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THE APPLICATION OF INTEGRAL PERFORMANCE CRITERIA TO THE ANALYSIS OF DISCRETE MANEUVERS IN A DRIVING SIMULATOR

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PURPOSE

The purpose of this study was to investigate the influence of vehicle transient response characteristics on driver-vehicle performance in discrete maneuvers as measured by integral performance criteria.

SUMMARY

A group of eight ordinary drivers was presented with a series of eight vehicle transfer function configurations in the Virginia Polytechnic Institute and State University driving simulator. Performance in two discrete maneuvers was analyzed by means of integral performance criteria. The following results were obtained:

1. The step wind gust disturbance regulation task was found to be more challenging and more sensitive to differences in vehicle characteristics than a task requiring correction of an artificially induced lane position error. Subsequent remarks apply to results obtained with the step wind gust task.

2. In comparing the various integral criteria, it was observed that the mean scores for all subjects for the Integral of Squared Time Multiplied by Squared Error (ISTSE) criterion showed the greatest separation among vehicle configurations.

3. Steering wheel angle was found to be the most sensitive output when used with this criterion, with yaw angle and lane position being less effective in that order.

4. Performance as measured by the ISTSE criterion showed the following effects for the various vehicle yaw rate transfer function parameters:
   - A natural frequency of 1.75 rad/sec resulted in significantly degraded scores in comparison with frequencies of 3.5, 7.0, and 14.0 rad/sec. The higher the natural frequency, the quicker the vehicle response.
   - A damping ratio of 1.6 resulted in a significantly higher integral score for steering wheel angle than did damping ratios of 0.4 and 0.8. Lateral position and yaw angle measures were insensitive to differences in this parameter. Higher damping ratios result in less vehicle overshoot in response to a step steering wheel input, but they also produce longer response times.

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- Setting the yaw lead time constant to zero significantly degraded the integral performance scores when compared with time constants of 0.26 and 0.57 sec. Adjustments to the lead time constant directly affected the rate of onset of the vehicle yaw rate response, with larger time constants producing quicker responses.
- The compound vehicle response parameter of response time divided by "effective" damping ratio was found to be highly correlated with the integral measure of lane position error.

Future efforts will be directed toward determining if integral measures, such as ISTSE, relate to subjectively-sensed problems of discrete control in full-scale testing, in addition to being discriminatory across different vehicle characteristics.

INTRODUCTION

There is a substantial background in the driving research literature relating to discrete maneuvers, although much of the material has been qualitative, e.g., [1-5]. There is also a considerable body of research in the automatic control field on the selection of integral performance measures of transient responses which lead to "satisfactory-appearing" responses, e.g., [6-8]. To accomplish the guidance and control functions of driving, the driver sets up a variety of closed loops about the vehicle, each of which depends on a variable such as lateral position or yaw angle [9]. By analogy, a satisfactory driver-vehicle system should mimic certain of the dynamic features of "good" automatic control systems. The goal here, then, is to find integral measures of one or several driver-vehicle system outputs which will lead to "satisfactory" handling responses. The motivation is that a single index of performance could be used instead of a recorded time history.

This report presents the effects of changes in vehicle control dynamics on driver-vehicle performance in discrete tasks as measured by integral performance criteria. The independent variables were the vehicle dynamics as defined by the yaw rate to steering wheel transfer function. Different configurations were obtained by changing one at a time either yaw rate natural frequency, damping ratio, or lead time constant. Two transient maneuvers were investigated; namely, step wind gust disturbance regulation and compensation for an artificially induced lane position error. The study was performed in a moving base driving simulator. Transient steering wheel inputs and vehicle motions were analyzed from strip chart recordings, and on this basis a variety of integral performance measures were evaluated.

This study is part of the overall efforts of the Driver-Vehicle Performance Project which is aimed at determining the influence of vehicle control characteristics on driving performance and comfort. The philosophy is to employ driving simulators as an experimental prelude to full-scale investigations, particularly in the development of the tests and measures required to meet the project's objectives.

DRIVING SIMULATOR FACILITY

The investigation was conducted on the Virginia Polytechnic Institute and State University (VPI & SU) driving simulator. This facility features a three degree of freedom motion platform (yaw, roll, and lateral translation) and a computer generated roadway scene. Closed-loop control of the simulated vehicle by the human subject is accomplished by sending signals from steering wheel, accelerator, and brake pedal transducers to the simulated equations of motion which, in turn, modify the platform motion and roadway scene. More complete descriptions of the simulator are found in [10-12].

The method used for representing different vehicles on the simulator involves the derivation of transfer functions that closely match the time domain responses measured for actual vehicles. The contributions of vehicle, tire, and suspension characteristics are accounted for in terms of transfer function parameters. The transfer function that closely approximates a vehicle's yaw rate response is given by [13]:

$$\frac{r}{\delta_{sw}}(s) = \frac{T_r\, s + 1}{\frac{1}{\omega_n^2} S^2 + \frac{2\zeta}{\omega_n} s + 1} \times \left(\frac{r}{\delta_{sw}}\right)_{ss}$$

where

r = yaw rate, deg/sec

δ_{sw} = steering wheel angle, deg

T_r = lead time constant, sec

ω_n = natural frequency, rad/sec

ζ = damping ratio

$\left(\frac{r}{\delta_{sw}}\right)_{ss}$ = steady state yaw rate gain, $\frac{\text{deg/sec}}{\text{deg}}$.

Eight experimental yaw rate transfer functions were chosen for investigation. Table 1 lists the specific parameter values employed for the different configurations as well as the values for other characteristics that were held fixed. The different configurations were partitioned into three comparison groups to determine the individual effects of changes in natural frequency, damping ratio, and lead time constant.

PROCEDURE

A group of eight subjects, ranging in age from 21 to 33 years and drawn from students and personnel at Virginia Polytechnic Institute

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and State University, were tested on each of the eight vehicle configurations. Two of the subjects were female. Each subject held a valid driver's license and had a minimum of three years of driving experience. None of the subjects had previously performed in the driving simulator. The order in which the configurations were presented was randomized by a Latin Square Design.

Upon arrival, each subject was asked to read the instructions (Appendix A) and was then seated in the simulator for further verbal instructions concerning its operation. Figure 1 shows a time line diagram of the events of a particular run. Following a one-minute practice period and prior to the discrete maneuvers, subjects performed in a random wind gust disturbance regulation task which was treated in a previous report [12].

DISCRETE MANEUVERS

Two discrete tasks were employed: compensation for an artificially induced lane position error and regulation of a step wind gust disturbance. One of the advantages of using a simulator is the ability to introduce artificial changes in vehicle output variables. Figure 2 shows time traces for one subject for different vehicle conditions following step changes in lateral position. The discontinuity on lateral position, 90 cm (3 ft) is readily apparent in the time trace and served as an unexpected error to be corrected by the subjects. Time traces on one subject for the step wind gust regulation task are shown in Fig. 3. This task differs from the previous one in that motion cues are present along with a steady side force.

PERFORMANCE MEASURES

The time traces shown in Figs. 2 and 3 appeared to be quite amenable to integral transient response measures that would provide a single index of goodness representative of an entire time history. The underlying difficulty was the choice of the best measure to use for these particular cases. One performance index will emphasize some properties of the response more than others. In addition, the performance index may be chosen so that only one or several system outputs affect its value. In the driver-vehicle system more than one output must be examined. Path and heading errors as well as steering wheel inputs should be considered, the former as measures of performance and the latter as a measure of driver effort or cost.

There have been various proposals and suggestions of specific integral measures in the literature, e.g., [6-8]. The ones that were examined include:

(1) **Integral of absolute error (IAE)**

$$I_1 = \int_0^T |e|dt$$

(2) **Integral of squared error (ISE)**

$$I_2 = \int_0^T e^2 dt$$

(3) **Integral of time multiplied by absolute error (ITAE)**

$$I_3 = \int_0^T t|e|dt$$

(4) **Integral of time multiplied by squared error (ITSE)**

$$I_4 = \int_0^T t\, e^2 dt$$

(5) **Integral of squared time multiplied by squared error (ISTSE)**

$$I_5 = \int_0^T t^2 e^2 dt$$

(6) **Integral of squared time multiplied by absolute error (ISTAE)**

$$I_6 = \int_0^T t^2 |e|dt$$

A geometric interpretation of the ITAE criterion is shown in Fig. 4.

