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TECHNICAL NOTE

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AN INVESTIGATION OF THE EFFECTS OF THE TIME LAG

DUE TO LONG TRANSMISSION DISTANCES

UPON REMOTE CONTROL

Phase I - Tracking Experiments

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SUMMARY

A series of pursuit tracking tasks were performed incorporating a transport lag in the control loop. The target was a mixture of four sine waves, the fastest having a frequency of 16 cycles per minute at full speed. An attempt was made to design the experiments so that they would provide data applicable to remote control of a ground vehicle over long transmission distances.

Three programs were run. In each the time lag was placed between the control and the display. In the first program a velocity control was used and the operator was told that his knob controlled a vehicle, the problem represented a road, and he was to drive his vehicle along the road, using the delayed vehicle position as feedback for whatever means he desired. The objective was not to match the display traces. In the second program, a velocity control was used, and the operator was told that the problem trace represented a road and the delayed trace represented a vehicle and he was to keep them together. The objective was to match display traces. The third program was identical with the first, except that an acceleration control was used rather than a velocity control.

Target speeds used were full speed, $1/2$ speed, $1/4$ speed, $1/8$ speed, and $1/16$ speed. Time lags were $1/4$ second, $1/2$ second, 1 second, $1-1/2$ second, 2 second, 3 second, and 6 seconds. The experimental results are presented in the last section of this report.

INTRODUCTION

This report covers a portion of the work being done at Stanford University under NASA contract No. NSG 111-61. The purpose of this work is to examine the effect upon remotely controlled tasks of the transport lag due to long transmission distances. The subject is of timely interest because of the increasing number of such situations due to the exploration of space. For reasons either of safety or of economy, machines will

frequently operate at extremely large distances (hundreds of thousands of miles) from man. However, because of his ability to recognize patterns, adapt to unprogrammed situations, and make decisions based upon incomplete data, man must be used to exert some degree of control over these machines. A good example of such a situation is NASA's Project Prospector.

A literature search at the beginning of the Stanford project showed little useful published data available. It therefore became necessary to undertake a program of rather exploratory nature. In order to narrow the problem down to a size compatible with the researcher, it was decided to concentrate upon distances on the order of that from the earth to the moon (mean of 239,000 miles, with an accompanying transmission lag of 1.28 seconds one way) and to choose the remote-controlled lunar surface vehicle as a typical task.

The Stanford project consists of three phases. The first phase has been completed. It was a series of tracking experiments incorporating a time delay in the loop. Tracking was chosen as an experimental control task because of the ease of controlling the variables; because it is extremely representative of human control tasks; and because of the great amount of work which has been done on tracking, which might be useable in later generalization of the experimental results.

The second phase is now under way. It consists of a series of experiments with an actual remotely controlled vehicle, so as to simulate more fully the situation of interest. A small, versatile vehicle is being remotely controlled, using television as the primary information feedback sensor.

The third phase will be a correlation of the results of the two series of experiments with each other, with what little theory exists, and with any new theory which can be developed. This phase will not be actively pursued until the first two are complete. The reason for this is that the first and second phases represent a two-sided experimental attack upon the problem. Phase I was closely controlled and limited to the variables of interest only. The experimental situation was necessarily divorced somewhat from the actual remotely controlled vehicle situation. The advantages of such experiments are ease of parameter variation and straightforwardness of cause and effect relationships. However, since the human operator blithely changes his transfer function for different tasks and environments, such experiments must be related to the actual situation.

Phase II represents the actual situation. It is somewhat cumbersome because of the many variables present. However, since it is a close simulation of the actual task of remotely controlling a lunar roving vehicle from earth, it is expected to yield data which is typical of actual man-machine performance.

The full report of the Stanford work will not be available until approximately December 1, 1961. However, because of the interest shown in the program and because of the impending schedule of Project Prospector, it was decided that the results of the tracking experiments of Phase I would be of sufficient interest to be released at this time.

This report consists of a description of the tracking experiments and a series of curves showing the results. A few words of warning are in order to those seeking to use this data. It is not moon-mobile data. When data from Phase II becomes available, the author will propose moon-mobile data. Until this time, it is requested that the reader keep in mind that this report is the Phase I data only. As long as its character is realized it is of interest, as it quantitatively describes the effect of transport lags on a control loop containing the human operator performing the experimental task.

TEST APPARATUS AND PROCEDURE

Philosophy of Experiment

The situation used as a physical model was the remote control of a ground vehicle with television as sole sensory input to the operator. An attempt was made to approach this situation with a simple, one-dimensional tracking experiment.

At this point it would be wise to briefly run through the situation encountered by the earth-based operator controlling a lunar roving vehicle if he has nothing at his disposal save vehicle-mounted television and a direct radio control link. A signal will require some time (approximately 1.3 seconds for the case of the moon) to travel between the vehicle and the operator. Therefore, at any time, t , the situation which the operator sees is not what is presently happening on the moon, but rather that which the vehicle saw at time $t - \theta$. He is further handicapped as any control input he might make will not reach the vehicle until time $t + \theta$.

It seems reasonable that in order to make a control input, the operator must know the vehicle situation (position, velocity, acceleration, etc.) at the time the control signal will affect it. Therefore, he must look at his display, which represents time $t - \theta$, and somehow update it to the vehicle situation at time $t + \theta$. The operator is able to do this with some degree of success, by using his recent control movements to project himself ahead along the vehicle path. Since his control signals take a time θ to reach the moon, the vehicle situation which he sees in his scope (time $t - \theta$) is obviously just being affected by a signal which left the earth at time $t - 2\theta$. The control movements sent between time $t - 2\theta$ and $t - \theta$ will affect the vehicle between times $t - \theta$ and t , so if they are integrated and added onto the vehicle situation shown on

the scope, the vehicle situation can be updated to time t . Continuing this process, since the control signals sent during the time period $t - \theta$ to t will affect the vehicle between times t and $t + \theta$, it is possible to update the vehicle situation to time $t + \theta$.

Should these mental gymnastics be possible for the operator, and should the vehicle retain a one-to-one relationship with the control input, and should a display be available which would make position plotting reasonably simple (such as a Plan Position Indicator display, which presents an "aerial" view showing the vehicle in the center of the screen) the operator might be able to know the vehicle's probable location well enough to make the proper control movements at the right time. At infinitesimal speeds, this would be easy, since progress during the time lag (2θ) would be negligible. However, even assuming a one-to-one relationship between control input and vehicle situation (which is unlikely in a cross country ground vehicle) and a display such as a PPI (which is also unlikely, since it requires a complicated system such as radar or an optical system which would allow a picture from a vantage point high above the vehicle) the process would become increasingly difficult at increasing vehicle speeds and terrain complexities.

The intention of this series of experiments was to attain a feeling for the deterioration of control as a function of the terrain-speed complexity and the time lag θ . In order to exclude other deteriorating factors, the operator was given a one-to-one control-vehicle relationship and a clear uncomplicated display. Quickening and aiding were not considered and such factors as lens angle, scan rate, and camera position were ignored.

Design of Experiment

Below is a simple diagram of the control loop which we are interested in.

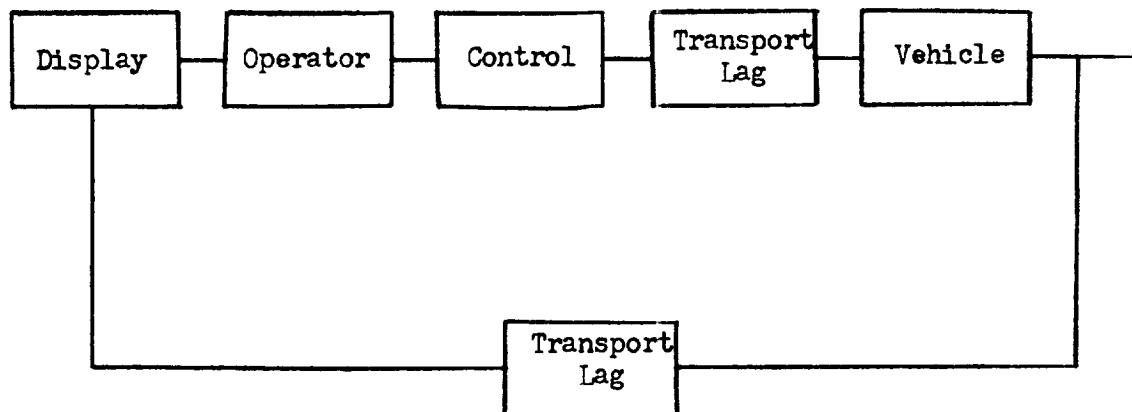


Fig. No. 1

The net requirement on the operator is the same, as far as updating his display to match his control, whether the time lag is distributed as shown in Fig. No. 1, whether it is lumped in the feedback loop, or whether it is lumped between the control and the vehicle. The performance of the system will also be the same, except for being displaced in time by the magnitude of the lag. Therefore, for the sake of experimentation, the lags were lumped together between the control and the vehicle.

Fig. No. 1 may appear a bit strange because it has no exterior input. This is because the operator must derive his own input from information gained from the display. An automobile driver receives his input from his own decisions as to his course and his view of the road ahead. A remote vehicle driver functions the same way, except that with a time lag the process is complicated by the previously mentioned necessity of "time matching" the view ahead with the control signal.

Ideally this series of experiments would have required exactly the same mental processes from the operator as the actual situation. Because of the difficulty of simulating the type of perspective display seen from a moving vehicle, this was not accomplished. Instead, two experimental situations were chosen which would utilize a conventional tracking display and hopefully would bracket the actual situation.

The actual situation would present the operator with the vehicle-road relationship at time $t - \theta$, enough future terrain information so that he could select where he should be at time $t + \theta$, and the previously mentioned memory of control movements which would allow him to project his vehicle to time $t + \theta$. Knowing where his vehicle probably was and where he wanted to be, he could control accordingly and check his progress (belatedly) by looking at the $t - \theta$ situation.

One of the experimental situations presented the operator with vehicle position at time $t - \theta$, and road position at time $t + \theta$. (This situation will be referred to in the future as Type I.) As in the actual situation, the operator had to project his vehicle position ahead to time $t + \theta$ in order to compare it with the road at time $t + \theta$. However, in the experimental situation he was given the road at time $t + \theta$ instead of being forced to derive it from a view of future terrain. This was an advantage. On the other hand, had he desired to check his progress by referring to time $t - \theta$, it was necessary to remember the road position at time $t - \theta$. This was a disadvantage from the real situation, where the $t - \theta$ road situation was given. The advantage would intuitively seem to outweigh the disadvantage, since short term memory was being substituted for the confusing task of selecting a route over rough terrain from out-of-date information. It was therefore suspected that this experimental situation was an upper limit on performance.

The other experimental situation (Type II) presented the operator with vehicle and road position at time $t - \theta$ (as would the actual situation) but allowed him no opportunity at all to see the road ahead. This is the

type of situation which might be encountered should the roving vehicle be forced to navigate a maze of obstacles tall enough to block the vision of the television camera. Since this is unlikely to happen to the extent simulated in the experiment, the experimental situation was more difficult than the actual one would be, and was considered a lower limit on performance.

Description of Experiment

Vehicle driving is a tracking task in that the operator is continually attempting to follow a target (the road) with a controlled quantity (the vehicle). Tracking can be either of two forms or a combination of the two. The first form is compensatory, in which only the error between the target and the controlled quantity is displayed to the operator. He continually attempts to minimize this error. The operator is handicapped because he cannot tell if display movement is due to his action or to target motion. With a time lag in the loop he would be much more handicapped, since identification of inputs would be even more difficult. Vehicle driving contains a few elements of compensatory tracking, since the operator is attempting to keep the target (the road) centered in the display (the windshield). He is trying to minimize the error between the car direction and the road direction.

However, driving is more analogous to the second type of tracking. This is pursuit tracking, where the object is to align the target and the controlled quantity. Both are presented separately on the display, so that the operator can easily see and identify movements in either. If a car could be steered from outside (from a helicopter, for instance) the control would be of pursuit nature, since the controlled quantity (the car) and the target (the road) could both be easily seen. Placing the driver inside the car places slightly compensatory qualities upon the control. However, the driver is essentially part of his controlled quantity, so that he receives many cues other than visual as to its motion. In addition, since he can see ahead to future obstacles, he at all times knows what his target is doing. Target movement is easily discernible from movement due to control input. Therefore, pursuit tracking was chosen for this experiment.

The display was an oscilloscope tube, showing a vertical line which extended from the horizontal center line to the top of the scope, and one which extended from the horizontal center line to the bottom of the scope. The bottom line was driven horizontally by the problem generator described in the apparatus section. The top line was controllable by the subject. Different lags could be introduced into the control loop. Different speeds could be given to the target. Different responses could be given to the knob. In order to test performance with no prediction possible (Type II), the subject was asked to match the two lines. In order to test performance with complete future road information (Type I), the

subject was asked to track the top line, using the bottom line as delayed feedback information to check his position. Scoring included a visual record of the target and the controlled quantity, the percent of time the controlled quantity was in an arbitrary target zone, and the integrated absolute error.

Apparatus

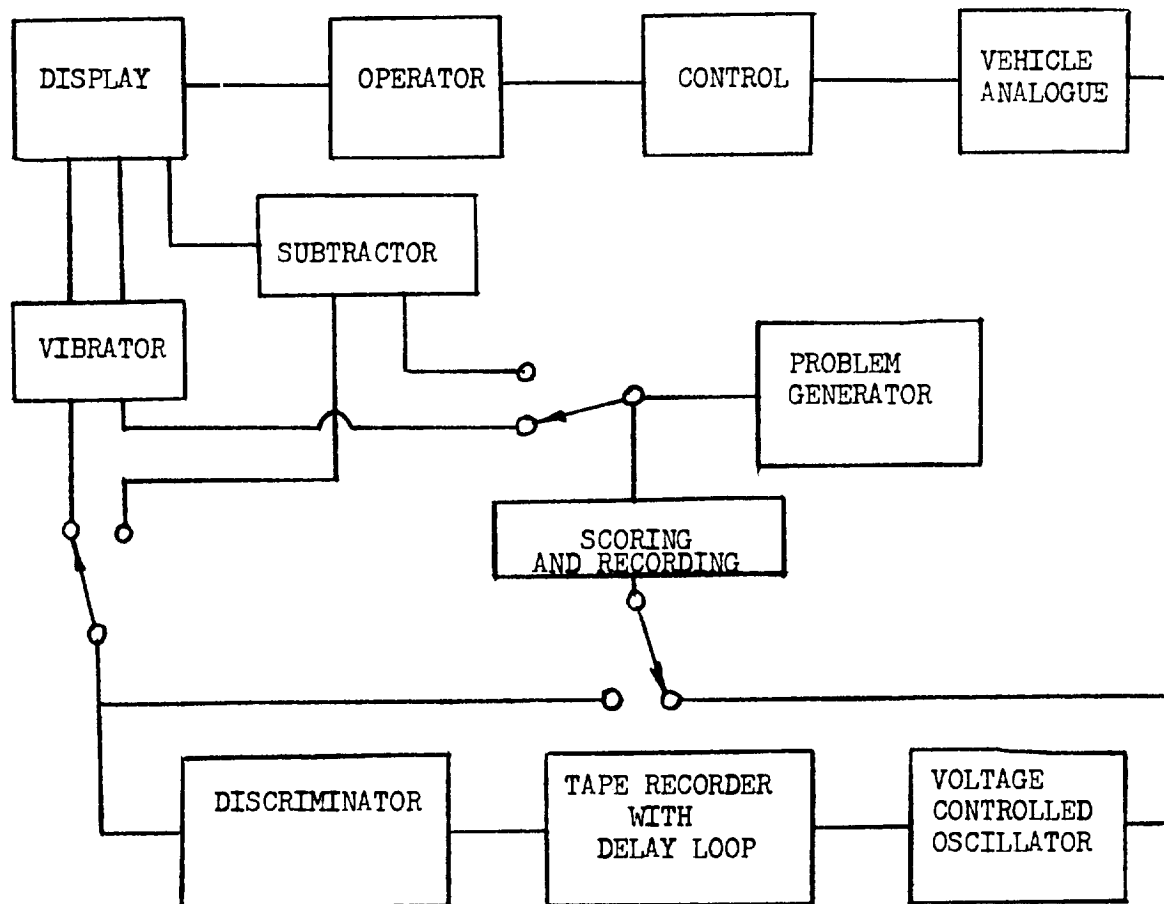


Fig. No. 2

Fig. No. 2 is a block diagram of the experimental apparatus. A description of each block follows:

1. Display. The display was a Tektronix model 514 oscilloscope with a five inch P-11 tube, a blue filter, and a red graticule light. Room lighting was low during the experiments, and the operator, together with the display and the control, was placed at some distance from the rest of the equipment so as to not be distracted.

