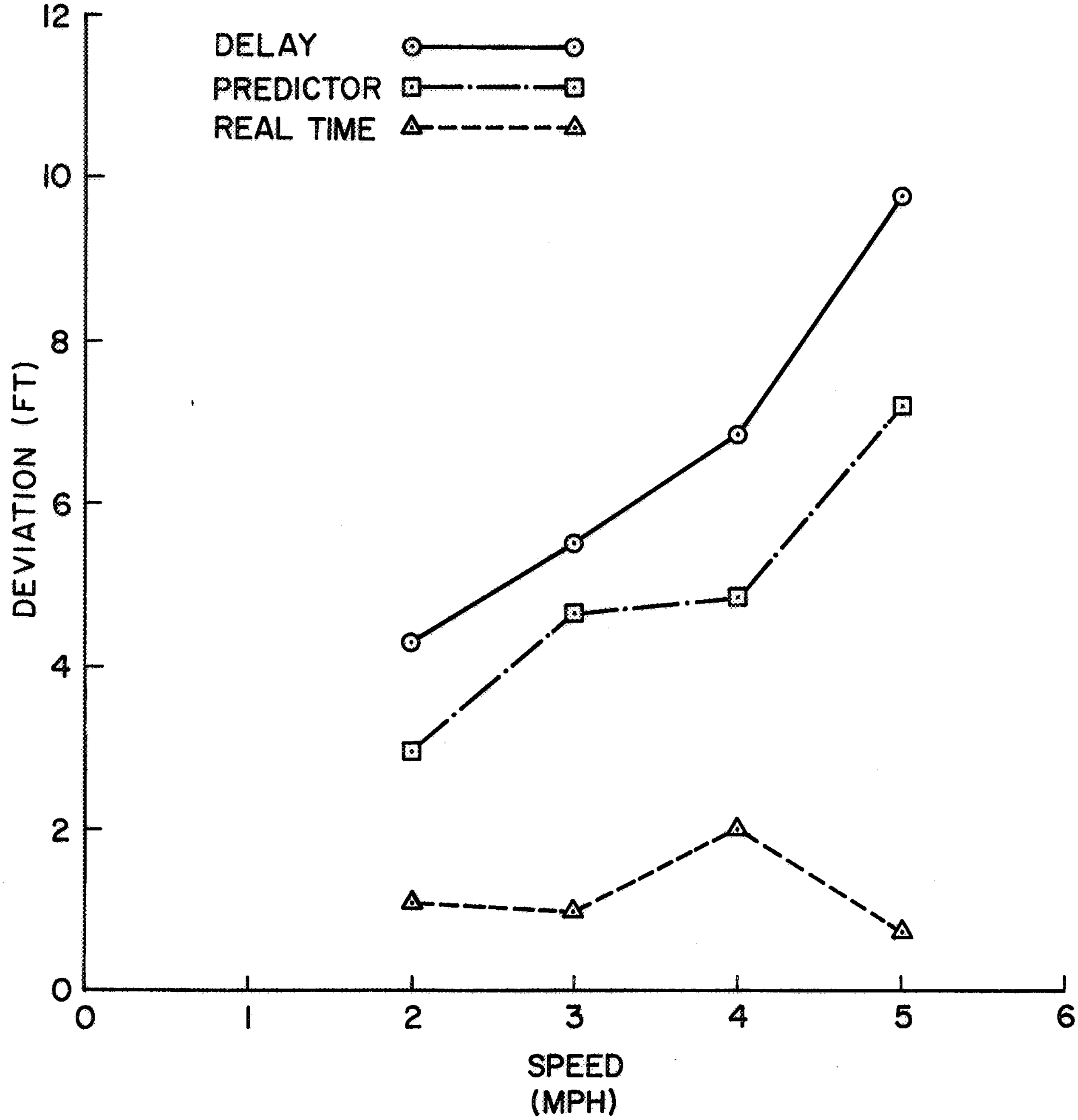

DELAY
PREDICTOR
REAL TIME
12
10
8
6
4
2
0
DEVIATION (FT)
0
1
2
3
4
5
6
SPEED
(MPH)

FIGURE 6



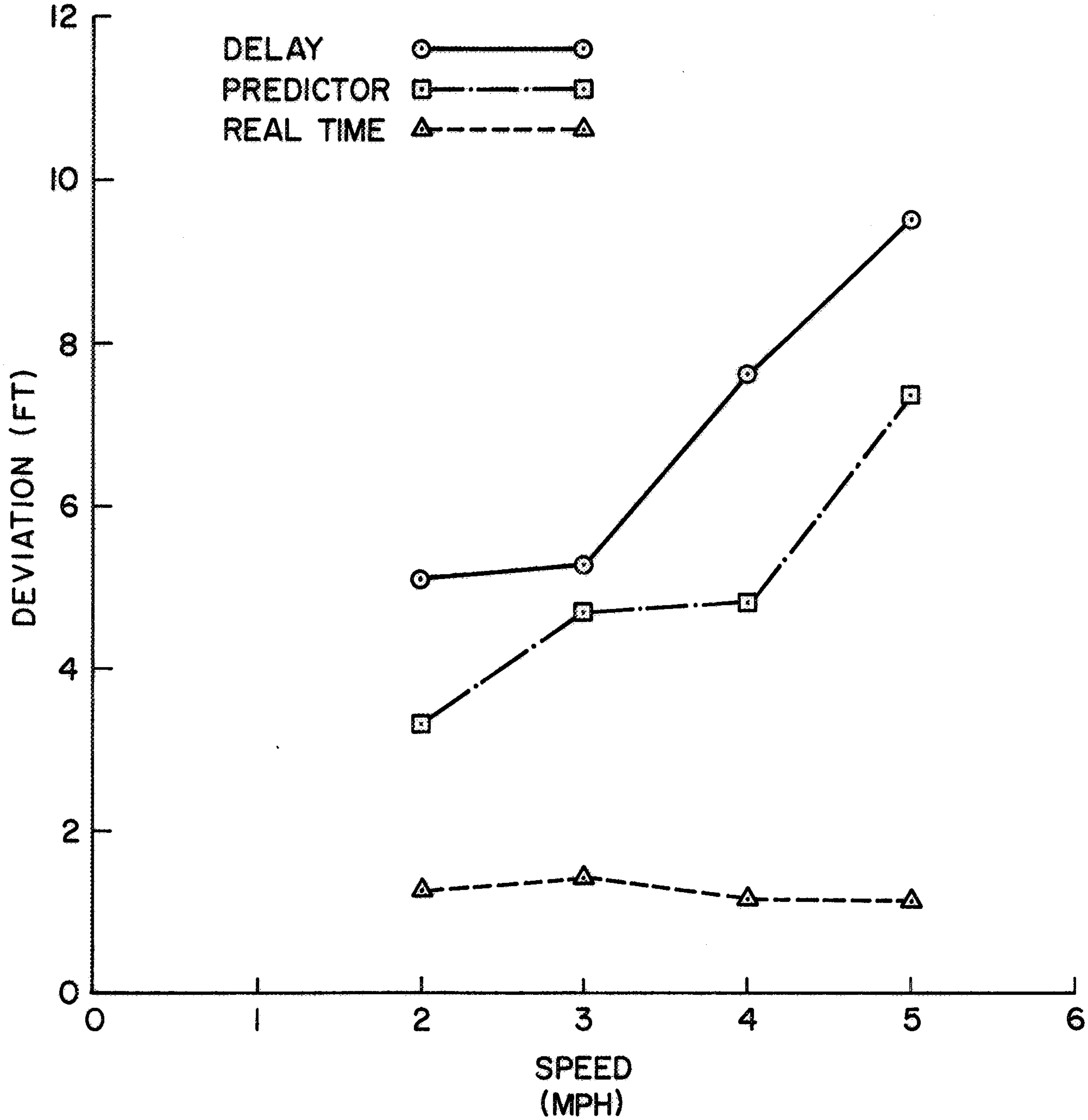
DELAY
PREDICTOR
REAL TIME
DEVIATION (FT)
0
2
4
6
8
10
12
0
1
2
3
4
5
6
SPEED
(MPH)