Three additional and somewhat unconventional measures involving multiplication by inverse time were also included for the purpose of giving additional emphasis to the initial aspects of the transient responses.

(7) **Integral of inverse time multiplied by absolute error (IITAE)**

$$I_7 = \int_{a>0}^T t^{-1} |e|dt$$

(8) **Integral of inverse time multiplied by squared error (IITSE)**

$$I_8 = \int_{a>0}^T t^{-1} e^2 dt$$

(9) Integral of inverse squared time multiplied by absolute error (IISTAE)

$$I_9 = \int_{\alpha>o}^{T} t^{-2}\,|e|\,dt$$

Numerical values for the various performance measures were obtained by digitizing time traces of lateral position, yaw angle, and steering wheel angle on a Bendix Graphscan Digitizer and then performing the required integrations digitally. An integration time of 10 seconds was used for the lateral position jump task and 14 seconds for the step wind gust task.

As a means of comparison with the various integral measures, peak lane position overshoot for the step wind gust task was also selected as a measure of performance, primarily because of its intuitive safety relevance.

DRIVER-VEHICLE PERFORMANCE RESULTS

Step Wind Gust Disturbance Regulation Task

Table 2 contains a summary of the statistical test results for the peak lane position overshoot measure. Application of Duncan's New Multiple Range Test [17] showed that in comparisons of natural frequency levels, Configuration #4 (ω_n = 1.75 rad/sec) was significantly different from the other three configurations (ω_n = 3.5, 7.0, and 14.0 rad/sec), and when comparing variations in lead time constant, that Configuration #8 (T_r = 0) was significantly different from Configurations #1 (T_r = 0.28 sec) and #7 (T_r = 0.57 sec). No significant differences were observed as a result of variations in damping ratio.

To make a comparison between the various integral criteria under consideration, the criterion scores are normalized and plotted versus natural frequency for lateral position, yaw angle, and steering wheel angle transients in Figs. 5-7. Also included for comparison in Fig. 5 for measures of lateral position error are Peak Lateral Position Overshoot Squared. To avoid unnecessary clutter, integral measures I_6-I_9 are omitted from the figures. These measures showed less discrimination across natural frequency than either of the top three criteria, ISE, ITSE, and ISTSE.

Because of its greater spread in scores across configurations, ISTSE was selected for closer examination. Table 3 summarizes the statistical test results for this measure, and Figs. 8-10 show the influences of variations in natural frequency, damping ratio, and lead time constant as determined by this measure. The mean scores for the eight subjects with the corresponding standard deviations are indicated.

Integral measures of yaw angle and steering wheel angle show the most discrimination across configurations. Application of Duncan's New Multiple Range Test to the data revealed the following:

> Natural frequency comparison: Performance for the configuration with a natural frequency of 1.75 rad/sec was significantly degraded from the others.
>
> Damping ratio comparison: The high damping configuration (ζ = 1.6) produced a significantly higher integral measure of steering wheel angle than the others.
>
> Lead time constant comparison: Performance for the configuration with T_r = 0 was significantly less than for the other configurations.

In an attempt to compare performance on all of the configurations in terms of a common and relevant response characteristic, the compound parameter of response time divided by "effective" damping ratio was employed. To do this, the damping ratio of the second order system without lead (i.e. having no transfer function "zero") that would give the same value of yaw rate overshoot that was observed for each of the configurations was assigned as the "effective" damping ratio. As shown in Fig. 11, a remarkably close fit to a straight line results when the Integral of Squared Time Multiplied by Squared Lateral Position Error is plotted as a function of this compound parameter. The Pearson Product Moment Correlation Coefficient corresponding to this relationship is 0.961 which is highly significant ($p < 0.001$).

COMPENSATION FOR ARTIFICIALLY INDUCED LANE POSITION ERROR

A comparison between the various integral criteria using steering wheel angle as the error signal is shown in Fig. 12 for the four natural frequency configurations. Because subjects varied widely in the time they took to initiate a correction for the step change in lane position it was decided that an explicit time penalty in the cost functional would be inappropriate. In addition, measures with explicit time, i.e., ITSE, ITAE, etc., resulted in a poorer performance score for the vehicle with a natural frequency of 7.0 rad/sec than for the one with 3.5 rad/sec which did not appear to reflect an accurate ranking of the vehicles. For these reasons, the ISE measure was chosen for a more complete analysis of the data.

Table 4 summarizes the statistical test results for this measure, and Fig. 13 illustrates the influence of variations in the three vehicle response characteristics as determined by the measure for steering wheel angle. Measures of lateral position error were insensitive to differences in vehicle configuration. ISE measures of yaw angle and steering wheel angle did show statistically significant differences between different levels of damping ratio and lead time constant but not for natural frequency, although the latter just missed being significant at the p = 0.10 level. Duncan's New Multiple Range Test again showed that a value of

$\zeta = 1.6$ was significantly different from the other levels of damping ratio and that $T_r = 0$ was significantly different from the other two levels of lead.

DISCUSSION OF RESULTS

Of the two discrete maneuvers employed in the present study, the step wind gust disturbance task was the more challenging and discriminating among vehicle configurations. Both visual and motion cues accompanied the disturbance, and unless rapid compensatory control on the part of the driver was taken, the vehicle would have been forced off the road. Introduction of a simple step change in lane position, however, resulted in widely varying responses on the part of the subjects. Subjects were not given specific instructions on this task other than the general instruction to make whatever corrections were necessary so as to maintain their normal highway position. Since the artificially induced lane position error was only 90 cm (3 ft) in magnitude, it may not have been sufficient to motivate an immediate correction on the part of the subjects. It is possible that more specific instructions or a larger induced error would make the task more sensitive to differences in vehicle configurations.

Integral measures of the various driver-vehicle system outputs appear to offer an effective means for comparing transient performance with different vehicle response configurations. The fact that the ISTSE measure was shown to discriminate among the different configurations on a statistical basis using only a single trial for each driver-vehicle combination is noteworthy. Comparison of the mean scores of the various performance measures across vehicle configurations must be done with some caution, however, since it does not take into account the variability inherent in a given measure. Thus, while Fig. 5 shows that mean scores for ISTSE appear much more discriminating than those for Peak Lane Position Overshoot (PLPO), for example, statistical tests with the two measures, Tables 2 and 3, indicate similar discrimination capabilities. Intuitively, the integral measure should be superior because it is determined by the complete transient response rather than a specific aspect of it. The peak overshoot appears to be the predominant feature in the lateral responses in this instance, however.

Findings on the effects of changes in the vehicle response characteristics are in good agreement with previously reported qualitative results. This result provides added support for the integral criteria. Linke, Richter, and Schmidt [1] found that the higher the resonant frequency of the vehicle, the better the mean subjective rating as determined from a group of unskilled drivers performing a high speed lane change maneuver. Although these authors discounted the importance of yaw damping, inspection of two of their vehicles with similar resonant frequencies reveals that the one with the least damping and hence, lowest response time was judged the most favorably. In its report to the International Standards Organization [2], Sweden showed a correlation coefficient of 0.926 between subjective ratings in a lane change maneuver and time lags between steering wheel inputs and yaw velocity responses. In terms of the parameters used in our study, the initial slope of the yaw rate response is given by

$$\dot{r}(o) = \left(\frac{r}{\delta_{sw}}\right)_{ss} \times T_r \times \omega_n^2 \times \delta_{sw} \ .$$

In a real vehicle, factors that cause an increase in T_r generally bring about a decrease in ω_n and as a rough approximation, $T_r \gtrsim 1/\omega_n$. The time lag between steering wheel angle and yaw rate, as used by the ISO, can be roughly approximated by steady state yaw rate divided by the slope. Thus,

$$\text{Time lag} \gtrsim \frac{r_{ss}}{\dot{r}(o)} = \frac{r_{ss}}{\left(\frac{r}{\delta_{sw}}\right)_{ss} \times \omega_n \times \delta_{sw}} = \frac{1}{\omega_n} \ .$$

If the ISO data are replotted in terms of natural frequency, the curve shown in Fig. 14 results which bears a striking resemblance to our own findings.