2. Operator. A compromise had to be made between a large number of experimental subjects, with correspondingly greater statistical validity to average performance, and a few subjects and a greater amount of experimental runs. Since the program was exploratory in nature, and since many runs were desired, a minimum of subjects was used. Two subjects were chosen, both between the ages of 20 and 25, well coordinated, with uncorrected 20/20 vision, and eager to participate. Both were excellent graduate engineering students, with knowledge of both mechanical and electrical aspects.

3. Control. Since no particular attention was to be focused upon the effect of different types of controls, a simple spring-centered knob was chosen. The knob was 2-1/2 inches in diameter and could be turned through 45° with a torque of approximately 1/2 inch pound. A very lightly loaded detent was provided so that there would be no question of the zero location. This detent was found to be extremely useful when the system was being operated as velocity controlled tracking, as it gave real-time information as to the zero velocity position of the knob. This information could not be seen in real time on the scope, as the controlled quantity was fed back through the delay. When the system was operated as a higher order tracking experiment, such as acceleration controlled tracking, the detent represented zero acceleration. In order to provide velocity information, a neon light was included in the display and driven by an open feedback analogue amplifier fed by the first integration of the voltage from the control knob. Since this integration amounted to velocity, the light would go out when the velocity was zero and give the operator an indication of his reversal points. This additional input was so easy to achieve, and such an obvious aiding device that it was considered basic in the control and not a display augmentation.

4. Vehicle Analogue. A Donner model 30 analogue computer was used to provide vehicle-control responses. Because of the flexibility of this computer, it was possible to easily change and experiment with various vehicle dynamics, control knob sensitivities, and so on.

5. Voltage Controlled Oscillator. A Hallamore model 0161 voltage controlled sub-carrier oscillator was utilized which produced a modulated FM carrier centering around 7.35 kilocycles.

6. Tape Recorder with Delay Loop. An Ampex model 307 instrumentation recorder was used. The recorder had both a recording and a playback head stack which could be used simultaneously for monitoring purposes. For this experiment the recorder was modified by constructing a tape loop between the record and the playback heads. By adjusting the size of this loop and the speed of the tape feed capstan, any time lag in the region being studied could be attained between record and playback.

7. Discriminator. A Data-Control Systems, Inc. Model GFD-2 Discriminator was utilized to convert the FM signal from the tape recorder

back to DC. The oscillator-tape recorder-discriminator group therefore functioned merely to take the slowly varying signal from the vehicle analogue (which represents control position and derivatives), delay it for some period of time, and deliver it at the end of that time in its original state.

8. Problem Generator. This device furnished the problem for the subject to track. It produced four sine waves of various maximum frequencies and amplitudes as shown in the following table.

	<u>Resolver</u>	<u>Frequency (Cycles) Minute</u>	<u>Amplitude</u>
D	No. 1	16.0	.4 volts
1	No. 2	12.6	.6 volts
2	No. 3	10.1	.6 volts
1	No. 4	3.8	.9 volts
1			

Table No. 1

Any or all of the four could be added together to produce one wave. The frequencies and amplitudes of the sine waves were chosen so that the wave which resulted from the sum of all four would be smooth enough so that the operator could track it, yet unpredictable enough so that it could not easily be "learned." Four type CS-11-AS-2 Clifton resolvers were geared together and driven through a ball-disc integrator by a gear motor. The gearing between the resolvers dictated the frequency ratios of the sine waves. The ball-disc integrator was used as a variable speed drive so that the resulting wave could be given any speed between zero and the speed represented by Table No. 1. Either the rotor or the stator windings of the resolvers could be excited by various AC voltages and the outputs phase sensitively demodulated to give sine waves.

9. Vibrator. The vibrator was a converted automobile radio vibrator used as a mechanical switch to produce the two traces necessary for pursuit tracking. The unit was driven with 60 cycle AC, which caused it to vibrate at a constant 120 c.p.s. It was then synchronized with the scope sweep so that as the sweep reached the midpoint of the tube face, the vibrator would switch from one information channel to the other. In effect, this resulted in a low cost dual beam scope. After some adjustment it was found that the vibrator produced a good enough square wave so that it was able to switch cleanly and regularly.

10. Subtractor. This was merely a switching box which would channel the difference between the problem voltage and the delayed control voltage to the scope. The result was a compensatory tracking presentation. This was useful as an indoctrination tool, but as yet has not been used for formal experiments. (See previous discussion.) The problem and the control signal were normally switched to the vibrator, as shown in Fig. No. 2, so that pursuit tracking resulted.

11. Scoring and Recording. Scoring and recording could be done either of two ways. As the switch is shown in Fig. No. 2, they were done between the vehicle and the problem. This was Type I tracking, as the aim was to keep the real time vehicle on the real time road, using the delayed vehicle situation as feedback. If the switch was thrown to the other position, scoring was done between the delayed vehicle position and the problem. This represented Type II tracking. In either case, visual records were made of typical runs showing both the problem and the associated scored quantity (vehicle or delayed vehicle). Two model BL 310 Brush Strain Analyzers were used as amplifiers for a two-channel model BL 202 Brush recorder. In addition, two error measurements were made for each run on the analogue computer. For the first, the two quantities being matched were subtracted, the absolute value taken of the difference, and the resulting absolute error integrated during the run. The second error measurement was a Time on Target Score. The absolute error (positive) was biased with an adjustable DC voltage (negative), and the result fed to an analogue amplifier with open feedback loop. Since these amplifiers saturate plus or minus in a situation such as this, it was possible to drive a micropositioner relay through a diode so that it was closed when the error-plus-bias was negative and open when the error-plus-bias was positive. A fixed DC voltage was then integrated through this relay. As a result the voltage would integrate when the error was smaller than the absolute value of the bias and not when the error was larger. The resulting integral over a run was therefore a measure of the time the subject had tracked with his absolute error smaller than the present value.

All four sine waves were added to provide the target wave. Although there was very small probability of all waves adding in phase, the apparatus was adjusted so that this maximum possible target value would correspond to full scale deflection on the recording graph and 1-7/8 inch deflection on the scope, which was slightly into the noticeably nonlinear region of the scope face. This proved to be a fortunate choice of ranges, because during the experimentation the problem stayed considerably below these bounds and the controlled quantity only exceeded them in obvious cases of out-of-control operation.

Conduct of Tests

The control-vehicle dynamics were kept as simple as possible in order to eliminate extraneous variables. The simplest possible type of control in a tracking task is zero order, or positional control. In this type of control, a knob position would correspond to a controlled quantity position on the target face. However, this was considered too unrealistic. A one-dimensional representation of a vehicle can be most easily pictured by imagining oneself standing behind a vehicle which moves away at a constant rate along a gently curving road. The third dimension is unimportant as long as the road is level. The second dimension is the

component of the vehicle velocity vector along the observer's line of sight. This is neglected in one-dimensional tracking. The dimension which is represented upon the display is the component of velocity normal to the observer's line of sight.

A position control would correspond to a vehicle which could move normal to the operator's line of sight in a one-to-one correspondence with the knob. Such a ground vehicle would be extremely difficult to construct. The simplest realistic vehicle would be a low-inertia "crab", in which steering would be accomplished by turning all wheels to the desired direction. The direction of the wheels would have a one-to-one relation with the control knob, except for lags caused by mechanical and ground friction and the inertias of the various parts of the steering mechanism. From the one-dimensional viewpoint discussed above, control of this vehicle would correspond to a velocity control on the tracking experiment. A position of the control knob would result in a sideways velocity. Since this is the simplest possible realistic control situation, it was adopted as a beginning point. Inertias were minimized, except for a very small quantity which was included to give the operator the impression that "something" was being controlled and to smooth out unintentional dither. The amount of inertia was not large enough to affect the operator's ability to track the target. The only important variables were time lag and target speed.

Should a vehicle steer like a conventional automobile, rather than a crab vehicle, a higher order of control would be involved. If inertias were again neglected and the front wheel position assumed to correspond perfectly with the control knob position, a displacement of the knob would result in a displacement of the wheels, which would result in a circular path. When viewed one dimensionally, this would result in a sinusoid. In order to check the effects of such a higher-order control, it was decided to test an acceleration control (knob displacement causes controlled quantity to accelerate) as well as velocity control.

Control sensitivities were selected by programming the computer so that knob movement never exceeded a value of about 45° each side of zero, but yet was large enough so that the spring loading would provide a "feel." Sensitivities were changed for each target speed, so that the same magnitude of knob movement would be required. Different target speeds therefore corresponded to different vehicle speeds, with terrain complexity remaining constant. At lower vehicle speeds, the effect of a given wheel displacement would be to introduce a correspondingly lower normal velocity vector.

It was desired to have runs short enough to allow several to be made at each speed-lag point for comparison. It was also necessary to have runs long enough so that the operator could settle down to his normal mode of operation. After some preliminary experimentation, a run length of five minutes was chosen, of which the last three minutes were scored.

The problem speeds used were full speed, corresponding to the sum of the sine waves shown in Table No. 1, half speed, quarter speed, eighth speed, and sixteenth speed. The time lags were zero, one-quarter second, one-half second, one second, one and one-half seconds, two seconds, three seconds, and six seconds. Six seconds corresponds to a delay in each side of the loop of three seconds, or a transmission distance of 560,000 miles.

The first series of experiments was performed using a velocity control. Scoring was between the vehicle (real time) and the problem (real time) with both the problem and the delayed vehicle position presented on the display (type I). The operator was told that his knob controlled a vehicle and the problem trace represented a road. He was to keep his vehicle on the road. His feedback represented the position of his vehicle x seconds in the past. Both operators were used in this series of tests and all speeds and time lags were given to both operators. The time lags were presented in consecutive increasing order with all speeds being run at each time lag. Learning transfer was therefore maximized.

D
1
2
1
1

The second series of experiments was with the Type II velocity control. Conduct of these was the same as with the Type I velocity control except that scoring was between the problem and the delayed vehicle position, and the subject was asked to align the vehicle line on the scope with the target line. The effect of this was to simulate driving with the lag in the system and no possible prediction. Only one subject was used for this series of tests. The reason for this was twofold. In the first place, this test represented the worst possible case in the best possible vehicle. It was not of the limiting character that either the best case in the best vehicle or the worst case in the worst vehicle would be. In addition, the operators performed sufficiently similarly on the first set of tests that one operator could be considered representative.

The third series was performed exactly as the Type I velocity control series, except that an acceleration control was substituted for the velocity control. The operator was again to align the real time vehicle with the real time road, and was presented with the real time road and the delayed vehicle feedback. Both subjects were used. Fewer speeds and lags were used as trends were desired rather than complete data.

EXPERIMENTAL RESULTS

Twenty-eight pages of experimental results follow this discussion. They are preceded by an index which shows the order in which they are presented. The first twenty present time-on-target and integrated-absolute-error scores for both subjects and all three modes of tracking. The curves on the first ten pages are drawn through the approximate mean of the experimental points. The curves on the next ten pages are drawn with slightly less emphasis on each set of points and slightly more on obtaining

a smooth curve. The last eight pages consist of the charts taken from typical runs. Runs with extremely good performance (low speeds, no lag) and runs with extremely foul performance (high speeds, long lags) are not included, as they are of little interest.

These charts are included because the purpose of this experimentation was to gain knowledge about a subject's ability to drive a vehicle. Good time-on-target and error scores are not sufficient, since good scores can result from an excellent performance 99 percent of the time and a delta function of error in the remainder. One single surge of error, even though so short in time that it does not integrate to much, can quite effectively wreck a vehicle. The charts give an indication of the distribution of the scored quantities.

The target zone was represented by a display distance of $3/16$ ths of an inch centered about the problem. As long as the controlled quantity was in this zone, it was considered to be on target. The approximate width of this zone on the charts is shown at the top of each chart page. Also shown on the chart pages is the rate of chart travel per second. When a run was not considered to be of sufficient interest to warrant the inclusion of the entire run, only one strip appears on the page. This represents 1-1/2 minutes, or half of the scored period. If two strips are shown, the entire scored period is represented.

Error scores are unitless, since the scores are of relative value only. The errors were read from the computer in volts, but these units are, of course, meaningless. In order to gain some feeling for error, a constant error of 1/2 inch on the scope face represented approximately 0.8 major divisions on the chart paper and integrated to 72 over a three-minute period. As a further indication of score value, if the control was centered with the controlled quantity stationary in the center of the scope face and a run made without the operator, the time on target was approximately ten percent and the error about sixty-five.

Some comments are in order about learning, which is an unavoidable variable in experiments including a human operator. In these experiments it was desired to approximate "fully trained" performance. In other words, any performance degradation should ideally be due to the speed and lag parameters, rather than lack of operator training. It was therefore necessary to develop a method of ascertaining when such a "fully trained" state had been reached.

At the beginning of the experimental program, each operator was given a series of runs in order to familiarize him with the apparatus, the display, and the duties expected of him. During these indoctrination runs, he was also given a chance to try different tracking techniques and choose the one which he considered most successful.

After the operator was thoroughly familiar with his task, the experimental runs were started. At each new setting of time lag or

target speed, it was necessary to determine the point at which the operator was no longer being influenced to any appreciable degree by further familiarization with the new values. This was the "fully trained" point.

Two methods were available to accomplish this. One was operator opinion; the other was the opinion of the experimenter. After a few hours experience with the apparatus, the operator could tell quite accurately when he had learned to control any particular speed-lag situation to the best of his ability. By observing the real time error, time-on-target, and integrated error scores, the experimenter could also ascertain when familiarization was complete. Depending upon the difficulty of the task, this point was reached in periods of tracking time ranging from five minutes to one-half hour.

After the operator and the experimenter agreed that steady state operation had been reached, two runs were made. If these runs agreed quite closely, the assumption was made that the learning period was completed. If the second run was higher than the first, it was assumed that learning had not yet been completed and the process was continued until a plateau was reached. If the second run was lower than the first, additional runs were made until the scoring stabilized. The scores achieved after the operator and experimenter agreed that familiarization was complete are those shown plotted in the data section.

This technique, of course, did not guarantee that the end of the learning process had been reached. For one reason, slow improvement was hard to recognize because of the scatter which characterizes data from a system containing a human. However, an impractical amount of experimentation time would have been necessary in order to perform sufficient tracking at each speed-lag point to ensure that no additional learning would take place. Long series of runs were therefore performed at a few test points to check for possible long term or discontinuous learning.

At the beginning of experimentation both subjects were given long series of runs at one-half speed, no lag, and Velocity Type I tracking. Eight five minute runs were performed with five minute rest periods between. These were followed by a continuous thirty minute run. After a day's rest, an additional four runs were performed at the same test point. No improvement was noticeable in either subject. However, after Subject No. 1 had gone through the entire Velocity Type I and Velocity Type II programs he repeated the one-half speed, no lag, Velocity Type I test point and achieved a time on target score five percent higher and an error two units lower.

Subject No. II was not retested at the above point. However, he was tested at one-half speed and no lag at the beginning and at the end of the acceleration control program and no improvement was noticed. After the entire experimental program had been concluded, Subject No. 1 was given a series of tests at one-fourth speed and three seconds lag with Velocity Type I control. After a total of one and one-half hours tracking time at

this point, he had improved his previous time on target score by seven percent and lowered his previous error score by six points.