FIGURE 7



DELAY
PREDICTOR
REAL TIME
DEVIATION (FT)
12
10
8
6
4
2
0
0
1
2
3
4
5
6
SPEED
(MPH)

FIGURE 8



DELAY
PREDICTOR
REAL TIME
DEVIATION (FT)
0
2
4
6
8
10
12
0
1
2
3
4
5
6
SPEED
(MPH)

FIGURE 9

2) <u>95% Error Distribution vs Speed</u>

The central tendency and two standard deviations from central tendency for each test were plotted with speed as the independent variable. Four plots were produced: one for each set of terrain conditions. These plots are presented in Figures 10 through 13.

3) <u>F Statistic Ratios</u>

The ratios of variances for delay conditions and terrain conditions and speeds are presented in Tables 5, 6, and 7.

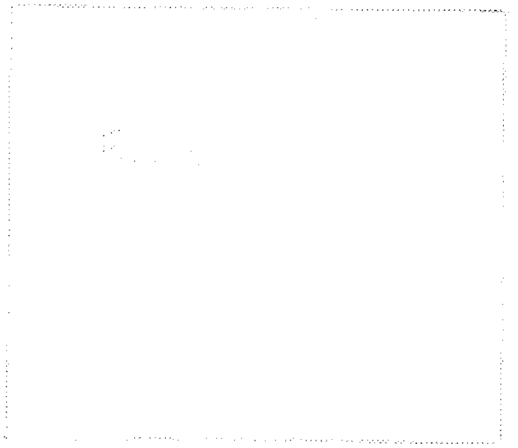


Figure 10 - 95% Error Distribution at Four Speeds on Flat Terrain

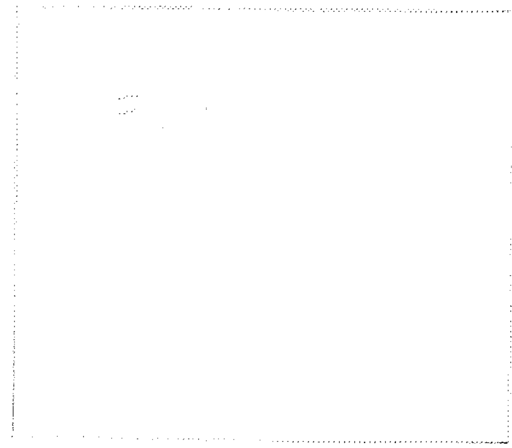


Figure 11 - 95% Error Distribution at Four Speeds on Roll Terrain

Figure 12 - 95% Error Distribution at Four Speeds on Pitch Terrain

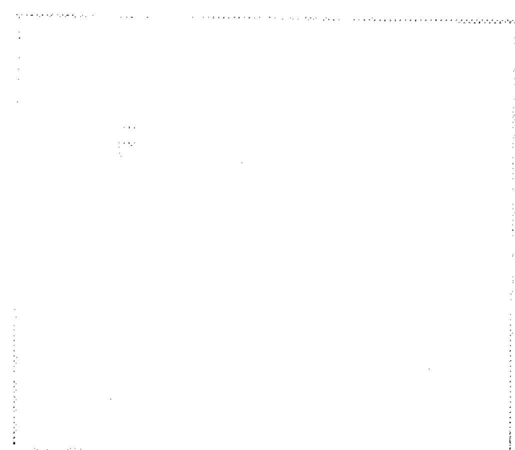


Figure 13 - 95% Error Distribution at Four Speeds on Roll and Pitch Terrain

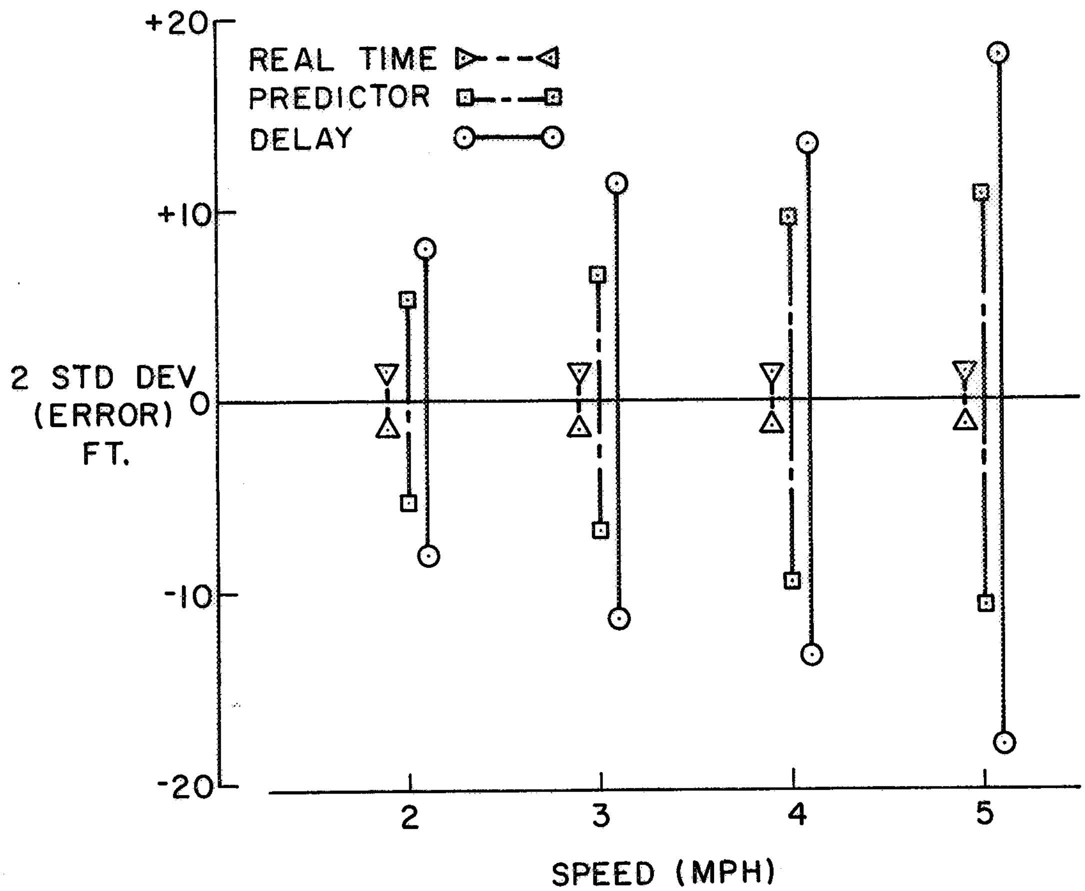
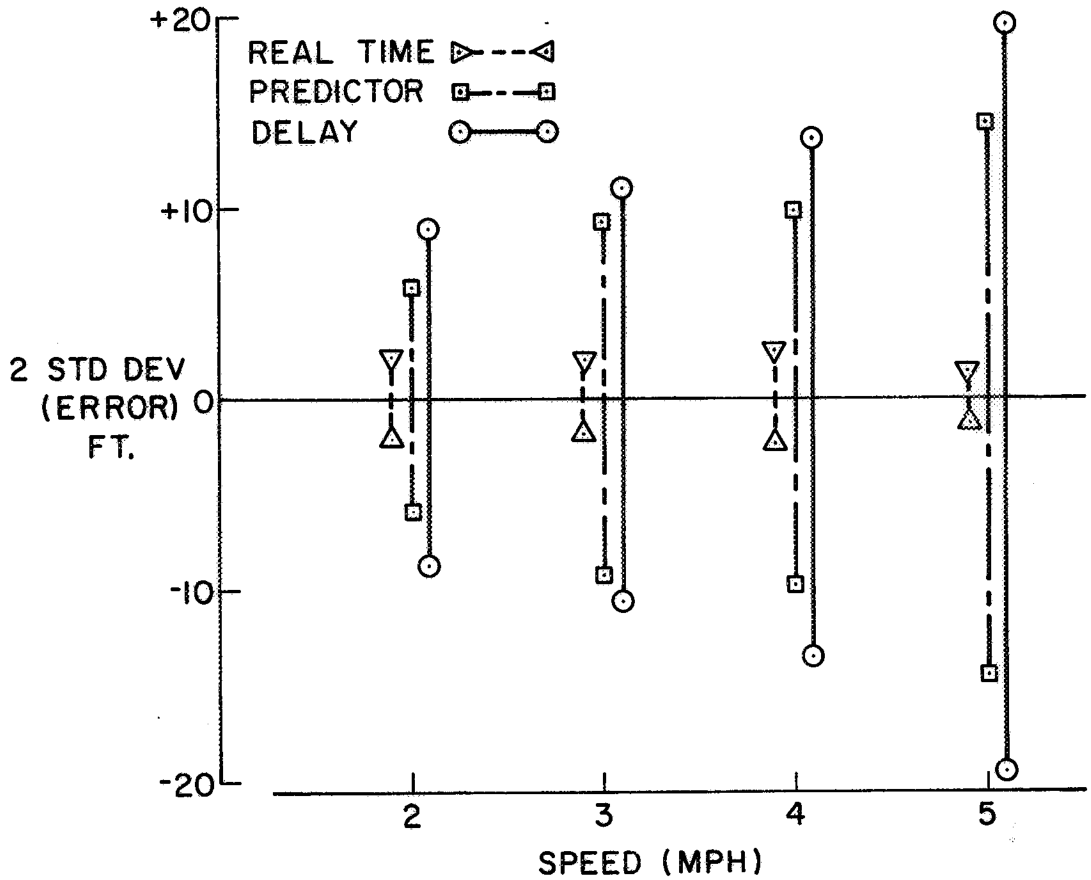
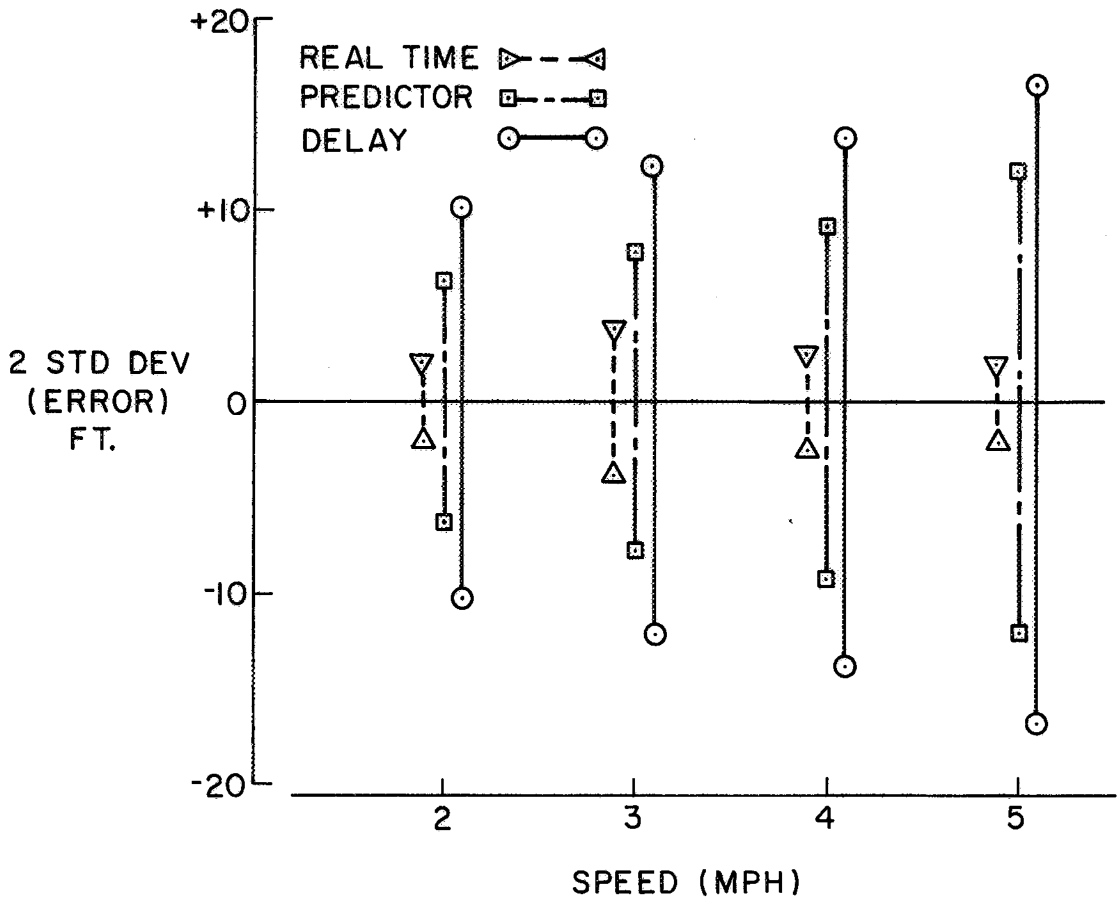