For transient maneuvers including double lane changes, unexpected obstacle avoidance, and step disturbance regulation, STI [5] has recently reported that natural frequencies below 3 rad/sec may represent a lower boundary for acceptable performance and that based on driver opinion ratings, natural frequency appears more important than damping ratio.

The effects of the vehicle characteristics on step wind gust performance are also very similar to those described in a previous GMR report on random wind gust disturbance regulation [12]. The significance levels are somewhat less for the present findings, but this is not at all surprising in view of the methodological differences. The present integral performance criteria were applied to the subjects' first exposure to a step gust disturbance with each vehicle, and the period of integration was on the order of 10 to 15 seconds. In the random gust disturbance case, subjects were allowed a one-minute practice period under gusting conditions before the 2½ minute data run was taken. The fact that the trends for the step gust disturbance case using integral performance criteria are as strong as indicated under the circumstances is justification for further use of this approach.

The work in the present study is based entirely on objective measures of directional control performance in a driving simulator, and the natural extension would be to correlate these measures with handling qualities ratings during discrete maneuvers under full-scale conditions. If the integral measures are found to relate to the subjectively sensed problems of discrete control in addition to being discriminatory among different vehicle conditions, then a reasonably simple means for measuring objective handling properties will be available. Such measures should lend themselves to easy data gathering and on-board mechanization. Steering wheel inputs are readily available, and approximate path and heading outputs can probably be computed on-board via "washed-out" integrations of lateral acceleration and yaw rate. The resulting signals can then be squared, time weighted, and integrated up to 10 or 15 seconds by an on-board analog circuit which is reset at the start of each maneuver. The resulting objective scores, i.e., ISTSE, and corresponding opinion ratings can then be logged for later comparison. Since the pilot simulator data show that integral measures of yaw angle and steering wheel angle are more sensitive to changes in vehicle response characteristics than measures of path error, possible difficulties in taking the second integral of lateral acceleration to obtain lateral position error should not seriously compromise the analysis.

Previous attempts to objectively measure driver-vehicle performance in discrete maneuvers have typically used for a score the number of cones displaced from a course or the maximum speed through the course without hitting any cones. The presence of the cone course itself allows anticipation on the part of the driver and requires considerable time to set up and maintain. The use of an integral performance criterion does not have these difficulties. The GM Variable Response Vehicle [14] has the capability to simulate a step disturbance input so the step wind gust disturbance regulation task can be largely duplicated under full-scale conditions. The step jump in lane position is obviously a simulator novelty. However, under full-scale conditions, at some unexpected time set by the experimenter and in a direction chosen at random, the subject can be commanded to switch from a center lane to either the right or left lane as rapidly as possible. The integral criteria should be equally suitable for this type of maneuver. The extension of this procedure to full-scale testing should be relatively straightforward, and combined with subjective opinion data it will hopefully lead to an improved method for distinguishing "good" and "bad" handling vehicles.

REFERENCES

1. W. Lincke, B. Richter, and R. Schmidt, "Simulation and Measurement of Driver Vehicle Handling Performance," SAE Paper No. 730489, May 1973.

2. "Experimental Study of a Lane Change Manoeuvre with Mechanized Sinusoidal Steering Input," ISO/TC 22/SC 9 (Sweden-5) 52, October 1974.

3. W. Bergman, "Measurement and Subjective Evaluation of Vehicle Handling," SAE Paper No. 730492, May 1973.

4. W. Bergman, "Considerations in Determining Vehicle Handling Requirements," SAE Paper No. 690234, January 1969.

5. D. T. McRuer and R. H. Klein, Automobile Controllability -- Driver/Vehicle Response for Steering Control, Volume 1, Summary Report, Systems Technology, Inc., Contract No. DOT-HS-359-3-762, February 1975.

6. D. Graham and R. C. Lathrop, "The Synthesis of Optimum Response: Criteria and Standard Forms," Trans. AIEE, Vol. 72, Part II, November 1953, 273-288.

7. W. C. Schultz and V. C. Rideout, "The Selection and Use of Servo Performance Criteria," Trans. AIEE, Vol. 76, Part II, January 1958, 383-388.

8. J. E. Gibson, et. al., "A Set of Standard Specifications for Linear Automatic Control Systems," Trans. AIEE, Vol. 80, Part II, May 1961, 65-74.

9. D. H. Weir and D. T. McRuer, "Models for Steering Control of Motor Vehicles," Fourth Annual NASA-University Conference on Manual Control, The University of Michigan, March 1968.

10. W. W. Wierwille, "A Part-Task Driving Simulator for Teaching and Research," Computers in Education for ASEE Transactions, December 1973.

11. W. W. Wierwille, "Driving Simulator Design for Realistic Handling," Proceedings of the Third International Conference on Vehicle System Dynamics, Swets and Zeitlinger B.V., Amsterdam, 1975.

12. B. S. Repa and W. W. Wierwille, "Driver Performance in Controlling a Driving Simulator with Varying Yaw Rate Characteristics," GM Research Publication GMR-2205, July, 1976.

13. R. T. Bundorf and R. L. Leffert, "The Cornering Compliance Concept for Description of Directional Control (Handling) Properties", Engineering Publication 2771, GM Proving Ground.

14. K. J. McKenna, "A Variable Response Vehicle -- Description and Applications", GM Proving Ground Engineering Publication 5665, June, 1974.

15. H. O. Hartley, "The Maximum F-Ratio as a Short Cut Test for Homogeneity of Variance", Biometrika, 1950, Vol. 37, 308-312.

16. G. Keppel, Design and Analysis, a Researcher's Handbook, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973, 465-466.

17. A. L. Edwards, Experimental Design in Psychological Research, Rinehart and Company, Inc., New York, 1960, 136.

TABLE 1 - YAW RATE CONTROL RESPONSE PARAMETERS

Condition	$1/T_r$ (sec^{-1})	ξ	W_n (rad/sec)
1	3.5	0.8	3.5
2	14.0	0.8	14.0
3	7.0	0.8	7.0
4	1.75	0.8	1.75
5	3.5	0.4	3.5
6	3.5	1.6	3.5
7	1.75	0.8	3.5
8	∞	0.8	3.5

Yaw Rate to Steering Whell Input Gain: 0.21 $\frac{\text{deg/sec}}{\text{deg}}$

Control Sensitivity (Lateral Acceleration to Steering Wheel Input Gain): 0.92 $\frac{G}{100\ \text{deg}}$

Roll Compliance: 6.2 deg/G

Roll Natural Frequency: 6 rad/sec

Roll Damping Ratio : 0.50

TABLE 2 - ANALYSIS OF VARIANCE SUMMARY FOR PEAK LANE POSITION OVERSHOOT IN THE STEP WIND GUST REGULATION TASK

Source of Variation	Degrees of Freedom		Maximum Lane Deviation		
	Uncorrected	Corrected†	Sum of Squares	Mean Square	F-Ratio
Natural Frequency (ω_n)	3	-	18.6	6.26	2.91*
Error	21	-	45.2	2.15	
Damping Ratio (ξ)	2	-	2.10	1.05	0.506
Error	14	-	29.1	2.07	
Lead Time Constant (T_r)	2	1	105.8	52.9	13.76***
Error	14	7	53.8	3.84	

Significance Level: *= 0.1, ** = 0.05, *** = 0.01

† The Greenhouse-Geisser correction [16] was applied to the degrees of freedom for those variables not meeting the homogeneity of variance assumption using Hartley's test [15].