This is not sufficient data on learning to be conclusive. However, it does appear that the performance of Subject No. 1 did improve slightly with the accumulation of many hours of tracking experience. Subject No. 2 did not demonstrate such long term improvement. However, it is of interest that Subject No. 2 was consistently a slightly better tracker, and that Subject No. 1's long term improvement served only to bring his performance up to the level of that of Subject No. 2. A difference in driving techniques might explain the difference in operator learning. Subject No. 1 might use methods more dependent upon the nature of the target than Subject No. 2. Improvement might therefore come about when Subject No. 1 had tracked long enough to extract additional information out of the target wave. This is theoretically possible, since the target is composed of four sine waves, rather than being completely random. Perhaps after long experience, it is possible to achieve a greater ability to predict future target motion.

The above-mentioned "long term" improvement is not sufficient to in any way invalidate the experimental results. The object of the experimentation was to establish trends and relationships of performance rather than absolute performance values. The method used to establish the point at which the operator was considered "fully trained" was consistent throughout, so any long term improvement would elevate the performance curves somewhat, but disturb their character and relationship to a much lesser degree.

A few of the curves warrant slight additional explanation. The first is the performance of Subject No. 1 with Velocity Type I control and 1/4 second time lag. The scores were little better (and sometimes worse) than the scores achieved with 1/2 second delay in the corresponding situation. Both subjects initially had trouble with the 1/4 second lag, although Subject No. 2 eventually overcame the difficulty. The reason is that a human mind has difficulty in identifying a time period as short as 1/4 second. This lag, therefore, does not have a definite quality as do longer lags. The control seems instead to merely be very sluggish and the operator tends to overcompensate. In many situations, this proved a more difficult situation for Operator No. 1 to handle than a lag of 1/2 second, which although twice as long, is easily identifiable.

Subject No. 1 did not choose to use the detent until a lag of three seconds had been reached. At shorter time lags he had preferred to rely upon the spring loading of the knob. However, at a lag as long as three seconds it became quite important to know the null point of the control knob to a greater accuracy than spring centering would allow. This may explain why the time-on-target scores for certain portions of the three-second-delay Velocity-Type-I run are as good as those for two seconds of delay. The detent cannot definitely be called the reason, however, since the error scores do not show this same character. Operator No. 2 used the detent for the entire program.

During the $1/16$ th, $1/8$ th, $1/4$ th, $1/2$ speed runs with 2 seconds of time lag, Velocity Type I control, and Subject No. 2, the number three resolver was not functioning in the problem generator. The subject was therefore tracking the sum of three sine waves instead of the sum of four. This could explain why his low speed scores were better than might be expected.

The charts on pages D21-D28 show that the error is in general quite uniformly distributed in time. In all cases perfect tracking would result in the dotted line lying exactly on the solid line. Up to a certain point, the charts for Velocity Type I and acceleration tracking show that the subject qualitatively made the proper control movements. The errors were quantitative, in that the subject turned too much or too little. For these runs the solid line represents the target in real time and the dotted line represents the controlled quantity in real time.

As an example of Velocity Type I tracking, see the $1/4$ speed runs at the bottom of page D-23. A good example of acceleration tracking can be seen at the bottom of page D-24. The curves are similar in character, except that acceleration control results in larger errors due to the increased burden it places upon the operator. In both cases the operator's control movements lag the problem movements only by the approximate magnitude of the operator's reaction time ($1/4$ second or more, depending upon the complexity of the decisions involved). This is what would be expected from the experiments, since the operator was presented with the target in real time and his position in delayed time. He could therefore "steer" with the target, but could not check his success until his feedback arrived after the time delay.

With Type II velocity control, results were quite different. A good example appears at the top of page D-24. In this case, the solid line represents the problem position and the dotted line represents the delayed controlled quantity position. Because of the time lag in the control, the operator would move when the problem moved, but the "follower" would not move until the time lag had elapsed. Therefore, as expected, the follower lagged the problem by the time delay plus the reaction time of the operator plus any additional hesitancy which was introduced by the difficulty of the task.

The controlled quantity path was not a perfect replica of the problem path, except for being displaced in time, because the operator attempted to outwit the system. Knowing the delay existed in his control, he would overcontrol in order to catch up with the problem, and then attempt to stop before the problem stopped in order not to overshoot. This became very pronounced in the six second delay, $1/4$ speed run on page D-24. The subject not only overcontrolled (note much sharper slopes on controlled quantity than on problem), but he also waited until he had an indication of what the problem might do before he moved the control. Instead of matching the problem, he therefore drove in a series of steps, which matched only the problem extremes.

At some point of increasing time lag and target speed, a marked instability became noticeable. Examples are the top chart on page D-26 (1/2 speed, 3 seconds lag, velocity Type II control), and the center portion of the third chart from the bottom of page D-26 (1/2 speed, 3 seconds lag, acceleration control). The controlled quantity was out of phase by almost 180° with the problem. This represents an absolutely out of control situation, and, of course, is far beyond the bounds of interest for vehicle control.

D In order to use this experimental data to provide information
1 applicable to a specific control situation, such as control of a lunar
2 vehicle, it is necessary to define acceptable performance. Some minimum
1 acceptable time-on-target score and some maximum permissible error must be
1 chosen using the charts on pages D-21-D-28 as an indication of control
precision. Once this is done, the first 20 pages of curves give a rapid
indication of the effect of the independent variables on performance.

When using these curves it should be kept in mind that low time-on-target scores are rather meaningless, since time-on-target can never become less than zero and the curves become asymptotic in nature no matter how uncontrolled the performance. Similarly, error curves become asymptotic at very high values since the target always remained upon the scope face. The asymptotic nature of the time-on-target scores is very apparent, since the minimum value is within the ordinate range. The error curves are not so clearly asymptotic, since the ordinate includes error scores only up to 70, whereas an average error of 1/2 of the useable scope face would have resulted in an error of approximately 300.

Although as mentioned previously, it is not the purpose of this report to derive moon-mobile design criteria, it is worthwhile to examine briefly the experimental data at the earth-moon lag time as an example of the use of the curves. As a starting point, let us assume that neither time-on-target scores below 50 percent nor error scores in excess of 15 are acceptable. This assumption should, of course, be based upon the terrain to be traversed. Obviously a different degree of precision is going to be required to drive through a narrow canyon which turns every 30 feet than to merely dodge obstacles placed 30 feet apart. However, at this point nothing is known of the nature of the terrain. Scores of 50 percent on-target and 15 error represent a reasonable starting point, since an examination of pages D-21-D-28 show that any scores worse than these resulted from a performance which would in all probability have been inadequate for vehicle control.

The curves on pages D-1 to D-20 are quite linear within this region of acceptability. The most notable exception to this linearity occurs in the region of low (below 1/16th) target speed on pages D-1 to D-10. Although data was not taken at these speeds, it appears that the curves bend rather sharply into the 100 percent on-target and 0 error points. This is reasonable, since at very small target speeds the operator should be able to continually remain on target due to the fact that target motion

during the time lag would be so small. Time-on-target scores plotted against target speed should therefore leave the 100 percent point with a very small slope. On the other hand, as soon as the operator must move the knob, he accrues a small amount of error due to stick-slip friction and imperfections in his manual movements. Error plotted against target speed therefore climbs rapidly to some small value and then begins its characteristic increase.

The effect of an earth-moon time lag (approximately 2-1/2 seconds) on these experiments can be seen on pages D-11 to D-20. Considering first the time-on-target limitation, page D-12 shows the effect of the lag upon the runs with velocity Type I control. With no lag the full target speed could be acceptably followed. With 2-1/2 seconds lag, the "controllable" target speed was slightly less than 1/4 speed. Page D-13 shows the same information for the velocity Type II control. With no lag, full speed could again be controlled. With 2-1/2 seconds lag, permissible speed was approximately 1/8 as high. Page D-15 presents the effect upon acceleration control. In this case only 1/2 speed could be controlled with no lag. With a 2-1/2 second lag, the maximum controllable speed was 1/8 speed.

Considering the error limitation, page D-17 shows that the lag reduced the "controllable" speed from full to slightly less than 1/4 speed with velocity Type I control. With velocity Type II control (page D-18) the speed was reduced from slightly under full to 1/8 speed. With acceleration control (page D-20) speed was reduced from 1/2 speed to 1/8 speed.

In order to investigate the effects of a tighter performance requirement, let us now assume that neither time-on-target scores below 80 percent nor error scores in excess of 5 are acceptable. Considering first the time-on-target criteria, a time lag increase of from zero to 2.5 seconds required a speed reduction of from 1/2 speed to between 1/8 and 1/16th speed for the velocity Type I control, from 1/2 speed to 1/16th speed for velocity Type II, and from 1/4 speed to much less than 1/16th speed for acceleration control.

Because of the error limitation, the increased time lag lowered the maximum permissible speed from 1/2 speed to between 1/16th and 1/8th speed for velocity Type I control, from 1/2 speed to 1/16th speed for velocity Type II control, and from 1/4 speed to much less than 1/16th speed for acceleration control.

Several comments result from this preliminary investigation of the curves. An example of the looser performance limitation is the 1/4 speed, 3 second lag, velocity control Type I chart on page D-23. An example of the tighter is the 1/16th speed, 3 second lag, velocity Type II run on page D-21. The time-on-target to error score relationships of 50-15 and 80-5 were chosen because they seemed to typify corresponding scores.

The first point of interest is that the time-on-target and the error limitations give very similar results. Since the curves are quite linear in the region of interest, it can be concluded that both time-on-target and error scores are valid performance measures, as long as the markedly asymptotic regions of the curves are not used.

The second interesting feature is the similarity of the lag effect at the two performance levels. In both cases with no lag the maximum speed "controllable" with velocity Type I and velocity Type II controls (which are identical at no lag) was roughly twice that "controllable" with the acceleration control. Acceptable speeds were approximately twice as high at the lower performance limit than at the tighter limit.

Performance decay due to the lag was slightly more serious in the case of the more severe limitation. With this criteria, maximum acceptable speed with velocity Type I control was reduced to between $1/8$ and $1/4$ of its no lag value, with velocity Type II to $1/8$ of its no lag value, and with acceleration control to less than $1/4$ of its no lag value. With the lower limitation, maximum permissible speed with velocity Type I control was reduced to slightly less than $1/4$ of its no lag value, with velocity Type II to $1/8$ of its no lag value, and with acceleration control to approximately $1/4$ of its no lag value.

Another interesting point is the close similarity of velocity Type I controlled runs at $1/8$, $1/4$, and $1/2$ speed with acceleration controlled runs at $1/16$ th, $1/8$ th, and $1/4$ th speed, respectively, at all experimental time lags. As speeds increased above this point, the relationship lessened. Full speed runs with velocity Type I control are quite superior to $1/2$ speed runs with acceleration control because of the cumulative confusion due to the acceleration control at higher speeds. However, in general the character of the acceleration curves is quite similar to that of the velocity Type I curves.

A very gross relationship between target speed and vehicle ground speed can be attained by considering only the highest frequency sine wave in the target function. This wave has a frequency of 16 cycles per minute at full target speed and shows up as the shortest duration "wiggle" in the target function. A vehicle traveling 10 miles per hour travels 880 feet in a minute. If the vehicle were travelling in a sinusoidal path, a frequency of 16 cycles per minute would be equivalent to one cycle every 55 feet. Full target speed, therefore, corresponds roughly to a vehicle speed of 10 miles per hour over terrain containing obstacles 30 feet apart (two per cycle).

The vehicle to be used in the Phase II experiments at Stanford has small inertias and simple dynamics. Assuming that it will be driven over a course which requires a degree of control similar to that discussed in this section and that the course contains obstacles on the average of 15 feet apart, the author is expecting a maximum no-lag speed of from $2-1/2$ to 5 miles per hour and a maximum speed with $2-1/2$ seconds lag of somewhere

between $1/4$ and $1/8$ of the no-lag speed. Less severe control requirements and less complex courses will, of course, allow higher speeds. More complicated control-vehicle dynamics and higher inertias will correspondingly reduce maximum allowable speed.

Stanford University,
Stanford, Calif., November 2, 1961.