+20
+10
0
-10
-20
2 STD DEV
(ERROR)
FT.
REAL TIME
PREDICTOR
DELAY
2
3
4
5
SPEED (MPH)

FIGURE 10



+20
+10
0
-10
-20
2 STD DEV
(ERROR)
FT.
REAL TIME
PREDICTOR
DELAY
2
3
4
5
SPEED (MPH)

FIGURE 11



+20
+10
0
-10
-20
2 STD DEV
(ERROR)
FT.
REAL TIME
PREDICTOR
DELAY
2
3
4
5
SPEED (MPH)

FIGURE 12

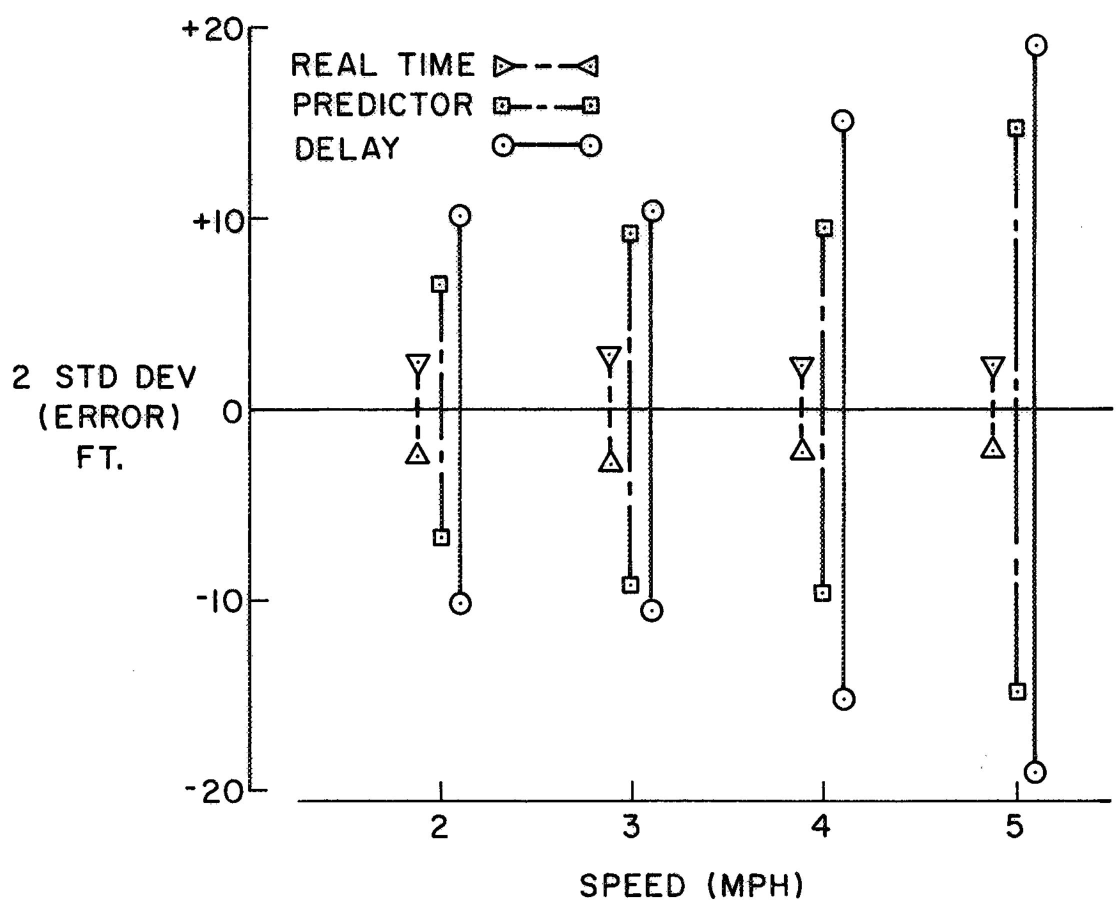

+20
REAL TIME
PREDICTOR
DELAY
+10
2 STD DEV
(ERROR)
FT.
0
-10
-20
2
3
4
5
SPEED (MPH)

FIGURE 13

Terrain	Control	Speed Ratio (mph/mph)					
		3/2	4/2	5/2	4/3	5/3	5/4
Flat	Real	1.35	1.06	1.36	0.78	1.00	1.28
Pitch	Real	0.83	1.19	0.44	1.43	0.53	0.37
Roll	Real	2.92	1.27	0.92	0.43	0.32	0.73
Roll and Pitch	Real	1.30	0.81	0.83	0.62	0.64	1.03
Flat	Delay	2.00	2.83	5.10	1.41	2.55	1.80
Pitch	Delay	1.63	2.48	5.10	1.52	3.13	2.05
Roll	Delay	1.41	1.81	2.61	1.28	1.85	1.44
Roll and Pitch	Delay	1.06	2.24	3.50	2.11	3.30	1.57
Flat	D-Pred	1.55	3.15	4.10	2.07	2.70	1.30
Pitch	D-Pred	2.50	2.77	5.99	1.11	2.39	2.16
Roll	D-Pred	1.48	2.08	3.65	1.40	2.46	1.76
Roll and Pitch	D-Pred	1.97	2.06	4.94	1.04	2.50	2.40