TABLE 3 - ANALYSIS OF VARIANCE SUMMARY FOR ISTSE CRITERION FOR THE STEP WIND GUST REGULATION TASK

Source of Variation	Degrees of Freedom		Lateral Position Error			Yaw Angle Error			Steering Wheel Angle		
	Uncorrected	Corrected†	Sum of Squares	Mean Square	F-Ratio	Sum of Squares	Mean Square	F-Ratio	Sum of Squares	Mean Square	F-Ratio
Natural Frequency (ω_n)	3	1	1.04x10^{8}	0.347x10^{8}	4.7*	6.02x10^{5}	2.01x10^{5}	10.53**	8.53x10^{10}	2.84x10^{10}	15.9***
Error	21	7	1.54x10^{8}	0.074x10^{8}		4.01x10^{5}	0.191x10^{5}		3.75x10^{10}	0.178x10^{10}	
Damping Ratio (ξ)	2	1	8.79x10^{6}	4.40x10^{6}	0.566	2.37x10^{5}	1.18x10^{5}	1.56	5.45x10^{10}	2.72x10^{10}	4.78*
Error	14	7	10.9x10^{7}	0.78x10^{7}		10.6x10^{5}	0.76x10^{5}		7.97x10^{10}	0.569x10^{10}	
Lead Time Constant (T_r)	2	1	7.01x10^{8}	3.5x10^{8}	6.93**	8.82x10^{6}	4.41x10^{6}	9.64**	4.14x10^{11}	2.07x10^{11}	14.45***
Error	14	7	7.07x10^{8}	0.51x10^{8}		6.40x10^{6}	0.457x10^{6}		2.00x10^{11}	0.143x10^{11}	

Significance Level: * = 0.10, ** = 0.05, *** = 0.01

† The Greenhouse-Geisser correction [16] was applied to the degrees of freedom for those variables not meeting the homogeneity of variance assumption using Hartley's test [15].

TABLE 4 - ANALYSIS OF VARIANCE SUMMARY FOR THE INTEGRAL OF SQUARED ERROR PERFORMANCE CRITERION FOR THE ARTIFICIALLY INDUCED LANE POSITION ERROR TASK

Source of Variation	Degrees of Freedom		Lateral Position			Yaw Angle			Steering Wheel Angle		
	Uncorrected	Corrected†	Sum of Squares	Mean Square	F-Ratio	Sum of Squares	Mean Square	F-Ratio	Sum of Squares	Mean Square	F-Ratio
Natural Frequency (ω_n)	3	1	663.6	221.2	0.841	14.8	4.94	0.940	1.30x10^{6}	4.35x10^{5}	3.50
Error	21	7	5525.0	263.1		110.5	5.26		2.61x10^{6}	1.24x10^{5}	
Damping Ratio (ξ)	2	1	633.5	316.7	1.618	65.7	32.9	4.67*	6.92x10^{6}	3.46x10^{6}	7.16**
Error	14	7	2740.0	195.8		98.5	7.04		6.76x10^{6}	4.83x10^{5}	
Lead Time Constant (T_r)	2	1	2140.0	1070.0	3.46	43.0	21.5	7.60**	1.74x10^{6}	8.69x10^{5}	15.61***
Error	14	7	4333.0	309.0		39.6	2.83		7.80x10^{5}	5.57x10^{4}	

Significance Level: * = 0.10, ** = 0.05, *** = 0.01

† The Greenhouse-Geisser correction [16] was applied to the degrees of freedom for those variables not meeting the homogeneity of variance assumption using Hartley's test [15].

APPENDIX A

INSTRUCTIONS

The purpose of this experiment is to obtain a better understanding of normal driving behavior.

You will be seated in the driver's seat of an automotive mock-up. You will be presented with a visual display consisting of a moving, geometrical roadway simulation and a dashboard speedometer. During operation of the simulator, you will experience simulated vehicle motions corresponding to the driving conditions and your control maneuvers. Your control of the simulator's speed and road position will be by means of a standard steering wheel and accelerator pedal as in a normal automobile. After being seated on the platform you will be given instructions by, and may communicate with the experimenter via the dash mounted (upper right) speaker/microphone.

The total experiment will take approximately 1 hour and 15 minutes to complete. There will be 8 experimental runs of approximately 7 minutes each. There will be a brief intermission between each experimental run. After 4 runs, you will be allowed to leave the simulator for a 5 minute rest. Thereafter, you will return to the simulator and the last four runs will be completed.

During the run you are to perform two tasks:

1. maintain a speed of 55 mph, and
2. maintain a normal right-lane highway driving position.

Please keep in mind that you are at all times to drive as you normally would on a highway.

During the course of the experiment, inputs will be artifically introduced into the simulation, causing the vehicle to deviate in different ways. Your job will be to make corrections for these deviations so as to maintain the normal highway position previously established. (Note: At the beginning of the experiment you are to accelerate to 55 mph.) Shortly thereafter deviations in the simulation will occur.

The experimental precedure will be as follows:

1. Be seated in the driver's seat; adjust seat position and fasten safety belt.
2. Become familiar with controls, speaker/microphones, and emergency motion cut-off button.

   NOTE: Activation (1 push) of the emergency motion cut-off button halts all motion of the simulator platform. If at any time during the experiment you sincerely fee that continued simulator operation would not be agreeable with you, please verbally notify the experimenter and depress (once), the emergency motion cut-off button. You may leave the platform (to the left only) if and only if all platform motion has stopped.
3. Communications checkout and questions.

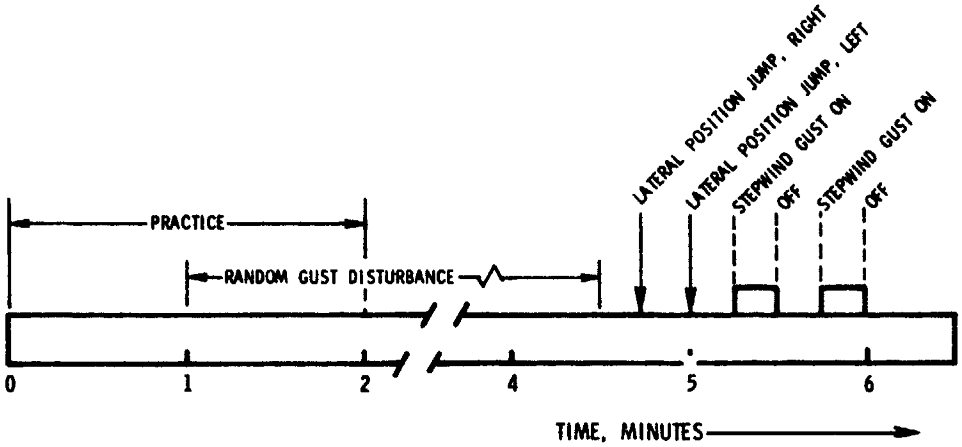
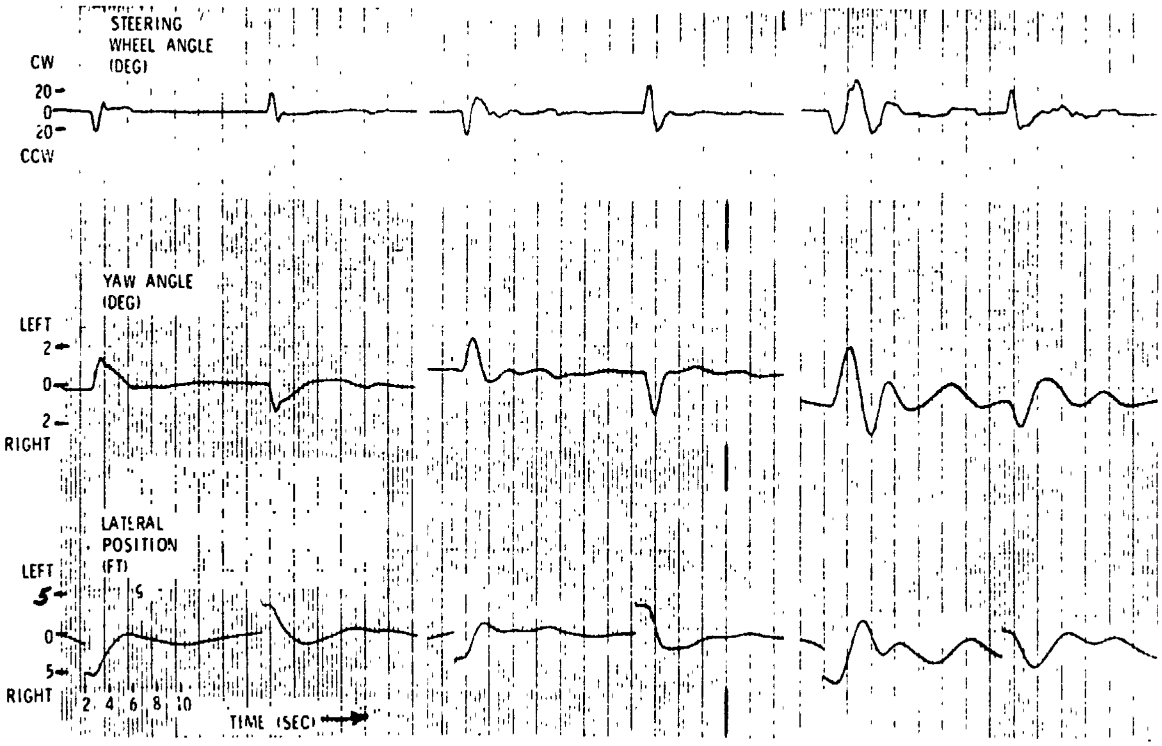