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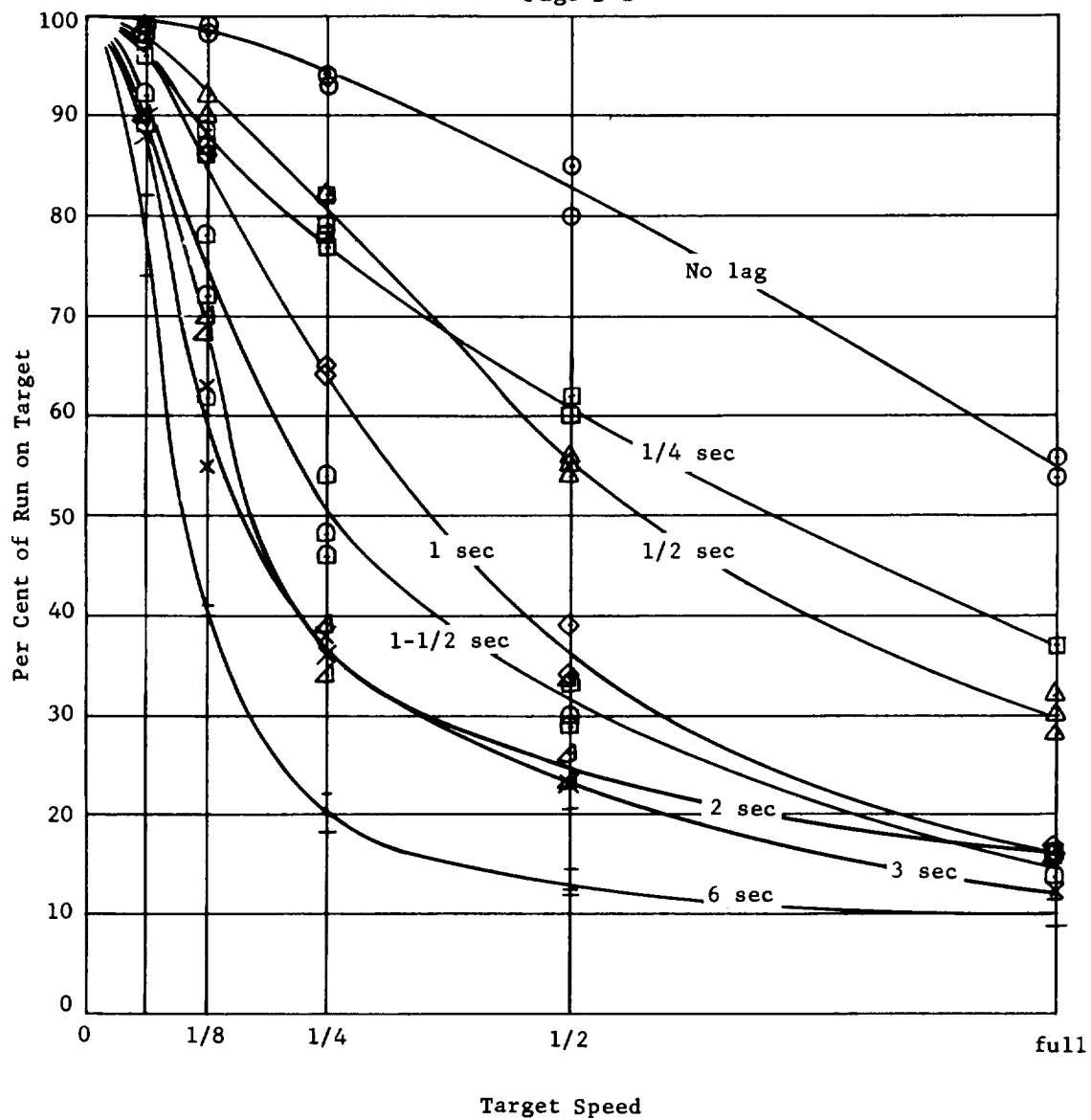
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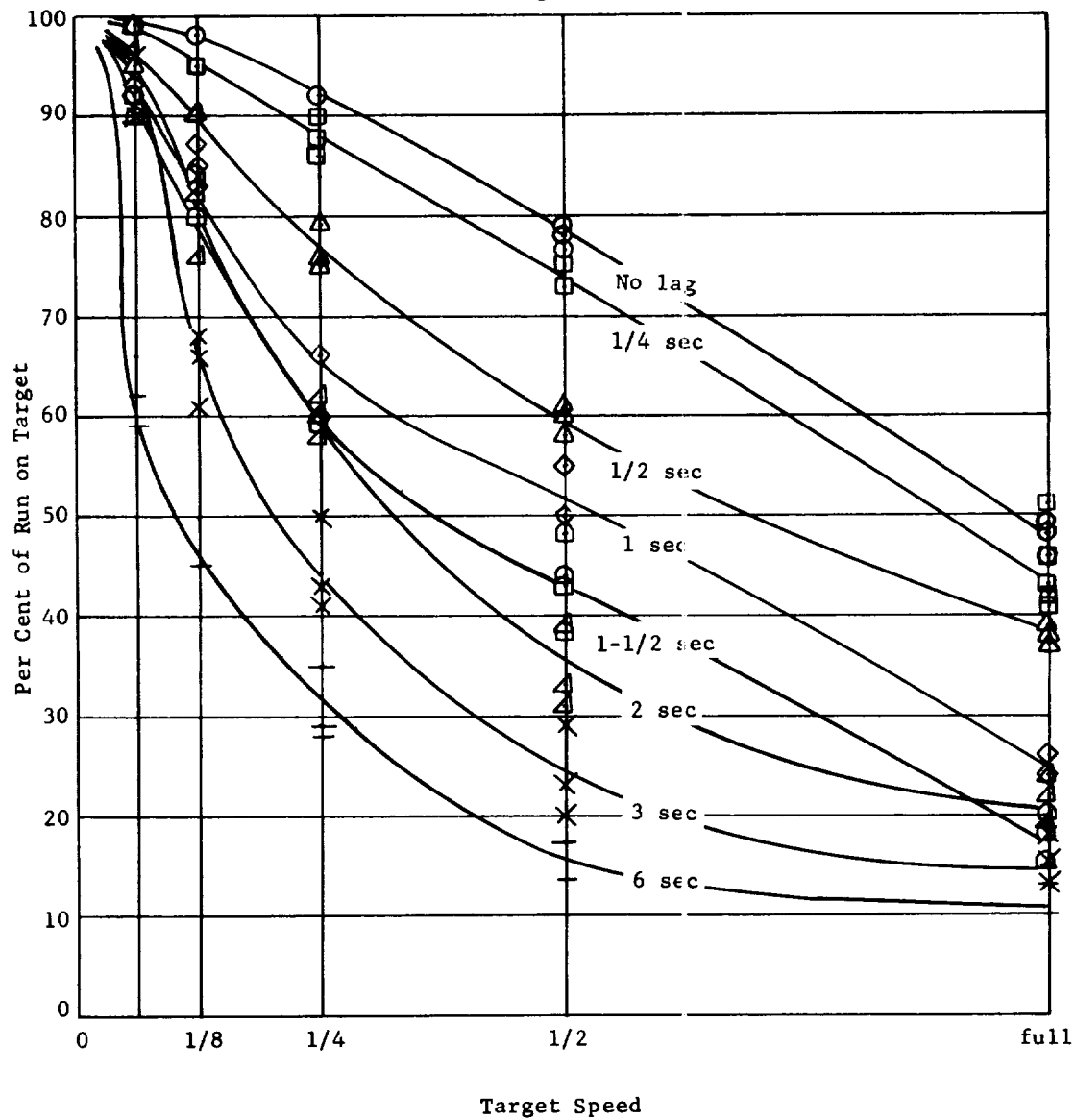
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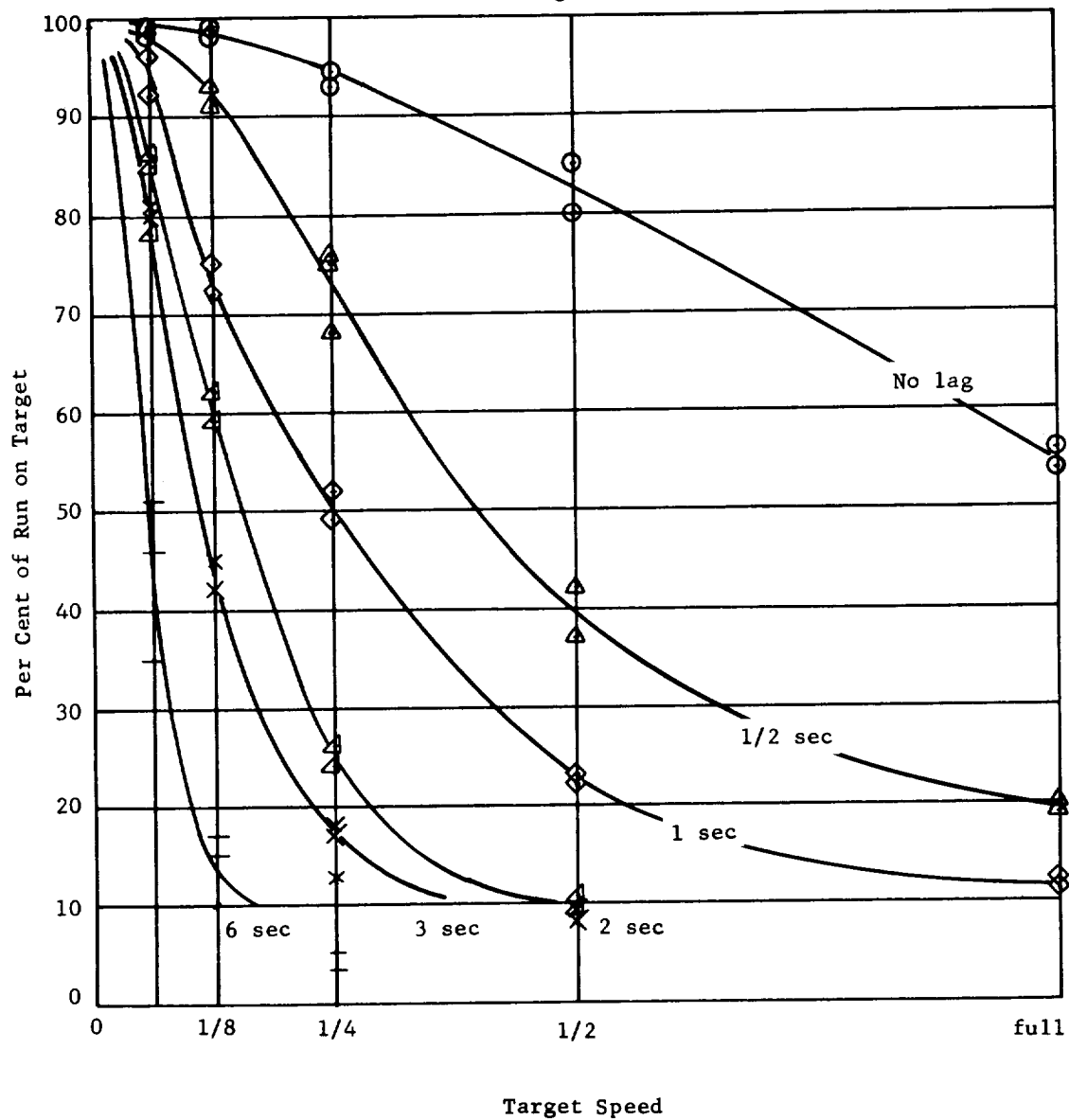


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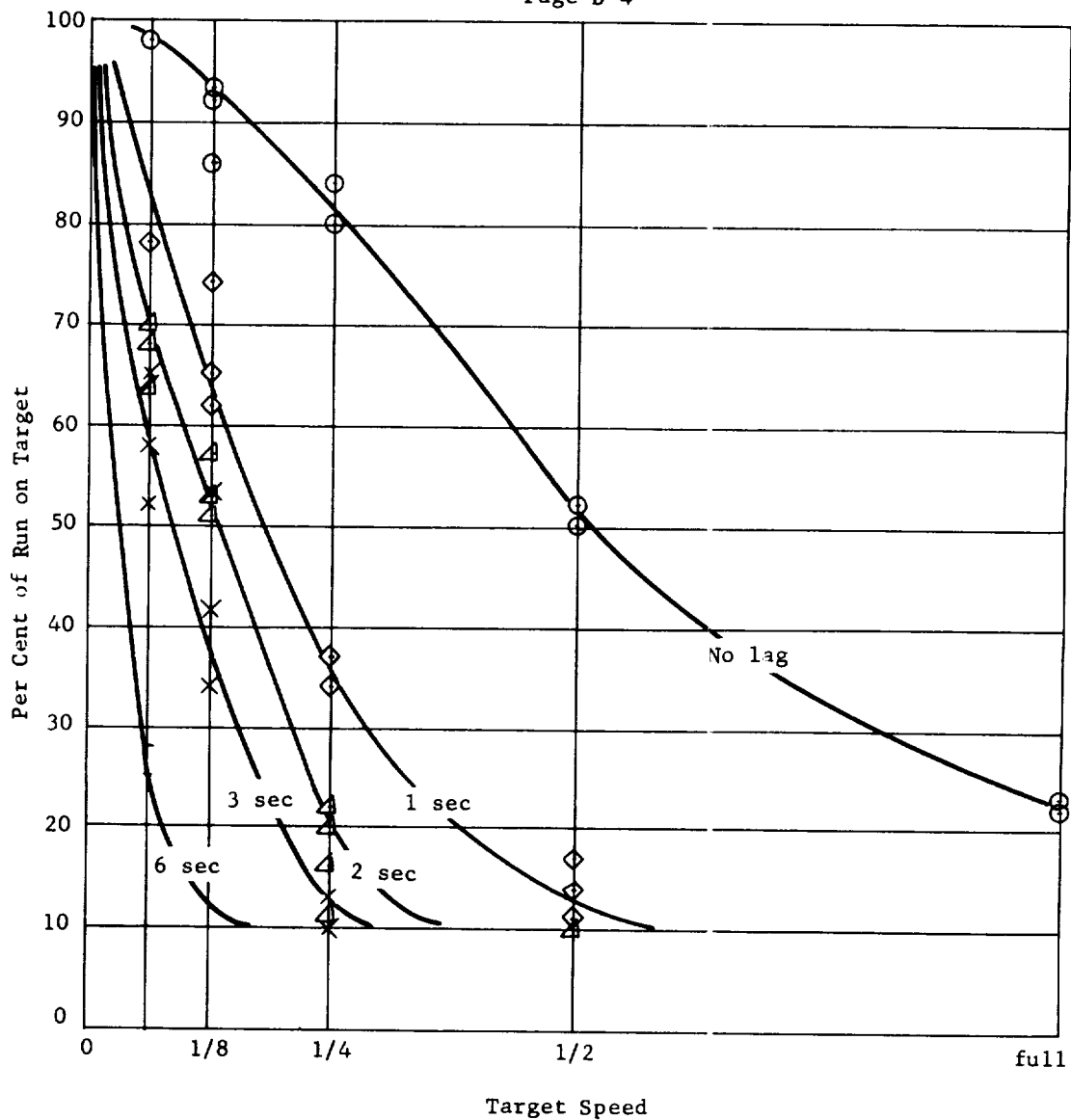


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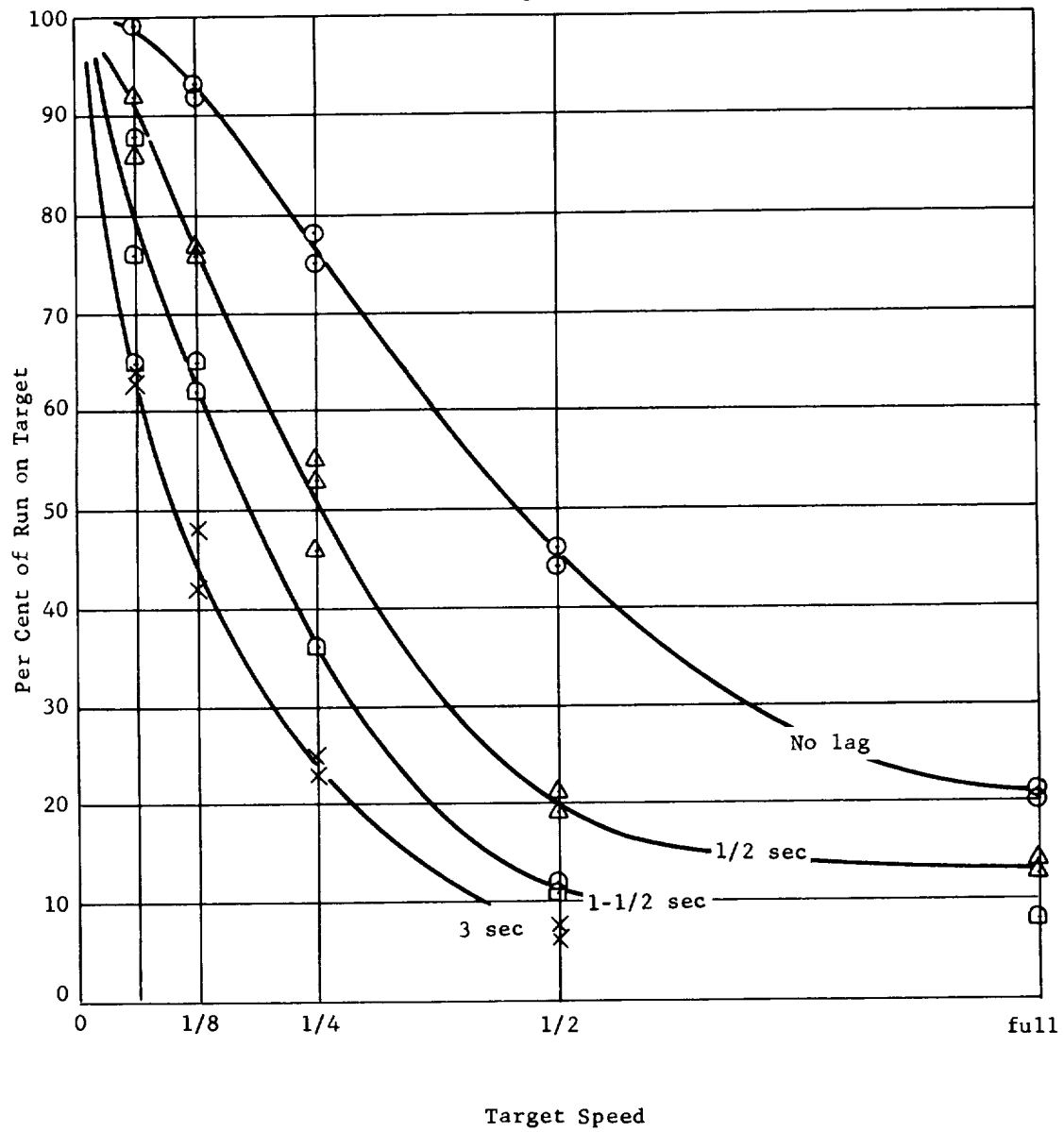