Table 5 - Ratios of Variances between Speeds for all Terrain Conditions and Control Modes

Speed (mph)	Terrain	Delay/Real	Delay/Predictor	Predictor/Real
2	Flat	33.63	2.25	14.93
3	Flat	49.78	2.97	16.75
4	Flat	89.74	2.03	44.28
5	Flat	126.54	2.80	45.20
2	Pitch	16.13	2.18	7.40
3	Pitch	31.60	1.42	22.25
4	Pitch	33.67	1.95	17.26
5	Pitch	186.62	1.85	100.63
2	Roll	21.17	2.62	8.08
3	Roll	10.24	2.50	4.09
4	Roll	30.33	2.29	13.25
5	Roll	59.99	1.88	31.98
2	Roll and Pitch	16.51	2.34	7.05
3	Roll and Pitch	13.50	1.26	10.72
4	Roll and Pitch	45.69	2.54	17.97
5	Roll and Pitch	69.40	1.66	41.79

Table 6 - Ratios of Variances between Control Modes for all Terrain Conditions and Speeds.

Speed	Control	Pitch/Flat	Roll/Flat	R&P/Flat	Roll/Pitch	R&P/Pitch	R&P/Roll
2	Real	2.43	2.63	3.28	1.08	1.35	1.25
3	Real	1.49	5.68	3.15	3.80	2.11	0.55
4	Real	2.72	3.14	2.50	1.15	0.92	0.80
5	Real	0.79	1.79	2.02	2.26	2.55	1.13
2	Delay	1.17	1.66	1.61	1.42	1.38	0.97
3	Delay	0.95	1.17	0.85	1.23	0.90	0.73
4	Delay	1.02	1.06	1.27	1.04	1.25	1.20
5	Delay	1.16	0.85	1.11	0.73	0.95	1.31
2	D-Pred	1.20	1.42	1.55	1.18	1.29	1.09
3	D-Pred	1.99	1.39	2.01	0.70	1.01	1.45
4	D-Pred	1.06	0.94	1.01	0.88	0.96	1.08
5	D-Pred	1.76	1.26	1.86	0.72	1.06	1.48

Table 7 - Ratios of Variances between Terrain Conditions for All Control Modes and Speeds

E. Discussion of Results

The primary objective of this study was to evaluate the effectiveness of the Braisted-type predictor under conditions of flat surfaces, roll, pitch, and roll and pitch terrain. The results of the study strongly support the hypothesis that the predictor is a significant aid to an operator who is subjected to driving a vehicle by remote control through a 2.6 second transmission delay.

The "F" tests between performance indicators showed the subject tracking performance with the predictor to be an improvement over that with no predictor to a confidence level of at least 99% for all conditions tested. The magnitude of this difference can be seen in the curves of tracking deviation versus speed, Figures 6 through 9. These curves also show a performance degradation (increase in deviation) as the speed is increased from 2 to 5 mph for the tests including delay. This degradation with each increase in speed is also significant to a level of at least 99%. The real-time (no delay) speed is also significant to a level of at least 99%. The real-time (no delay) tests showed the level of tracking performance to be relatively constant over the range of speeds tested with only two exceptions: at three miles per hour on roll terrain and at four miles per hour on pitch terrain there was a significant degradation in performance. These speeds seem to be well below the corresponding cutoff frequency for the real-time task. Several hypotheses have been suggested to explain the phenomenon but none have proven satisfactory. Even with the departure from flat response, it is reasonable to conclude that the subjects had little difficulty in tracking the course, in real-time, at speeds of 2 to 5 mph.

A significant difference in performance was noted between the flat terrain tests and all other terrain tests. In general there was not a significant difference between roll, pitch, or roll and pitch tests. Although introduction of roll and pitch increased the difficulty of the tracking task, the type of motion did not make much difference. One explanation for this observation involves the fact that constant amplitude and frequency of the roll and pitch motions were used. The subject may have learned to compensate partially for these attitude changes. The character of his compensation would be similar for both roll or pitch, so the effect on his performance for either condition may be similar. An additional contribution to performance degradation under roll and pitch conditions probably lies in the predictor itself. The computed predictor position does not account for roll and pitch motion. Consequently, the anticipatory information displayed by the predictor to the driver may be somewhat misleading.

The drivers' opinions toward the usefulness of the predictor were sampled in a questionnaire. Very few thought it was a significant aid, and most felt it was of little or no help. This reaction is particularly important in view of the apparent assistance the device offered each of the drivers. An explanation may be that the predictor produced some anxiety in the subjects, and there are at least two possible reasons for this.

The subjects were strongly encouraged, by the experimenter, to concentrate closely upon holding the predictor marker on the printed road and ignore the actual position of the vehicle in respect to the road. In a sense, they were asked to project themselves one time delay period ahead on the road and imagine themselves travelling in an imaginary vehicle represented by the predictor marker. The subjects may have become frustrated by their inability to keep the marker on the road even though, on an average, they may have been doing an excellent steering job by maintaining their oscillations to either side within narrow limits.

A second possible explanation is that the subject quickly learned that the predictor was not a perfect performance aid. It did not enable him to drive with as much ease and accuracy as he had experienced in driving the system in real time. As a result, the predictor may have become a target for his feelings of frustration and anxiety.

The drivers' opinions, qualitative as they were, point up the necessity of isolating those characteristics of the predictor that contributed to their lack of confidence in the device. Presumably, if the predictor were an order of magnitude better, the subjects would have had more confidence in it. But, if the subjects had had more confidence in the predictor, the device might have proven to be a much greater aid to them. Here lies one of the needs for future research.

F. Future Areas for Research

Several areas for future investigation are suggested by this study. Although the predictor was made available to the subject, and he was instructed and encouraged to use it, there was no control maintained over his actual use of the device. In future studies, this variable could be controlled by restricting the operator's visual field to the predictor and immediate road only. Another important variable which requires tight control is the amount of anticipatory information available to the subject under delay conditions. In this study, the driver often had several time delay lengths of road visible before him. The subject had his choice of the degree to which he would use this information in place of, or in addition to, the predictor. Thirdly, pitch, roll, and pitch and roll studies should be made under conditions where the subject does not have the opportunity to predict the time of occurrence of each attitude change, or the frequency and amplitude of it. Finally, predictors of other concepts and designs should be evaluated.

REFERENCES

1. Warrick, M. J., "Effects of Transmission-Type Control Lags on Tracking Accuracy," USAF Technical Report No. 5916, 1949.