FIG. 1 SCHEDULE OF EVENTS

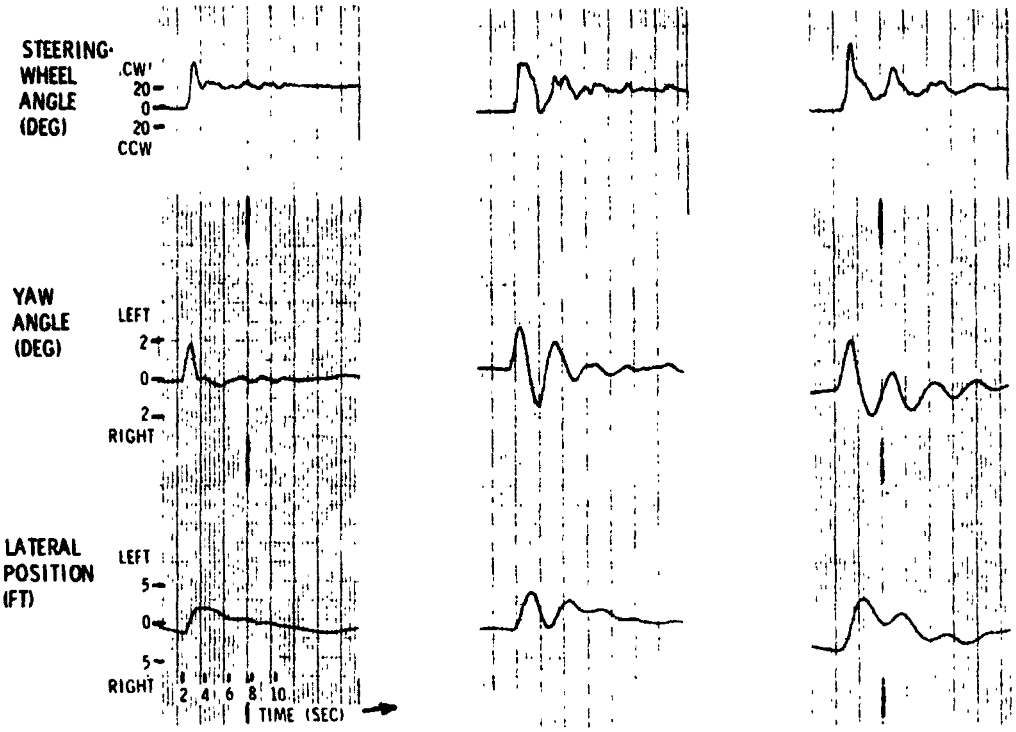


CONDITION #2 $\xi = 0.8, \omega_n = 14.0$

CONDITION #1 $\xi = 0.8, \omega_n = 3.5$

CONDITION #4 $\xi = 0.8, \omega_n = 1.75$

FIG. 2 TIME TRACES FOR THE ARTIFICIALLY INDUCED LANE POSITION ERROR TASK WITH DIFFERENT LEVELS OF NATURAL FREQUENCY



CONDITION #2 $\xi = .8, \omega_n = 14$ CONDITION #1 $\xi = .8, \omega_n = 3.5$ CONDITION #4 $\xi = .8, \omega_n = 1.75$

FIG. 3 TIME TRACES FOR STEP WIND GUST REGULATION FOR DIFFERENT LEVELS OF NATURAL FREQUENCY

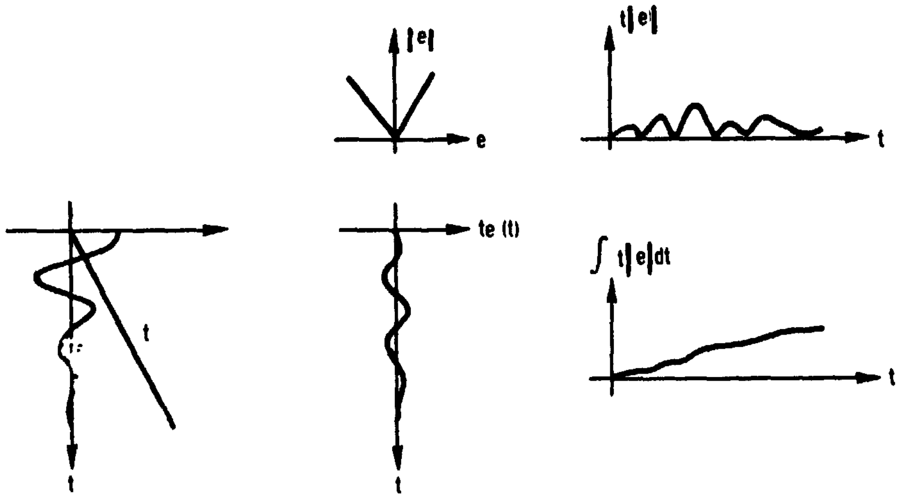


FIG. 4 GEOMETRIC INTERPRETATION OF INTEGRAL OF TIME MULTIPLIED BY ABSOLUTE ERROR (ITAE) CRITERION [7]