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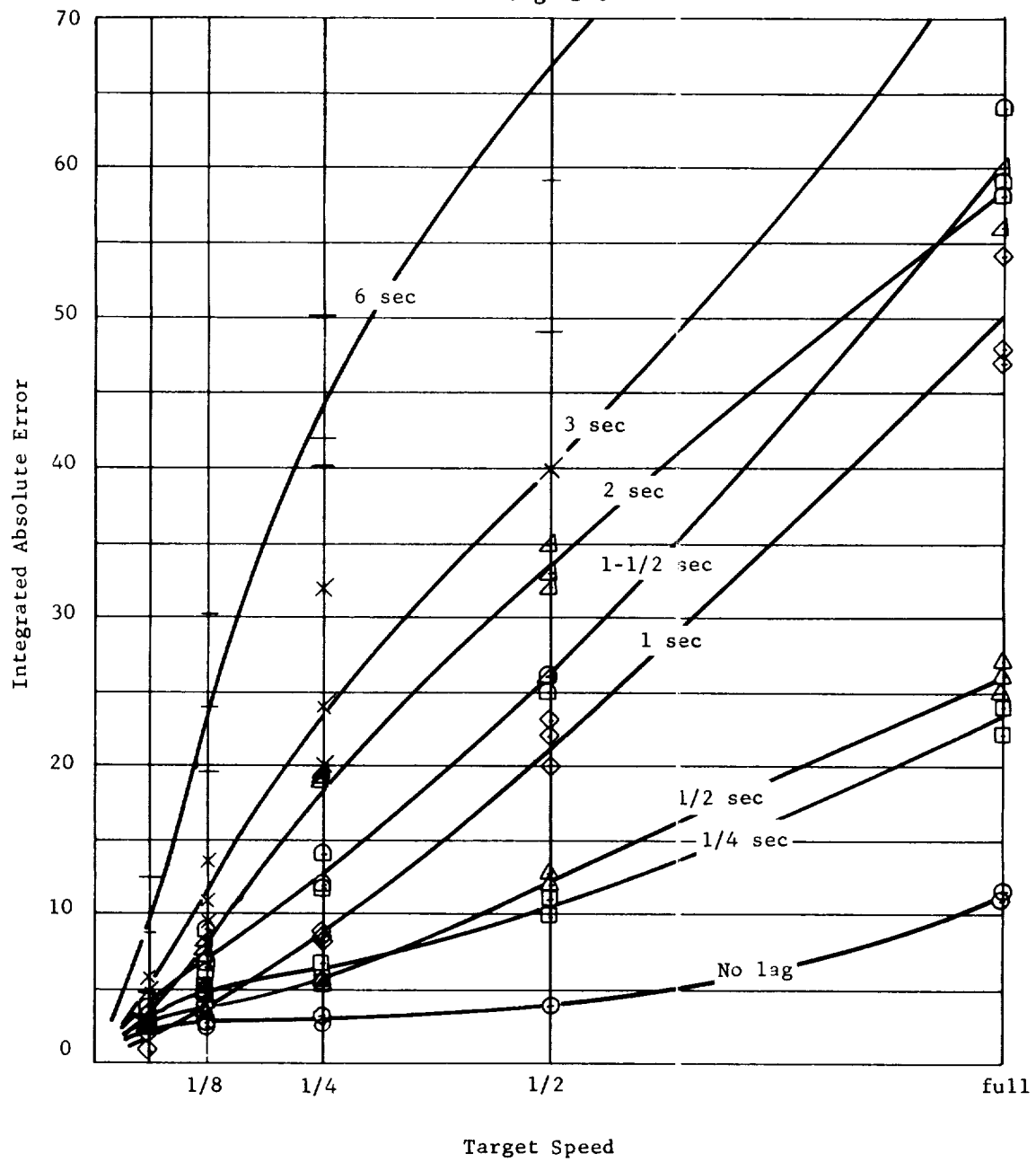


Time on Target vs. Speed
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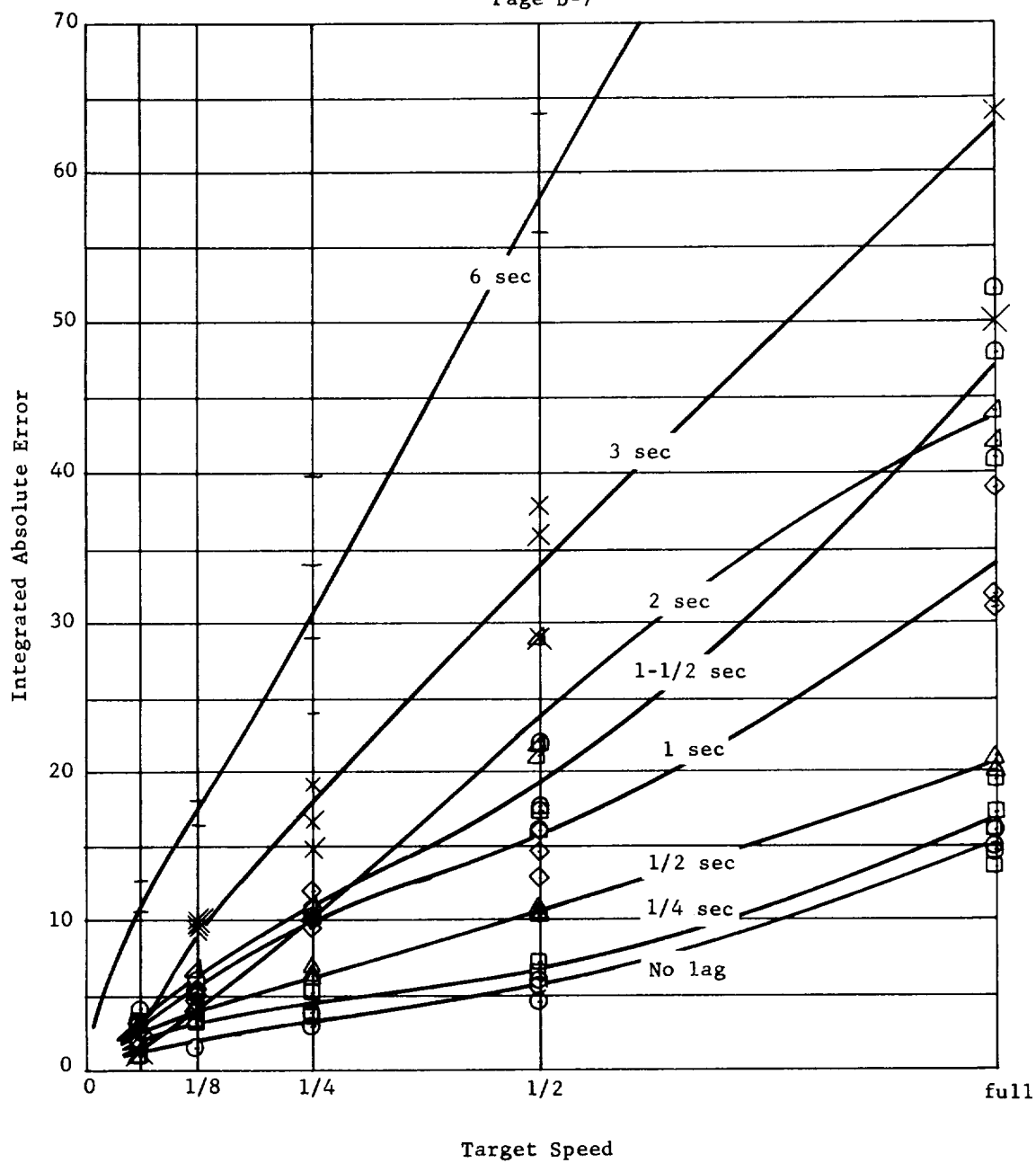


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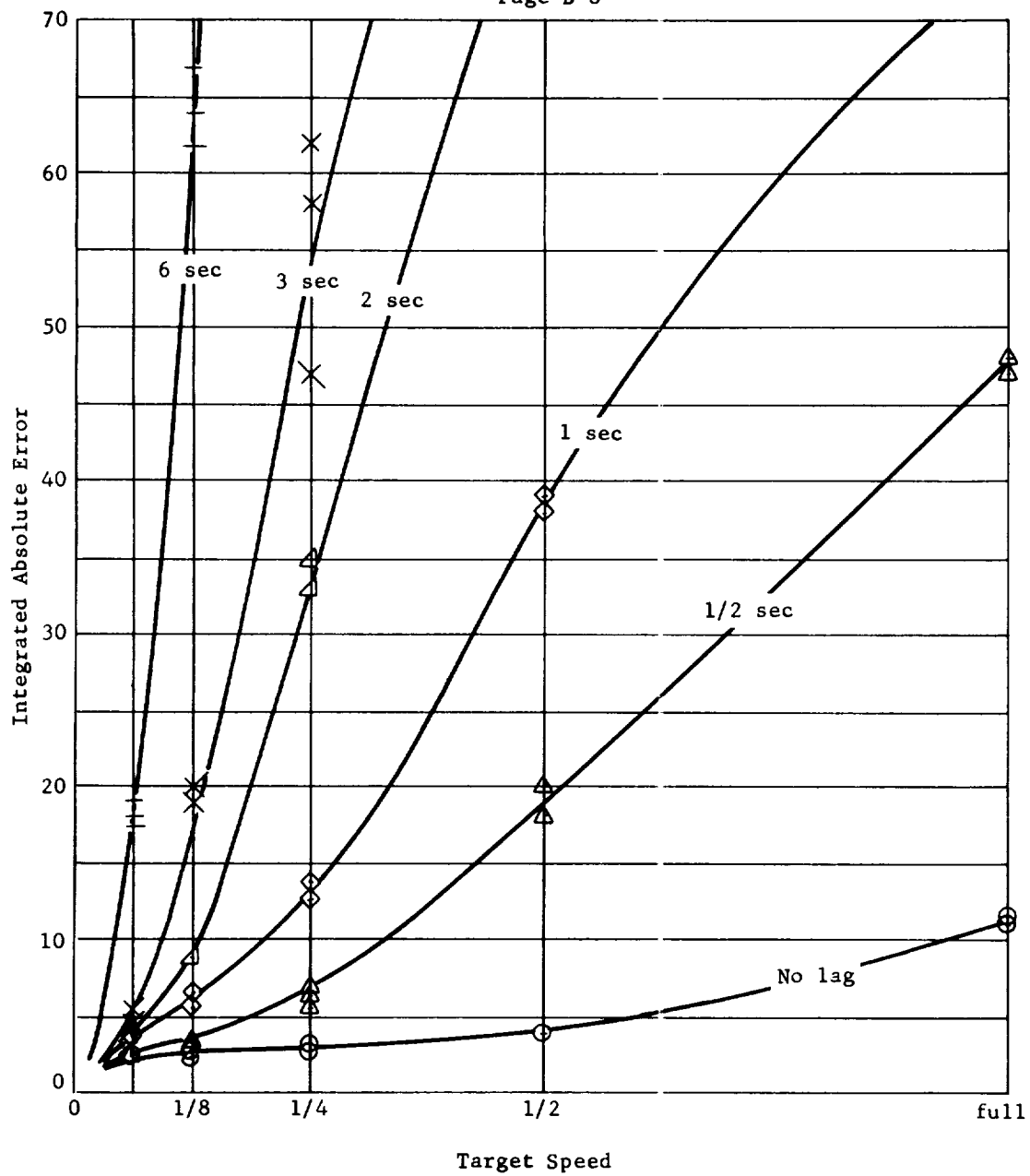


Error vs. Target Speed
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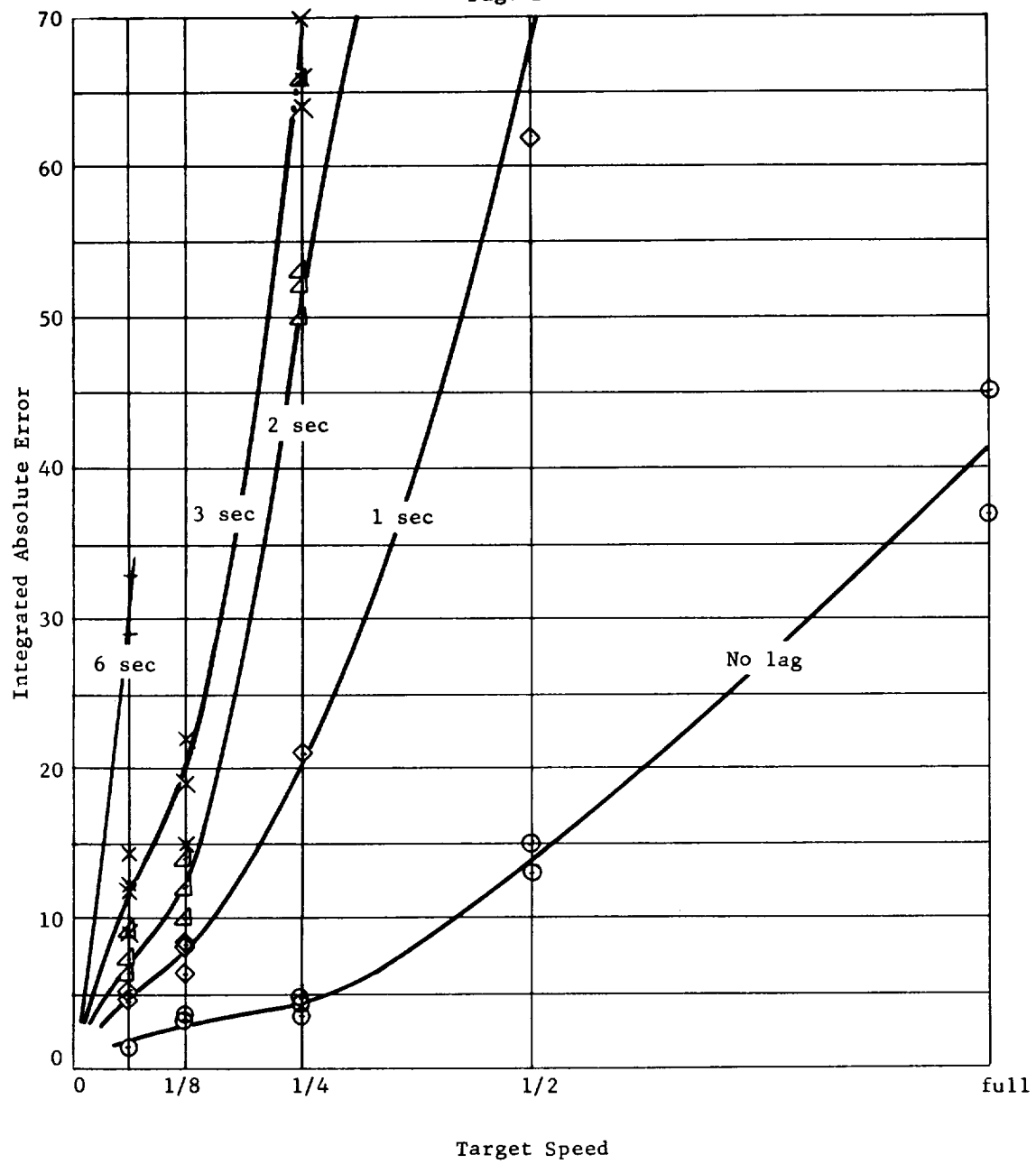