2. Adams, J. L., "An Investigation of the Effects of Time Lag Due to Long Transmission Distances upon Remote Control, Phase I - Tracking Experiments," NASA Technical Note D-1211, 1961.

3. Adams, J. L., "An Investigation of the Effects of Time Lag Due to Long Transmission Distances upon Remote Control, Phase II - Vehicle Experiments, Phase III - Conclusions," NASA Technical Note D-1351, 1962.

4. Adams, J. L., Remote Control with Long Transmission Delays, Doctoral Dissertation, Stanford University, 1961.

5. Chomet, M., Freeberg, N., and Swanson, A., "A Simulation of Operator Capability in Robot Vehicle Control," IRE International Convention Record, Part 9, 1962.

6. Fox, G. J., "Perceptual-Motor Factors in the Remote Control of a Lunar Vehicle, Phase 1: The Effects of a Communication Time Delay on Steering Performance as a Function of Vehicle Speed and Course Complexity," Grumman Aircraft Report No. ADR 09-07061.1, 1962.

7. Braisted, P. W., Study of a Predictor for Remote Control Systems Operating with Signal Transmission Delays, Doctoral Dissertation, Stanford University, 1963.

8. Braisted, P. W., and Arnold, J. W., "Design and Evaluation of a Predictor for Remote Control Systems with Signal Transmission Delays," NASA Technical Note D-2229, 1963.

9. Leslie, J. M., Effects of Time Delay in the Visual Feedback Loop of a Man-Machine System, Dissertation for the Degree of Engineer, Stanford University, 1965.

APPENDIX A - ROAD AND VEHICLE MOVEMENT SIMULATION

The input to the road and vehicle movement simulation system was furnished by the rotation of the driver's steering wheel. The wheel was attached to a mechanism containing two modified telephone dial assemblies. These assemblies were equipped with overrunning clutches so that only one assembly was operative when the wheel was turned in one direction, the other being operative when the wheel was turned in the opposite direction. As each dial assembly was rotated, a cam produced a pulse output through a microswitch located in the assembly.

The control action of the pulse output from the steering wheel dial assemblies is described in reference to Figure A1.

Since stepping motors were used in the system, the changes in vehicle motion were not continuous so curves were traversed in a series of straight line segments. Each pulse corresponded to an apparent change in the direction of vehicle motion of 1.8°. Thus, in order to change the direction of vehicle motion by 18°, the operator turned the wheel through an angle which produced 10 output pulses from the appropriate dial assembly. From the driver's booth the pulses travelled to a tone generator. Upon receiving a pulse, a one-shot multivibrator opened a gate in the tone generator for approximately 6 milliseconds per pulse, permitting a 1390 cps (right turn pulse) or 960 cps (left turn pulse) signal to pass through the gate. This signal was fed to an FM Datacoder where it modulated a 6.75 kc carrier which was then recorded on one track of a two track tape recorder. After a 2.6 second delay in passing through a tape loop on the recorder, the signal was played back to the Datacoder where it was then demodulated (operation of the system without transmission delay was obtained through bypassing the Datacoder and tape delay). The mixed signal was then fed to a filter which detected the 1390 cps or 960 cps frequency, converting the bursts of these frequencies to pulses. These pulses were then applied to a stepping motor, each pulse producing a shaft rotation of 1.8°.

Through a pulley attached to the motor shaft, the stepping motor turned a sine-cosine potentiometer. The output of this potentiometer provided an input to two servomotors. One servomotor provided forward motion of the paper roll containing the road, the other provided transverse motion of the cart in a way which resulted in a constant velocity in the direction of the simulated vehicle motion. If the vehicle were travelling with velocity V in a direction parallel to the camera axis, the forward velocity v of the paper would be

$$v = kV$$

where k is a scale factor. The cart velocity in a transverse direction would be zero. If an 18° turn to the right were desired, the forward velocity of the paper would be v cos 18° and the transverse velocity would be v sin 18°. The sine-cosine potentiometer provided voltages corresponding to these quantities to the servomotors.

The stepping motor was also used to turn the mirror through an angle of one-half the desired turn angle. In the example above, if the turn angle were 18°, the mirror would rotate 9°, resulting in a change in viewing direction of 18°. This rotation coupled with the corresponding motion of the paper and cart created the illusion to the driver of motion in the desired direction.