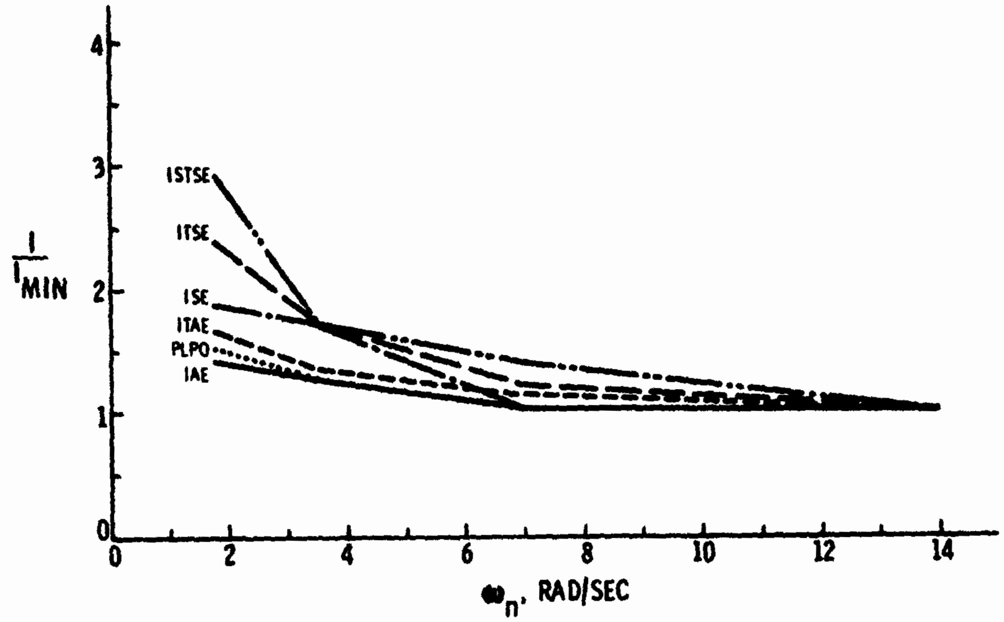


FIG. 5 COMPARISON OF PERFORMANCE CRITERIA AS A FUNCTION OF NATURAL FREQUENCY, WITH LATERAL POSITION AS THE ERROR

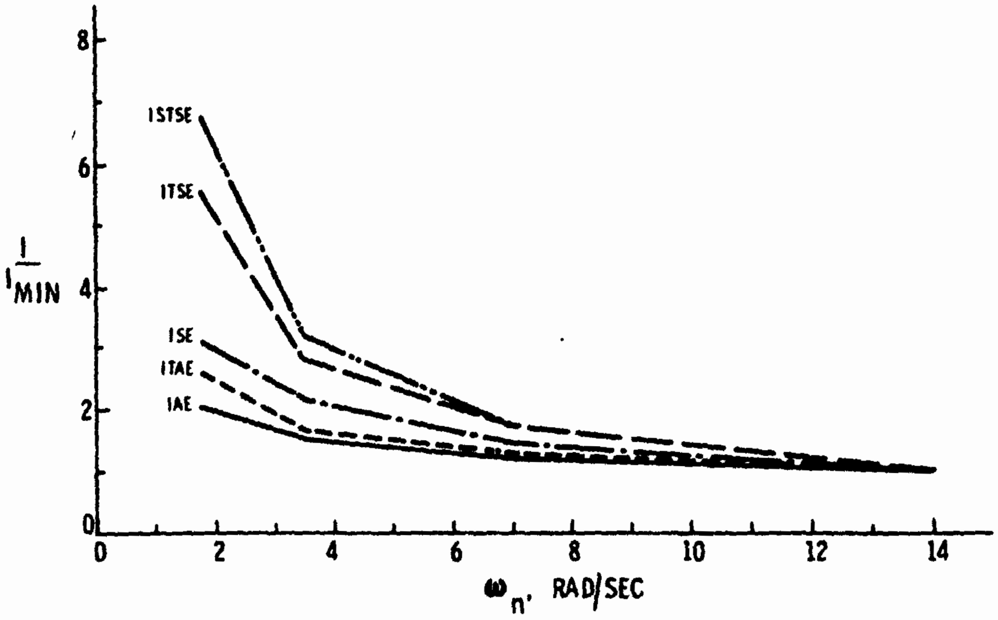


FIG. 6 COMPARISON OF PERFORMANCE CRITERIA AS A FUNCTION OF NATURAL FREQUENCY, WITH YAW ANGLE AS THE ERROR

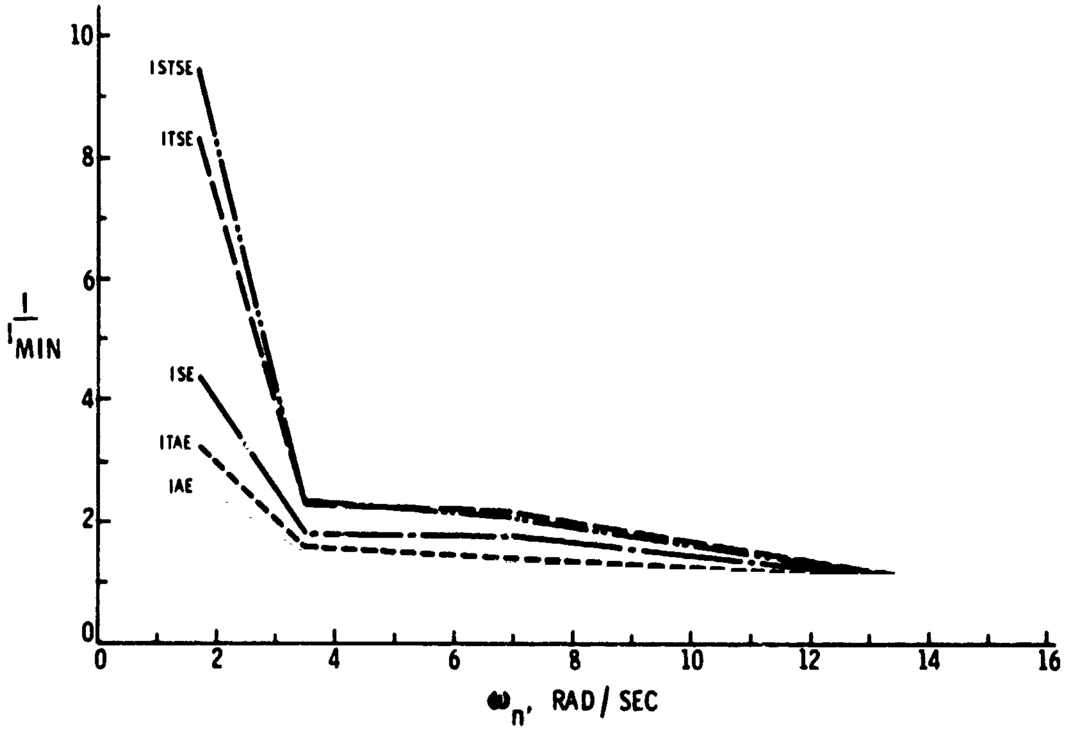


FIG. 7 COMPARISON OF PERFORMANCE CRITERIA AS A FUNCTION OF NATURAL FREQUENCY, WITH STEERING WHEEL ANGLE AS THE ERROR