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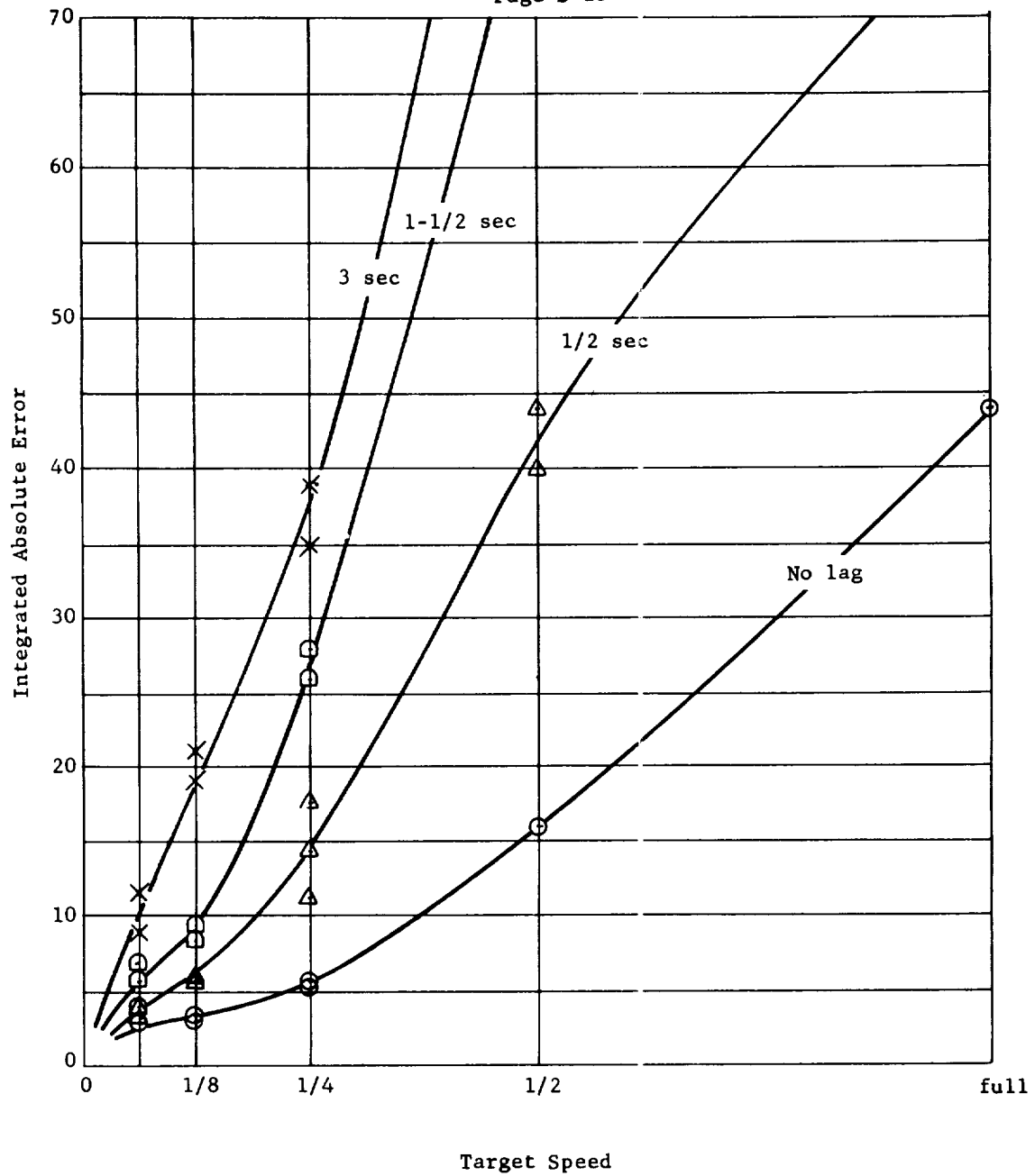
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Velocity Control - Type II

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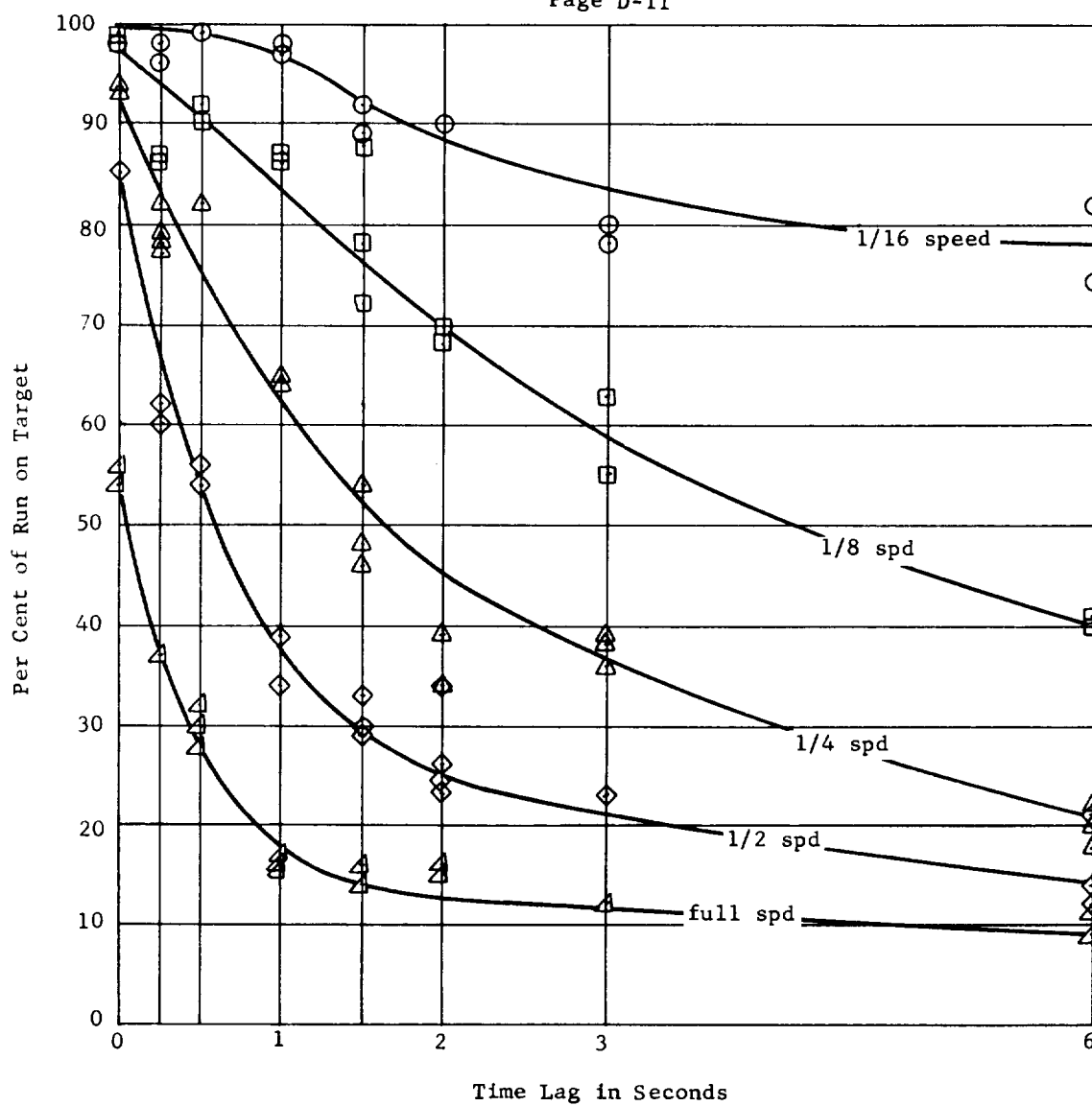
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 Subject No. 1
 Acceleration Control

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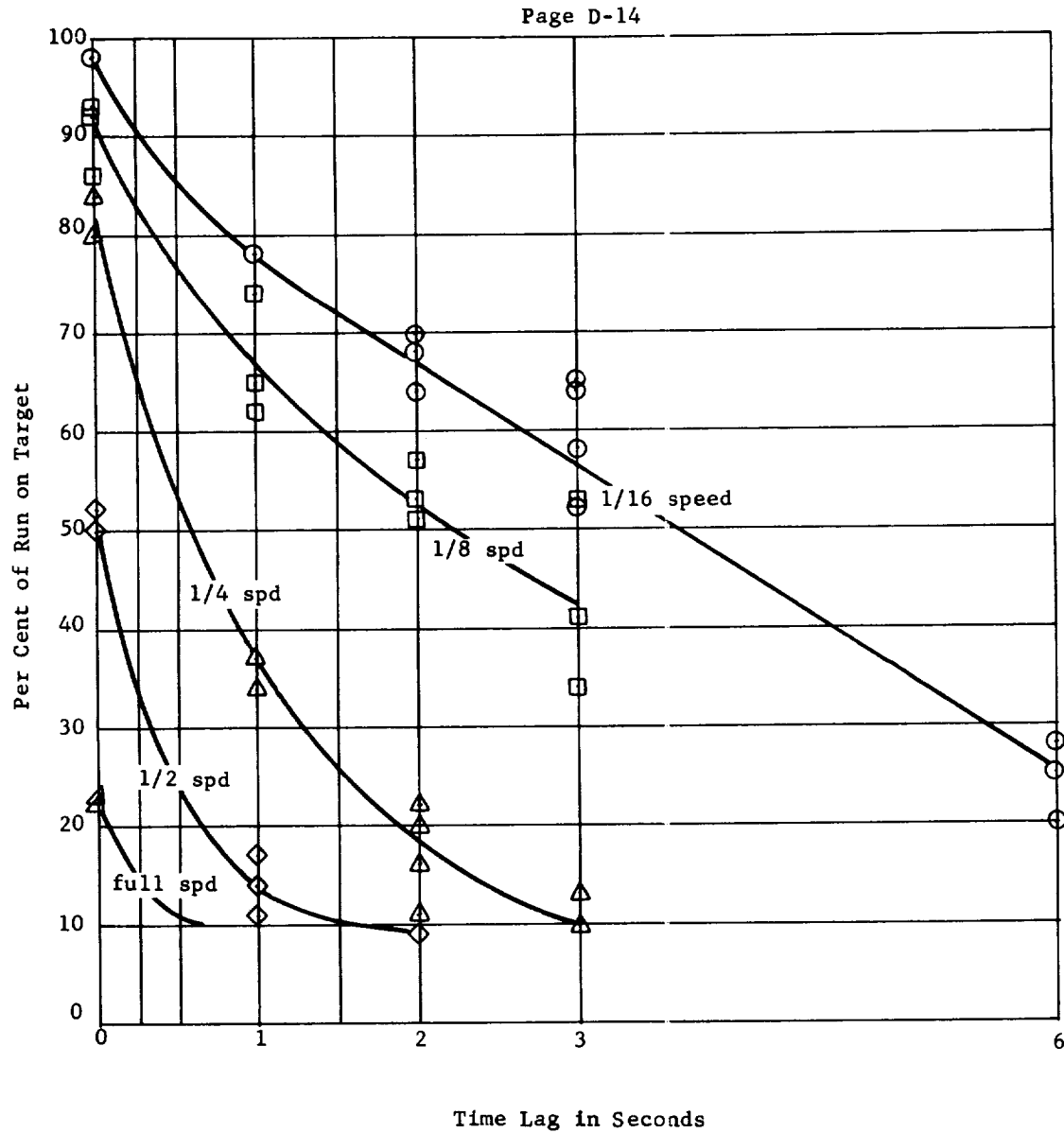


Error vs. Target Speed
Subject No. 2
Acceleration Control

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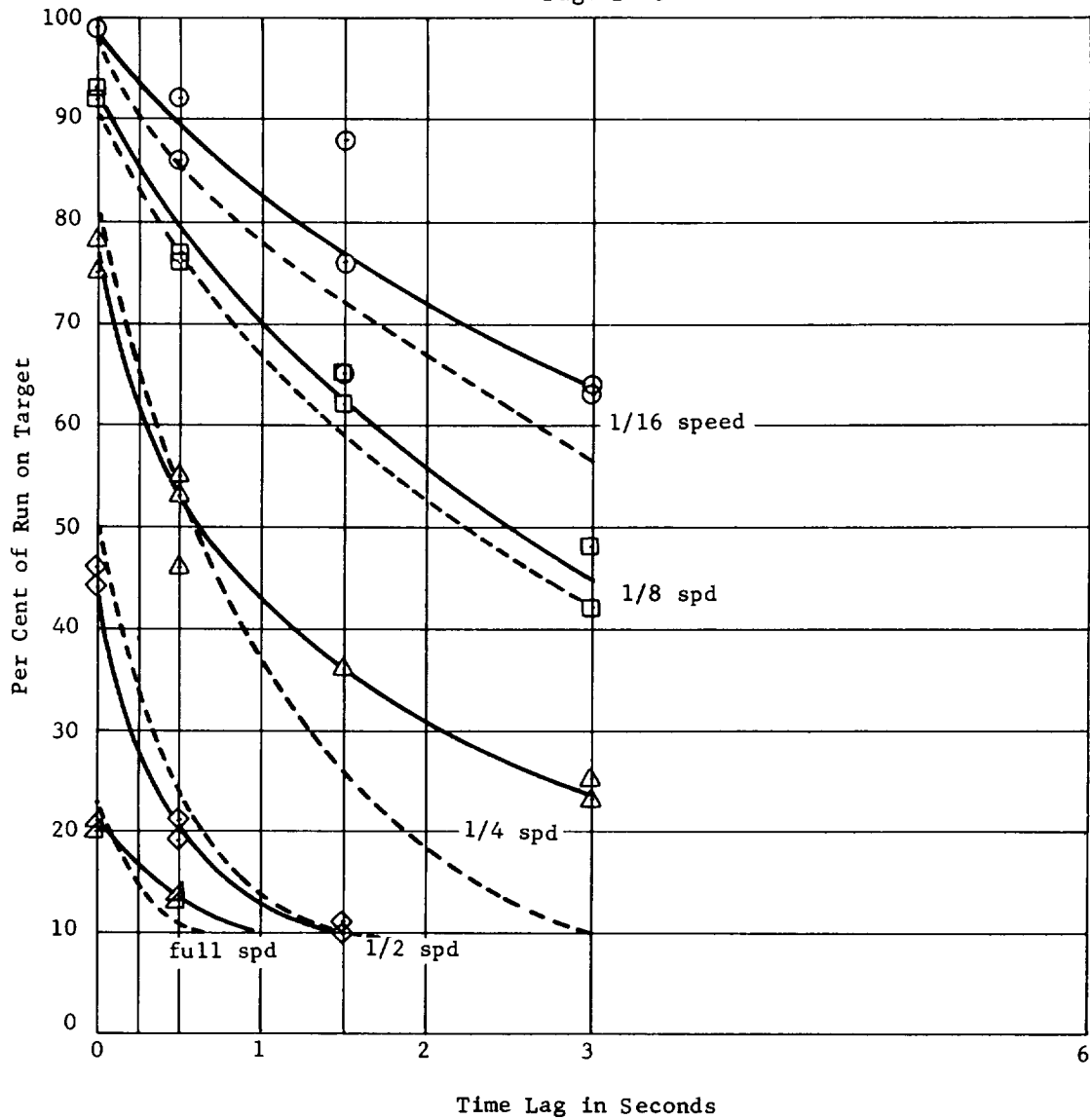


Time on Target vs. Lag
Subject No. 1
Velocity Control - Type I

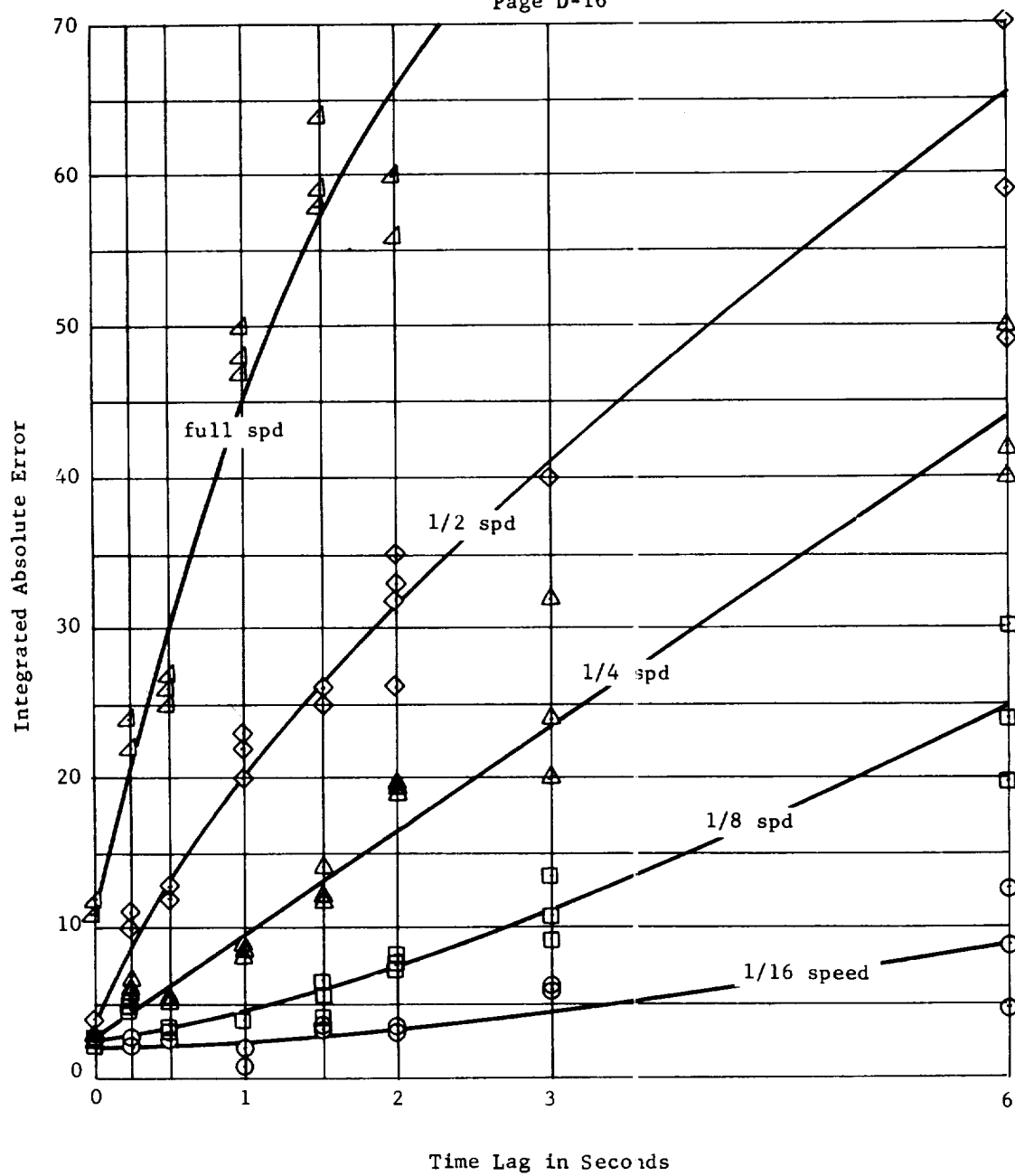


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Subject No. 1
Acceleration Control