Figure A1 - Road and Vehicle Simulation
System Schematic

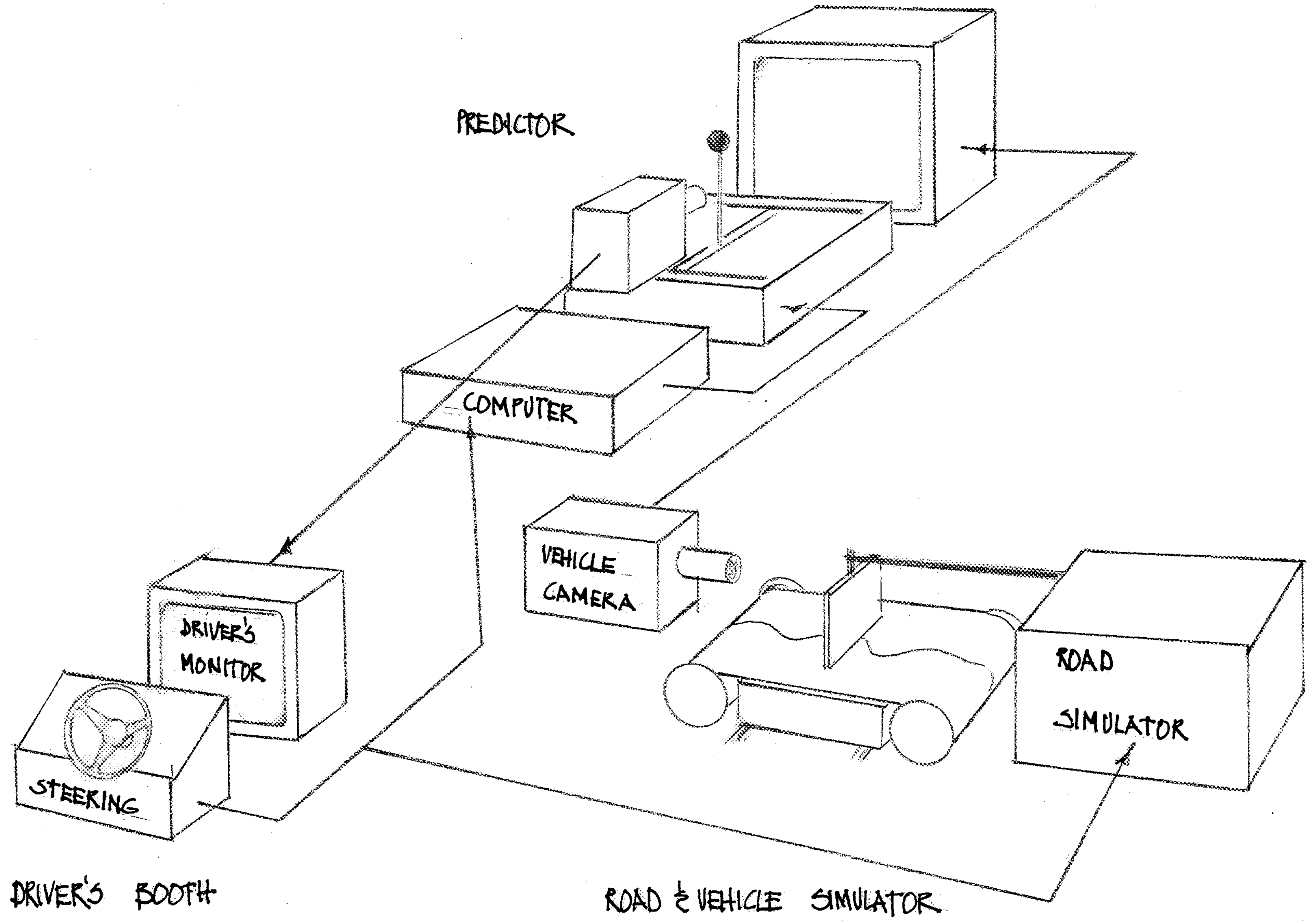

PREDICTOR
COMPUTER
VEHICLE CAMERA
DRIVER'S MONITOR
STEERING
ROAD SIMULATOR
DRIVER'S BOOTH
ROAD & VEHICLE SIMULATOR

FIGURE A1

APPENDIX B - PREDICTOR CALCULATIONS

A short description of the predictor was given in Section II. In this appendix, the computer calculations and predictor characteristics will be described. The development will follow closely that of Braisted.[7, 8]

Computer Calculations

Figure B1 is a plan view of the position of the predictor marker P relative to the viewing direction of the vehicle television camera V. The position of the predictor marker at any instant represents the projected vehicle position at the end of the next delay period. Thus P must always lead V by a distance equal to the distance traveled by the vehicle during one delay period. The predictor computer used the steering commands issued during the previous delay period (the effects of which are not yet visible to the driver) in calculating the correct position of the predictor marker P relative to V.

The computer was used in real time, in the sense that it carried out maneuvers at the same rate that the vehicle (or simulated vehicle) carried out its maneuvers. The vehicle steering system used stepping motors which changed the direction of motion in 1.8° steps. Thus any curved path was traversed in a series of straight line segments which approximated the path. The computer calculated a predicted segment, which represented by one straight line, the cumulative effect of all steering commands issued during the previous delay period. This segment continually grew at the end represented by the predictor marker and decayed at the end representing the present vehicle position.

To avoid cumulative error, growth and decay were determined from a single set of calculations used to represent both the motion of the predictor marker and the viewing point of the displayed television picture. The calculations were developed in immediate response to all steering commands. The resultsof these calculations were delayed for one delay period using a tape recorder with a tape loop. The two sets of calculations were then subtracted continuously. A rotation to coordinates corresponding to the present viewing direction of the vehicle television camera yielded the position of the predictor marker relative to the vehicle camera. This scheme had the advantage of no cumulative error. Any error present in the initial calculated result was always subtracted one delay period later. The calculations were always referenced to the origin of the experimental run.

The calculations performed by the computer are illustrated in Figure B2. The coordinates (x, y) in Figure B2(a) represent the calculated position of the vehicle based on all steering commands issued from the beginning of the run. For a typical segment of the path

$$\delta x_i = V_R \ \Delta t_i \ \sin \left(\sum_{k=1}^{i} \alpha_k \right)$$

$$\delta y_i = V_R \ \Delta t_i \ \cos \left(\sum_{k=1}^{i} \alpha_k \right)$$

where V_R is the reference speed of the vehicle (a constant), Δt_i is the time duration of the i^{th} segment, and $\sum_{k=1}^{i} \alpha_k$ is the accumulated angular direction of travel. Summation of the segmental values yields the coordinates (x,y):

$$x = \sum_{i=1}^{n} V_R \ \sin \left(\sum_{k=1}^{i} \alpha_k \right) \Delta t_i$$

$$y = \sum_{i=1}^{n} V_R \ \cos \left(\sum_{k=1}^{i} \alpha_k \right) \Delta t_i$$

The summations were performed on an analog computer integrator resulting in

$$x = \sum_{i=1}^{n} V_R \ \sin \left(\sum_{k=1}^{i} \alpha_k \right) \int_{t_i}^{t_{i+1}} dt$$

$$y = \sum_{i=1}^{n} V_R \ \cos \left(\sum_{k=1}^{i} \alpha_k \right) \int_{t_i}^{t_{i+1}} dt$$

The calculated values of x and y appear one delay period later as

$$xD = \sum_{i=1}^{d} V_R \ \sin \left(\sum_{k=1}^{i} \alpha_k \right) \int_{t_i}^{t_{i+1}} dt$$

$$yD = \sum_{i=1}^{d} V_R \ \cos \left(\sum_{k=1}^{i} \alpha_k \right) \int_{t_i}^{t_{i+1}} dt$$

where $d < n$. It should be noted that the summation for xD and yD is over d segments. When xD and yD reappear from the tape delay, the summation of the integrators has progressed to n cumulative segments. The coordinates xD and yD represent the vehicle position with respect to the origin at any given time (Figure B2(d)). The prediction segment was calculated as the difference

$$\Delta x = x - xD \quad , \quad \Delta y = y - yD$$

These coordinates, $(\Delta x, \Delta y)$, give the position of the predictor relative to the vehicle in coordinate axes parallel to the axes at the start of the test. Since the vehicle television camera points in the direction of present motion, a rotation of the x - y coordinate system to a system with one axis parallel to the camera axis was required. The coordinate rotation yielded new coordinates x' and y' given by

$$x' = \Delta x \cos\left(\sum_{k=1}^{d} \alpha_k\right) - \Delta y \sin\left(\sum_{k=1}^{d} \alpha_k\right)$$

$$y' = \Delta x \sin\left(\sum_{k=1}^{d} \alpha_k\right) + \Delta y \cos\left(\sum_{k=1}^{d} \alpha_k\right)$$

The voltages corresponding to (x', y') were fed to the X-Y recorder where the perspective generation was accomplished as described in Chapter II.