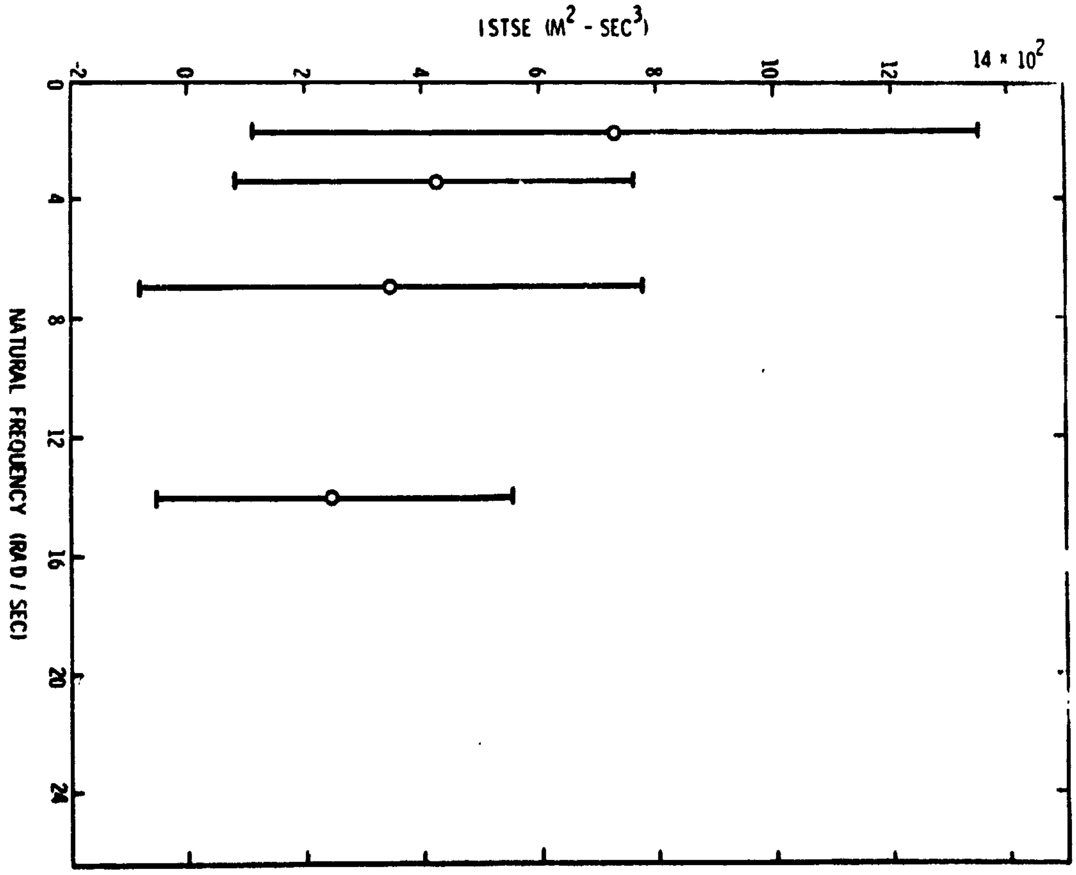


FIG. 8a EFFECT OF NATURAL FREQUENCY ON STEP GUST PERFORMANCE WITH LATERAL POSITION AS THE ERROR

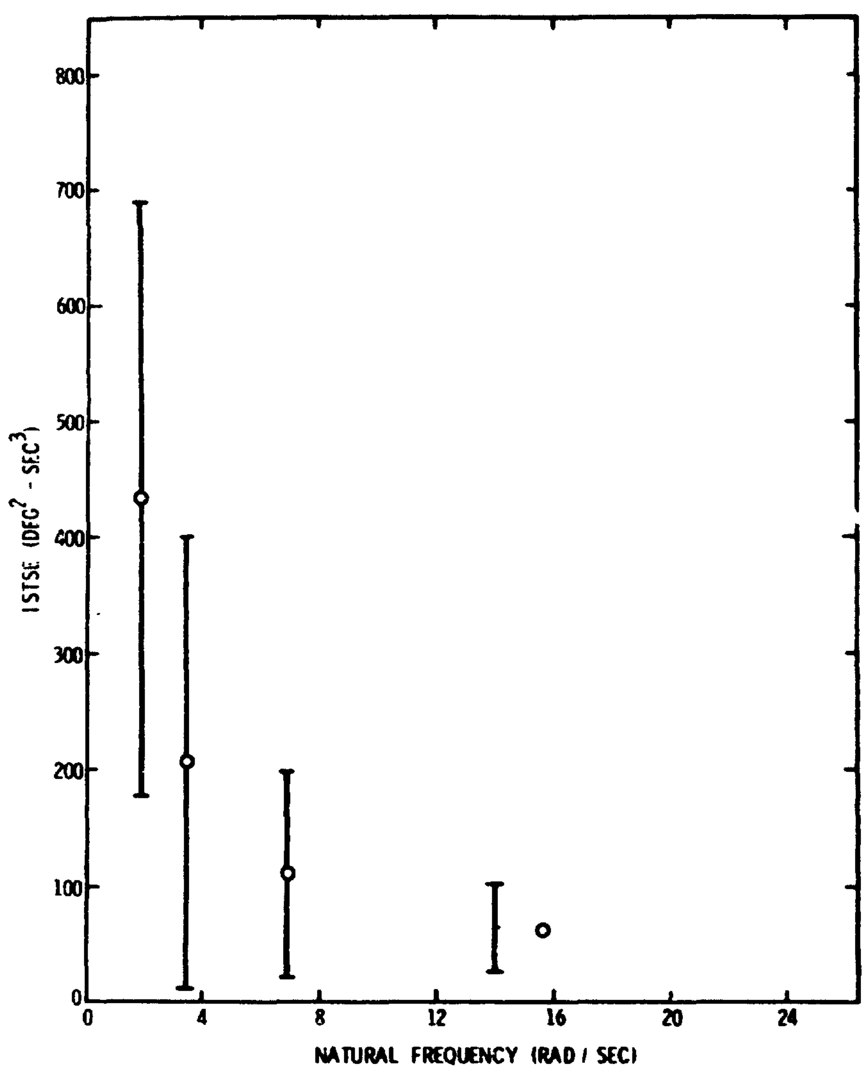


FIG. 8b EFFECT OF NATURAL FREQUENCY ON STEP GUST PERFORMANCE WITH YAW ANGLE AS THE ERROR

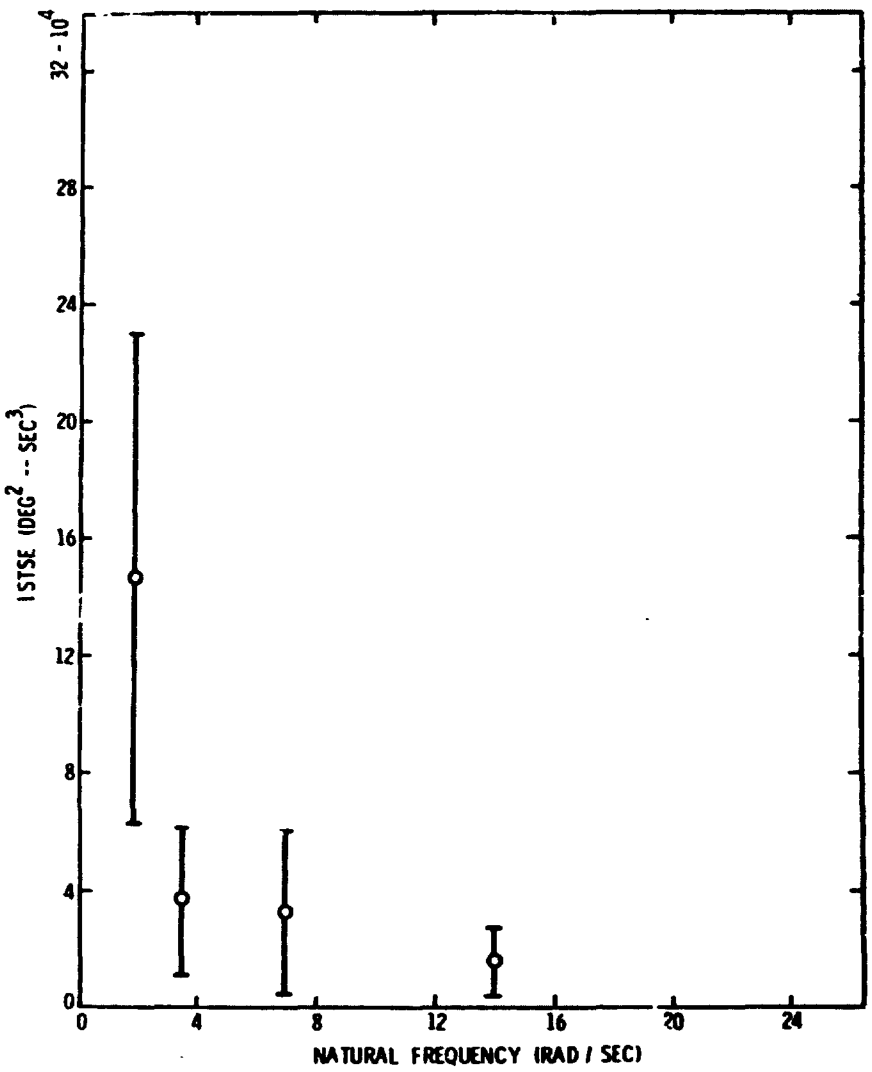


FIG. 8c EFFECT OF NATURAL FREQUENCY ON STEP GUST PERFORMANCE WITH STEERING WHEEL ANGLE AS THE ERROR