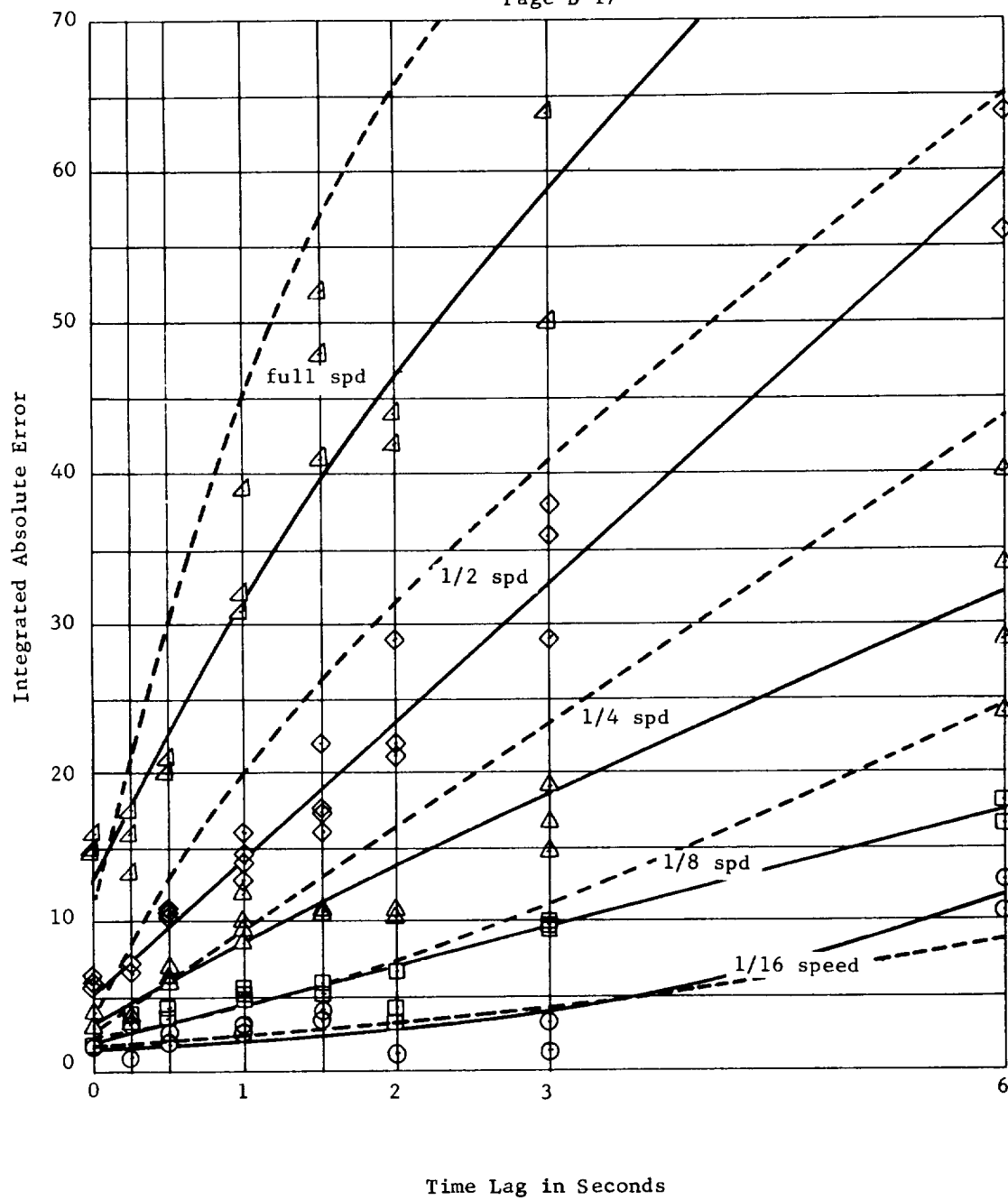
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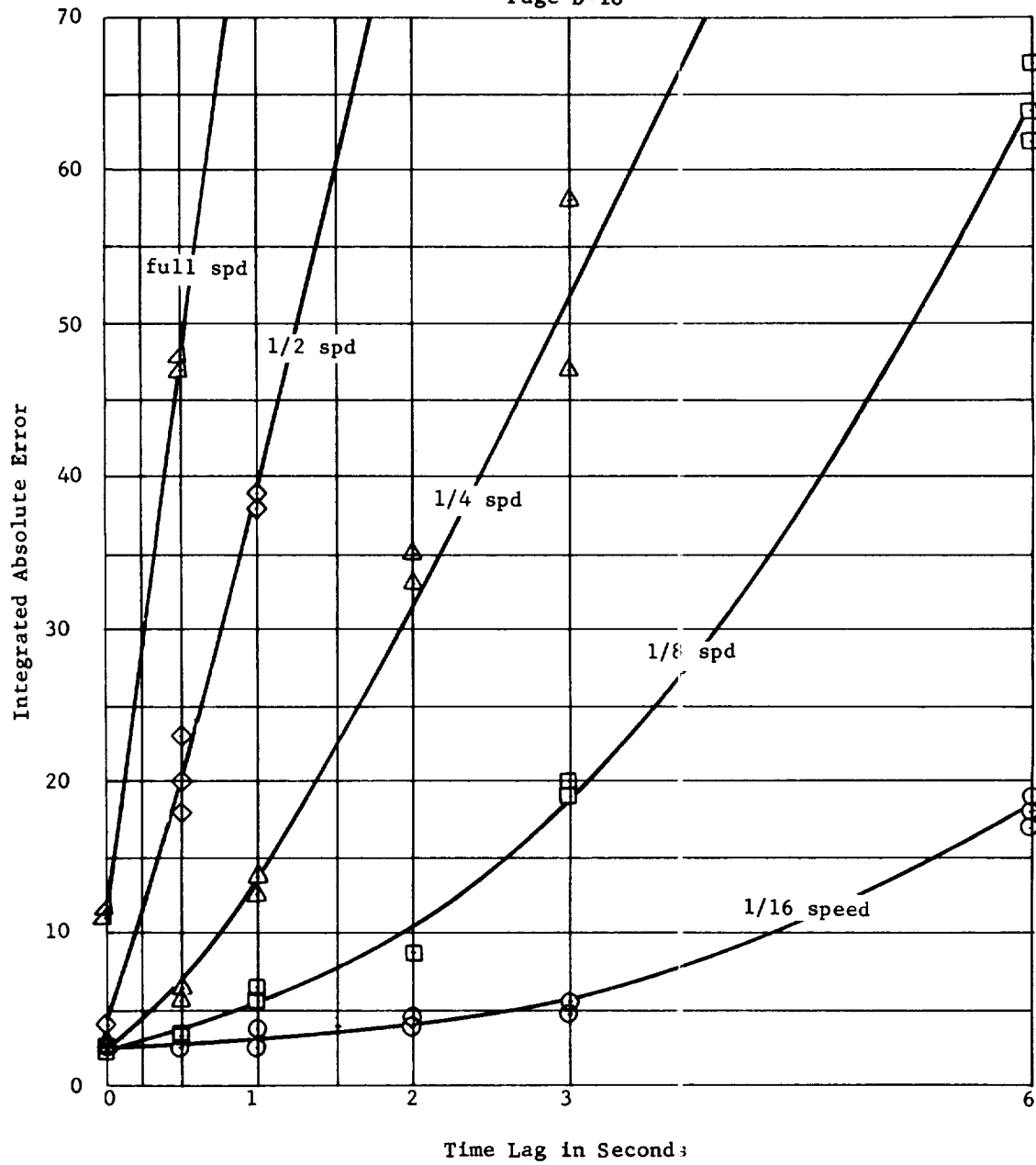
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 Subject No. 1 - Dotted Line
 Subject No. 2 - Solid Line
 Acceleration Control



Error vs. Lag
 Subject No. 1
 Velocity Control - Type No. 1

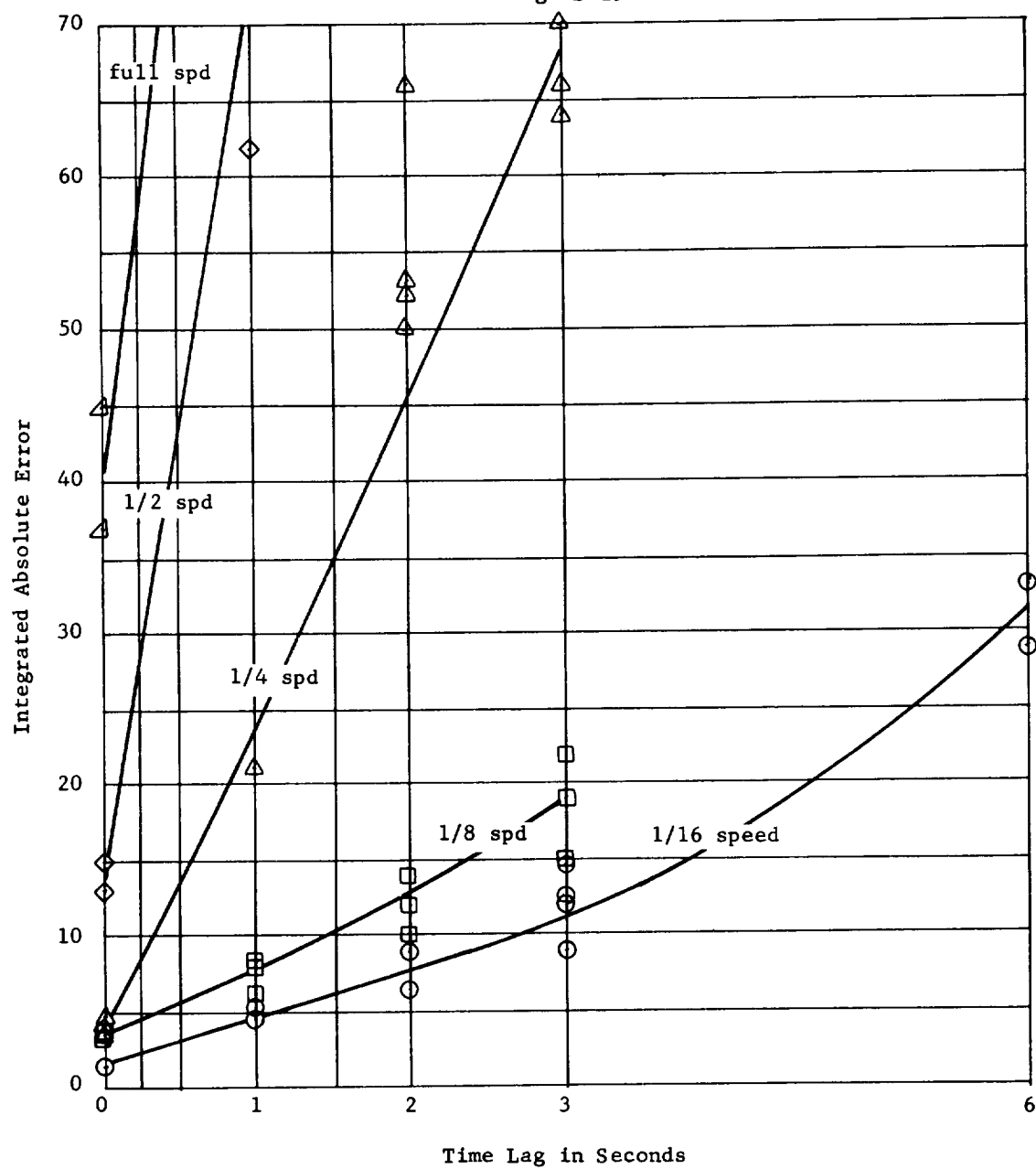


Error vs. Lag
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 Subject No. 2 - Solid Line
 Velocity Control - Type No. 1