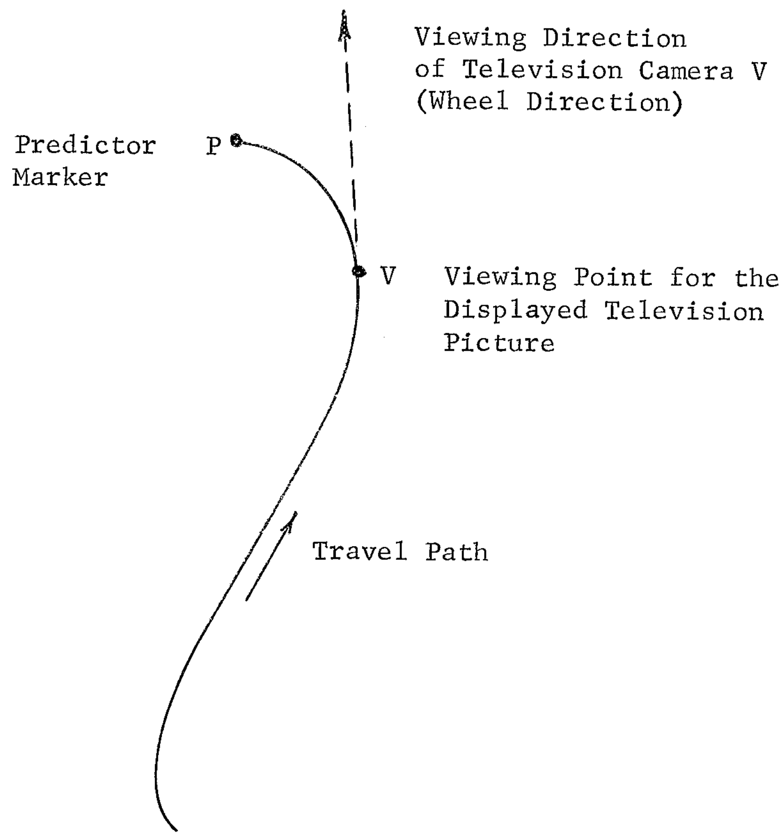
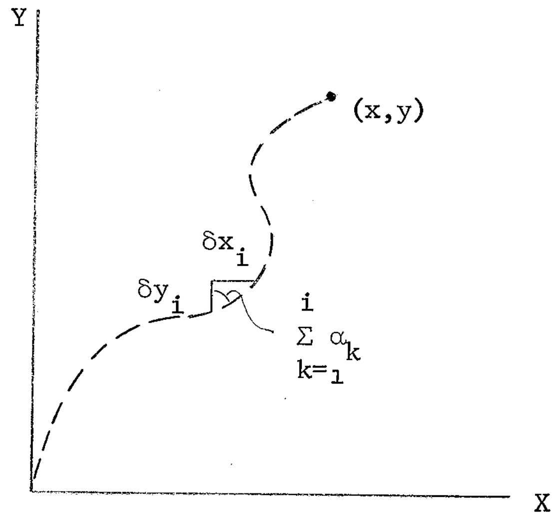
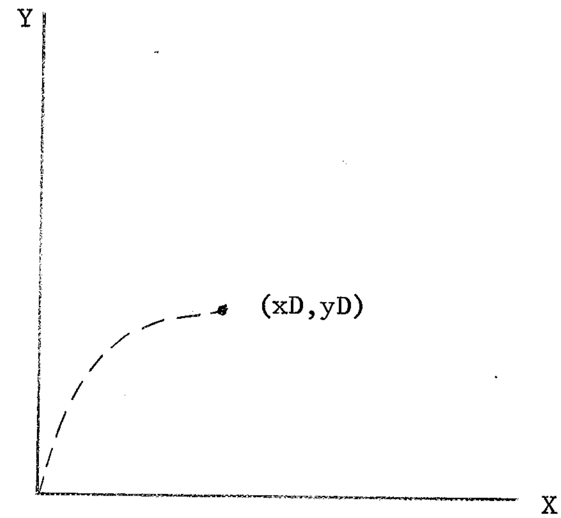


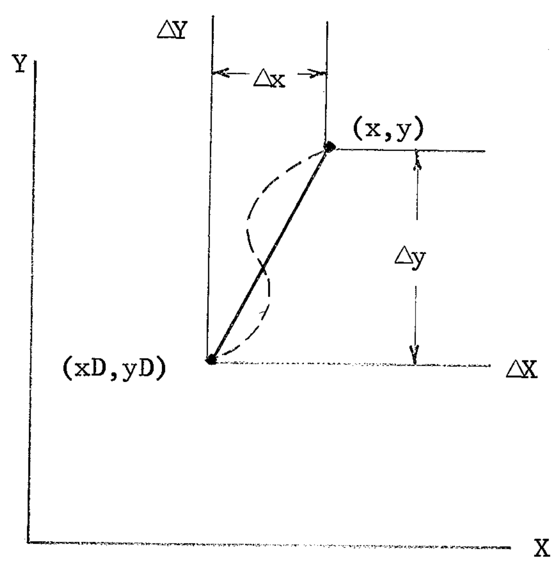
Figure B1 - Plan View of Predictor Marker
Relative to View Direction of Road



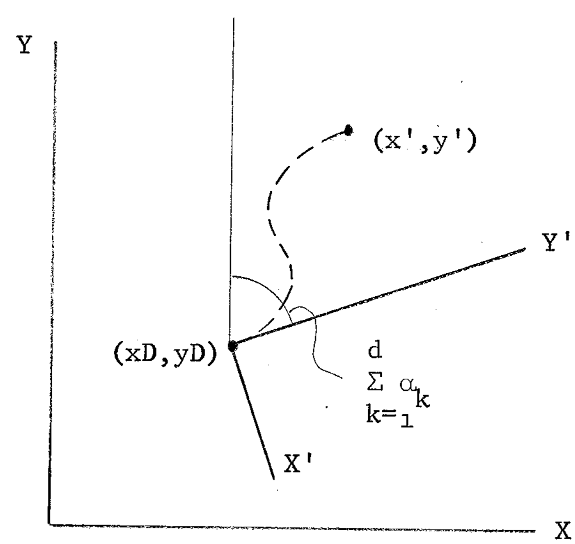
(a) Vehicle position based on all commands from the first.



(b) Delayed vehicle position based on steering commands executed.



(c) Prediction segment.



(d) Rotation of coordinates to coordinates in vehicle.

Figure B2 - Computer Calculations