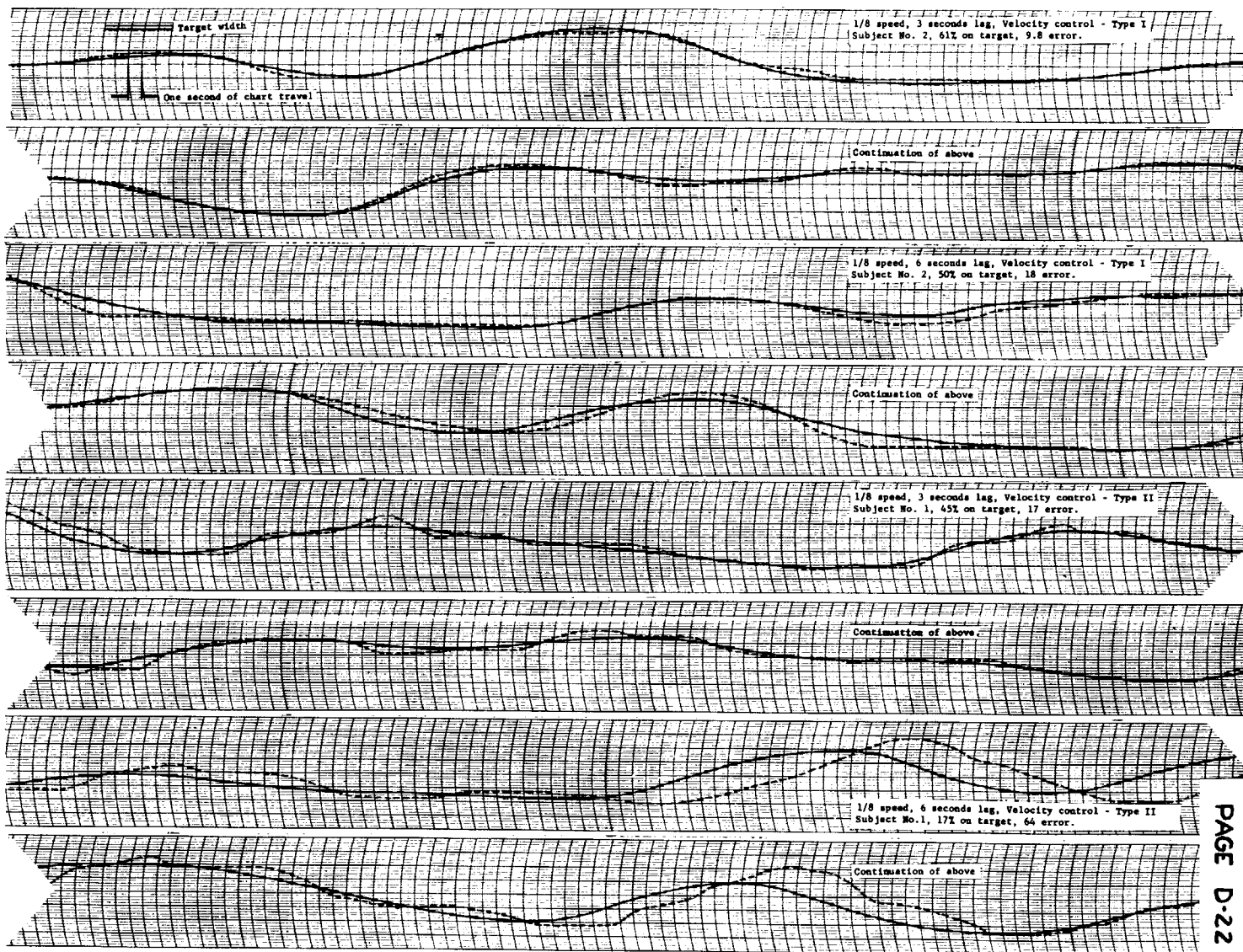
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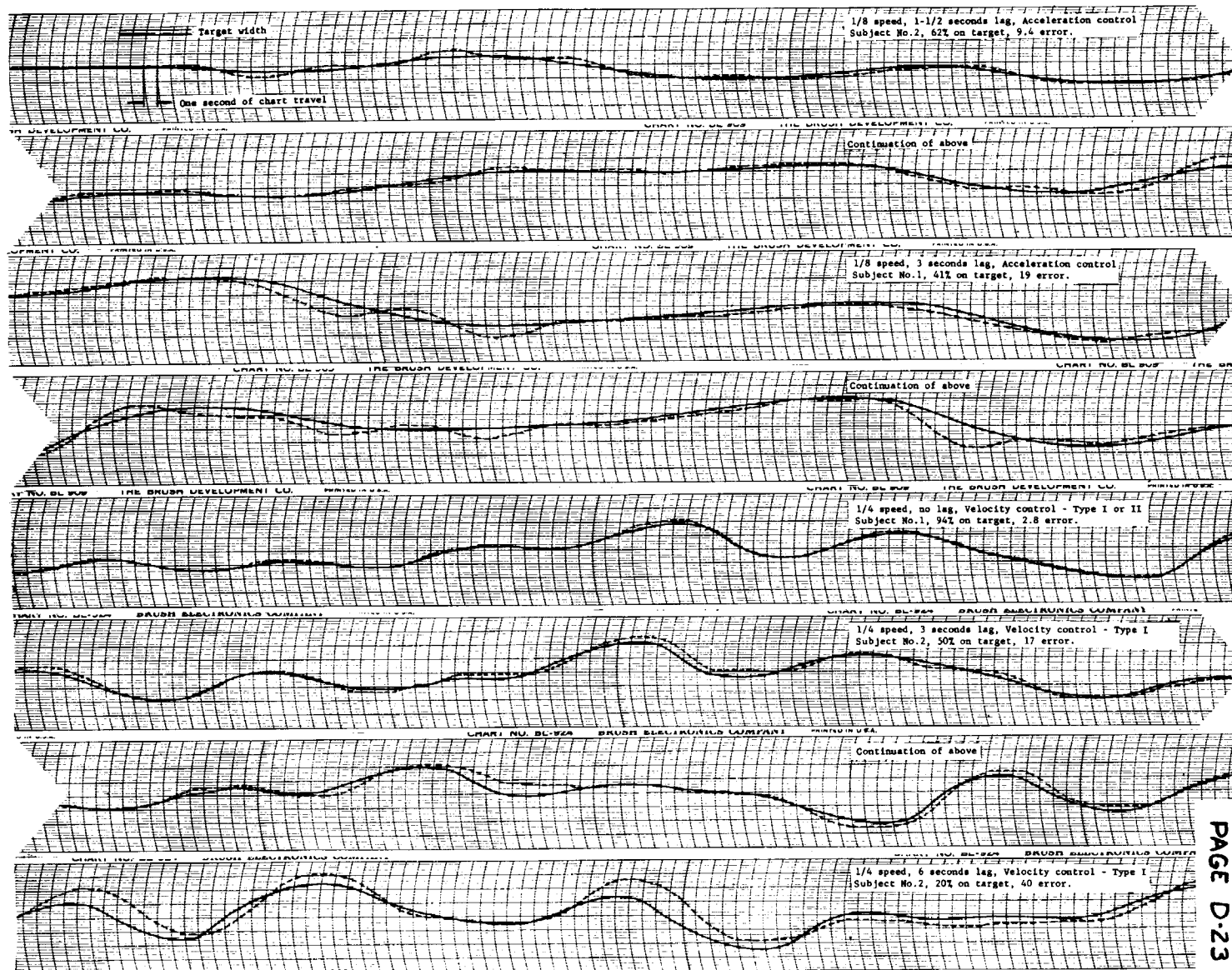
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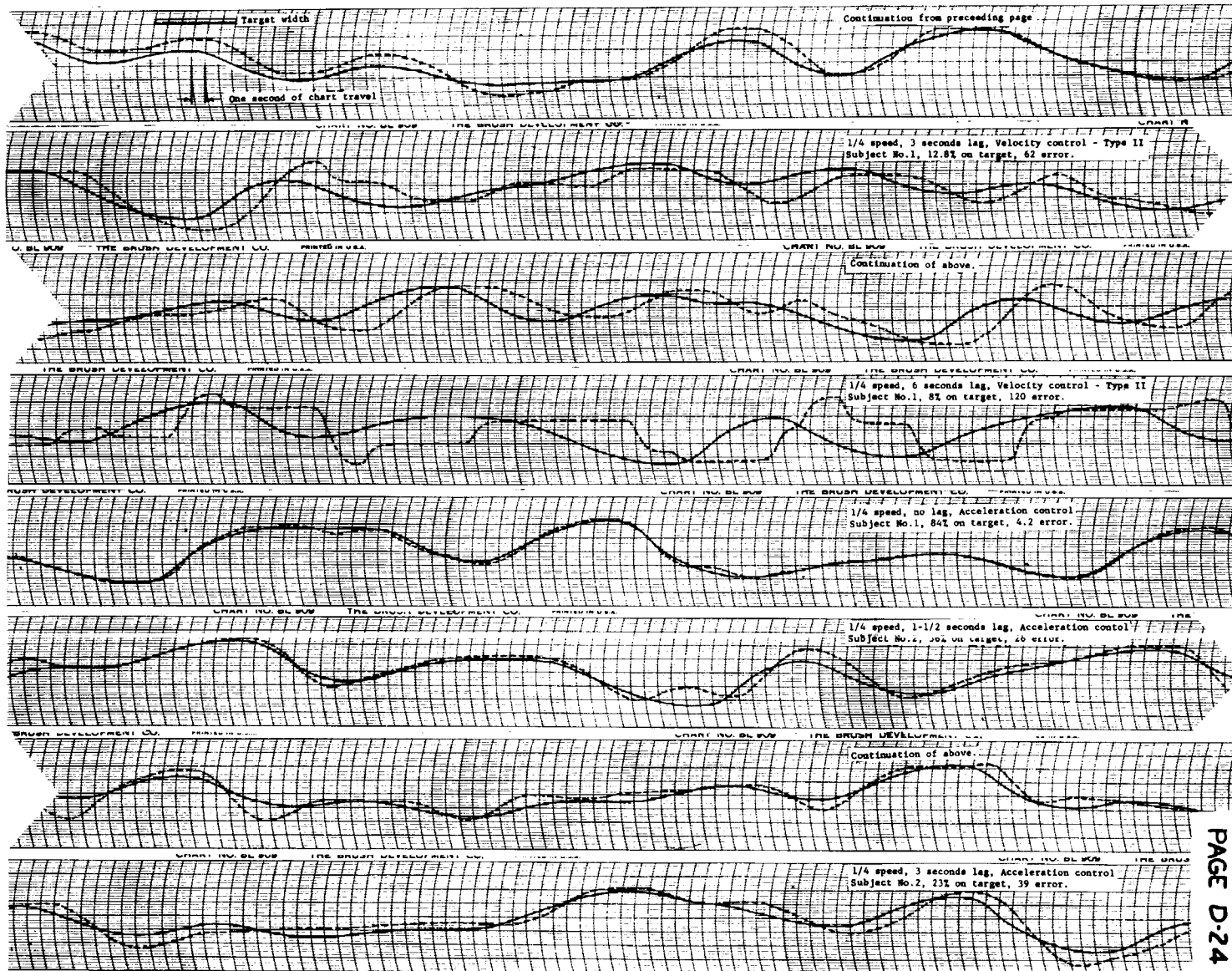


Error vs. Lag
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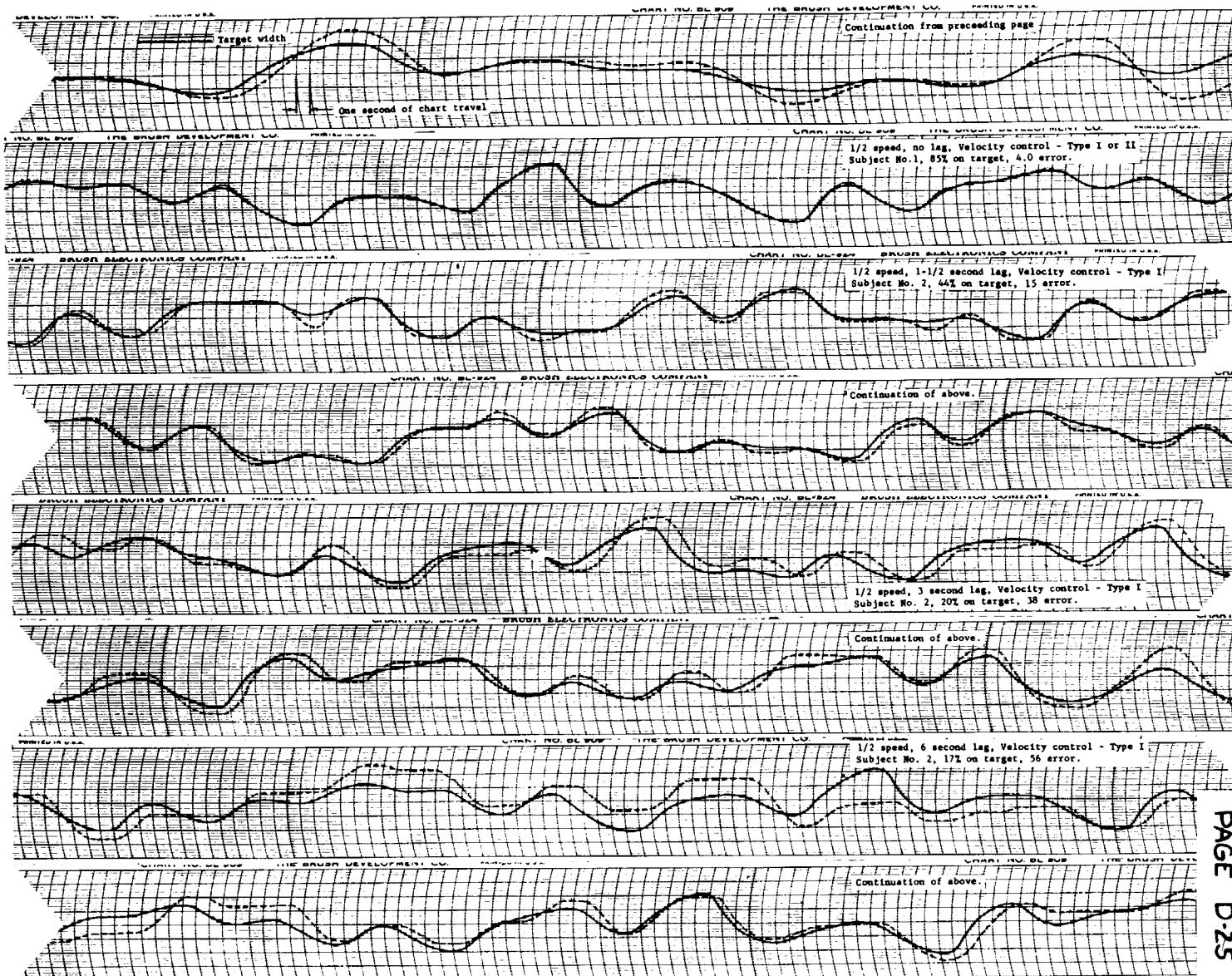
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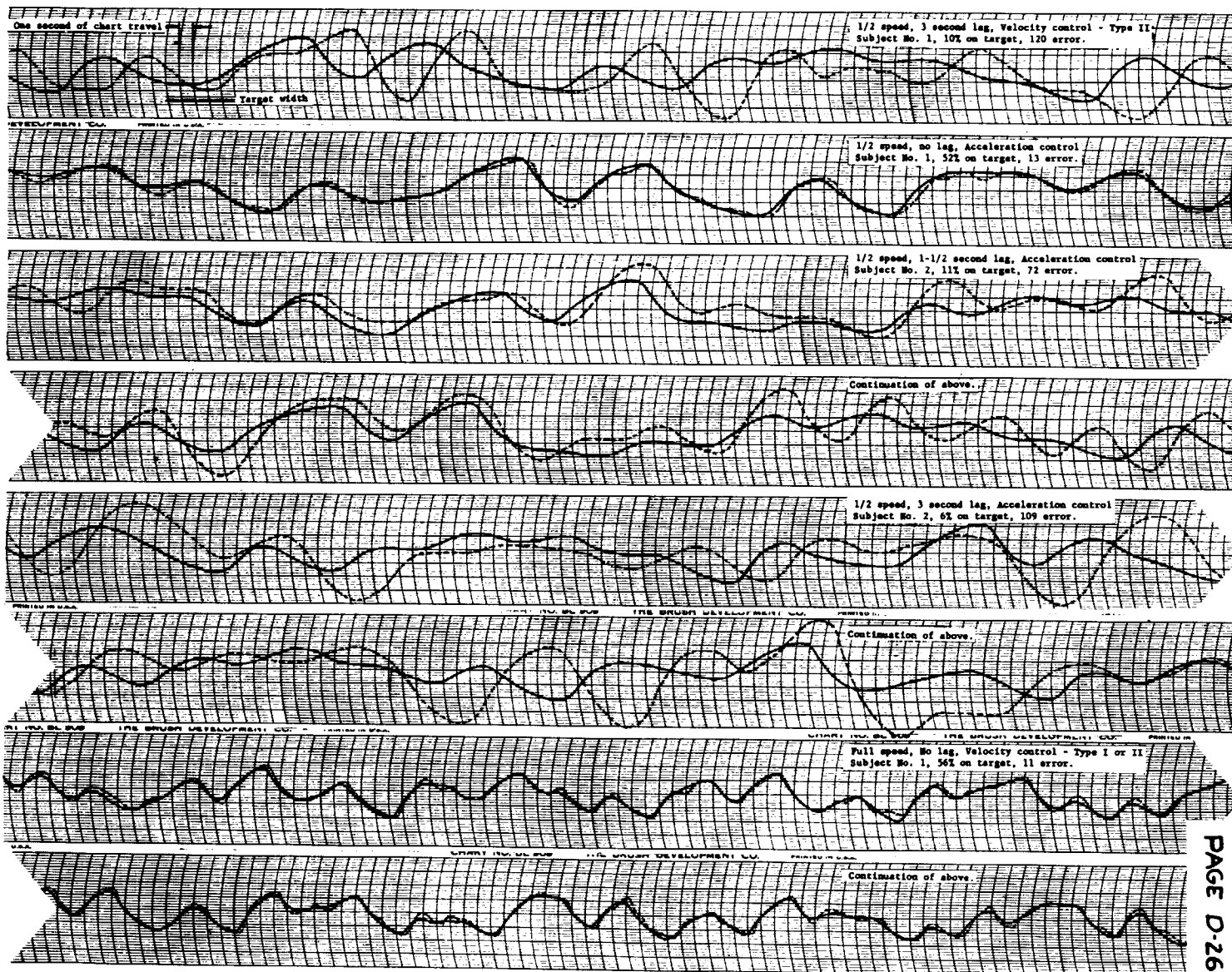






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