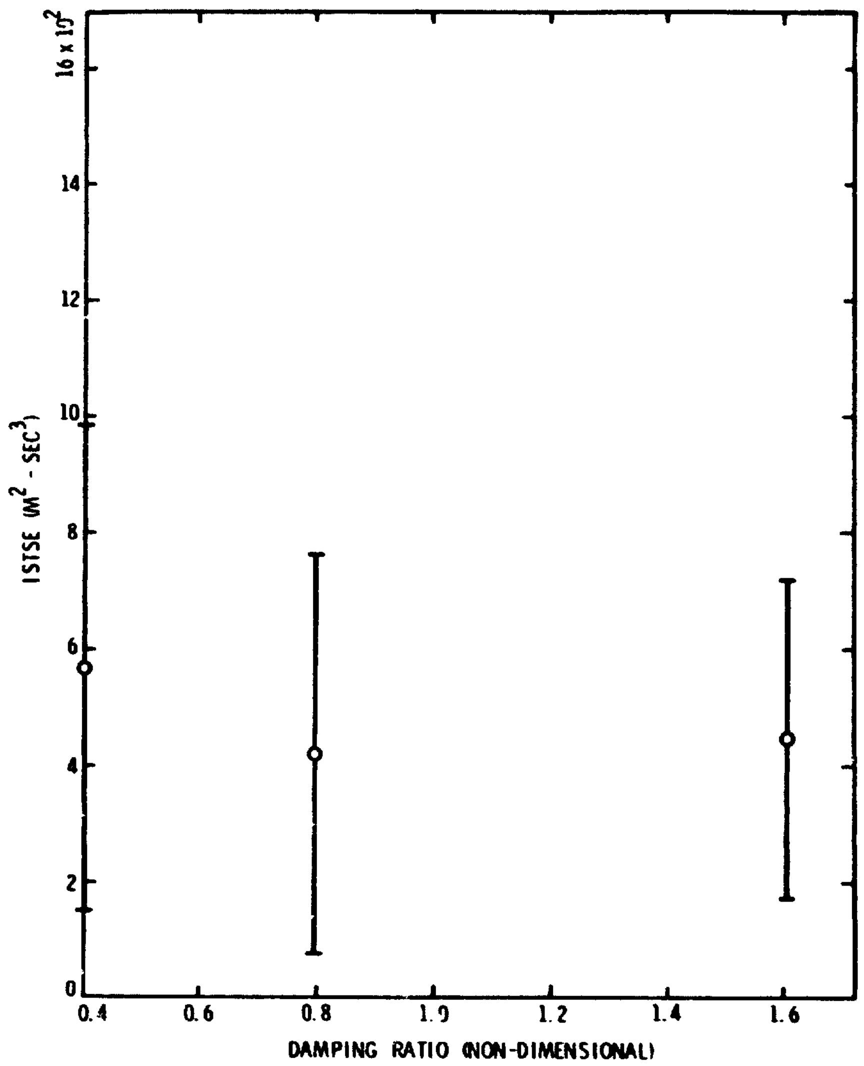


FIG. 9a EFFECT OF DAMPING RATIO ON STEP GUST PERFORMANCE WITH LATERAL POSITION AS THE ERROR

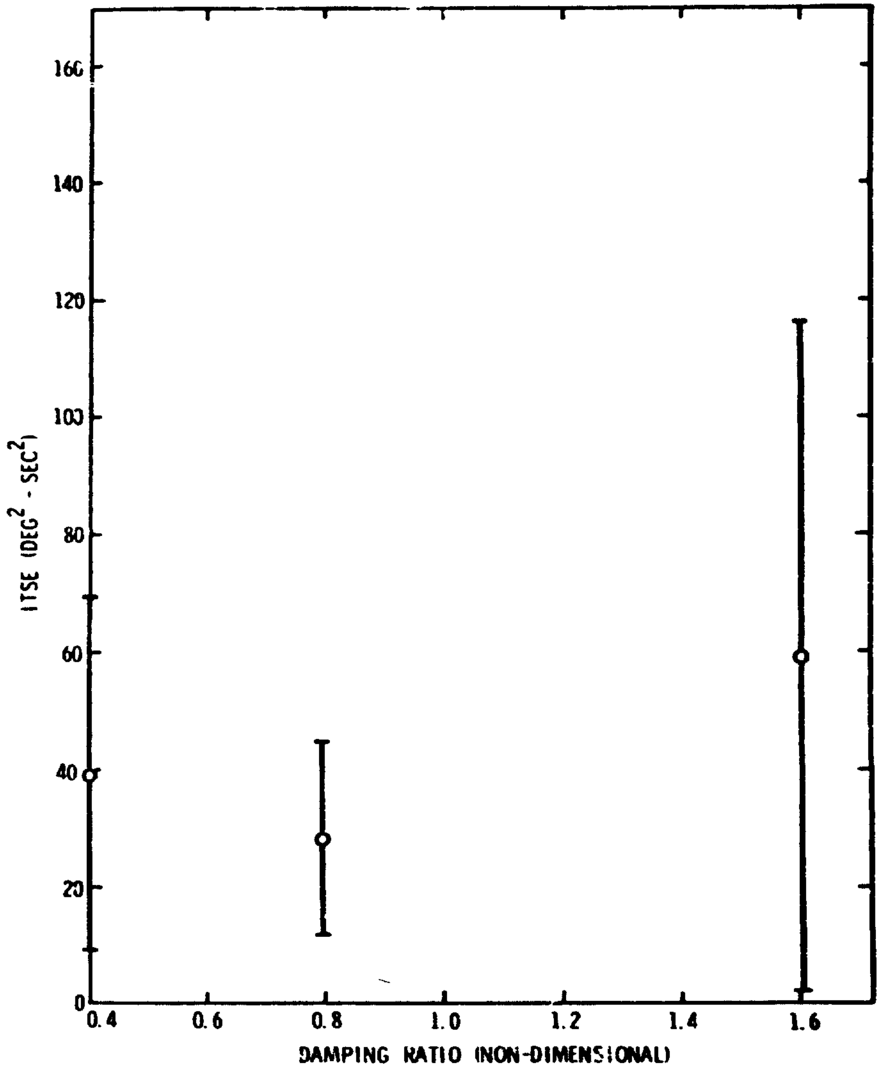


FIG. 9b EFFECT OF DAMPING RATIO ON STEP GUST PERFORMANCE WITH YAW ANGLE AS THE ERROR

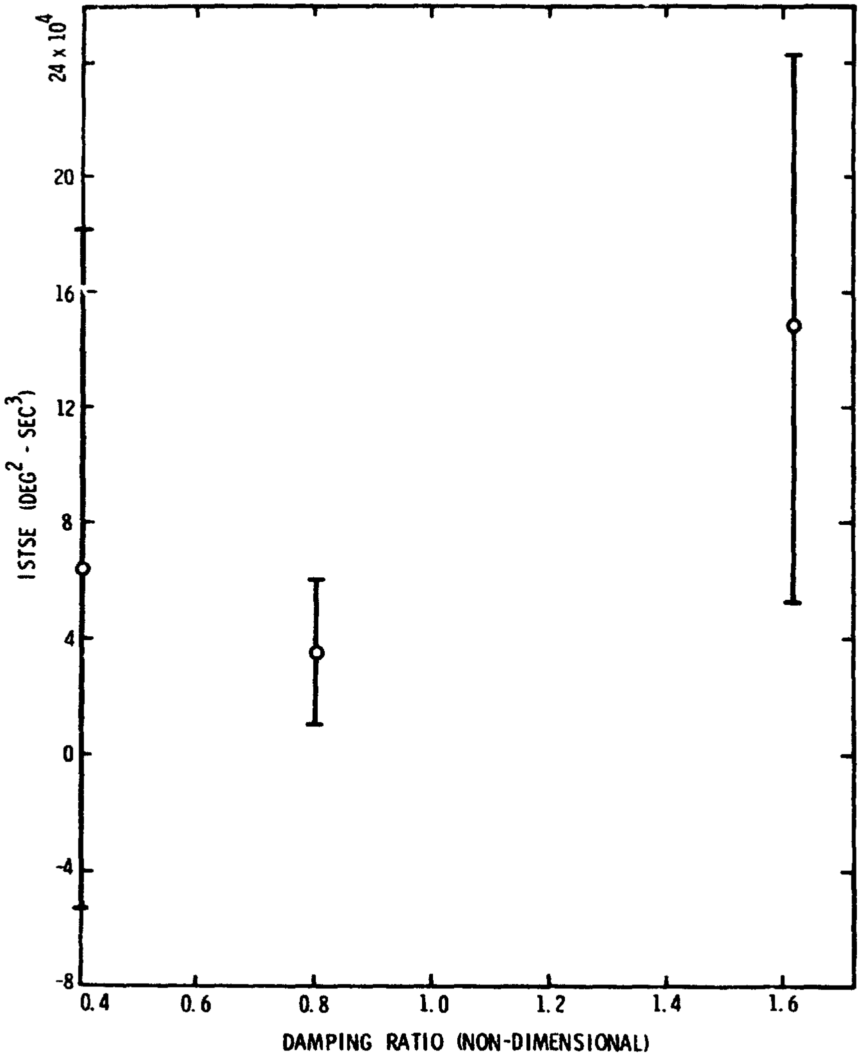


FIG. 9c EFFECT OF DAMPING RATIO ON STEP GUST PERFORMANCE WITH STEERING WHEEL ANGLE AS THE ERROR

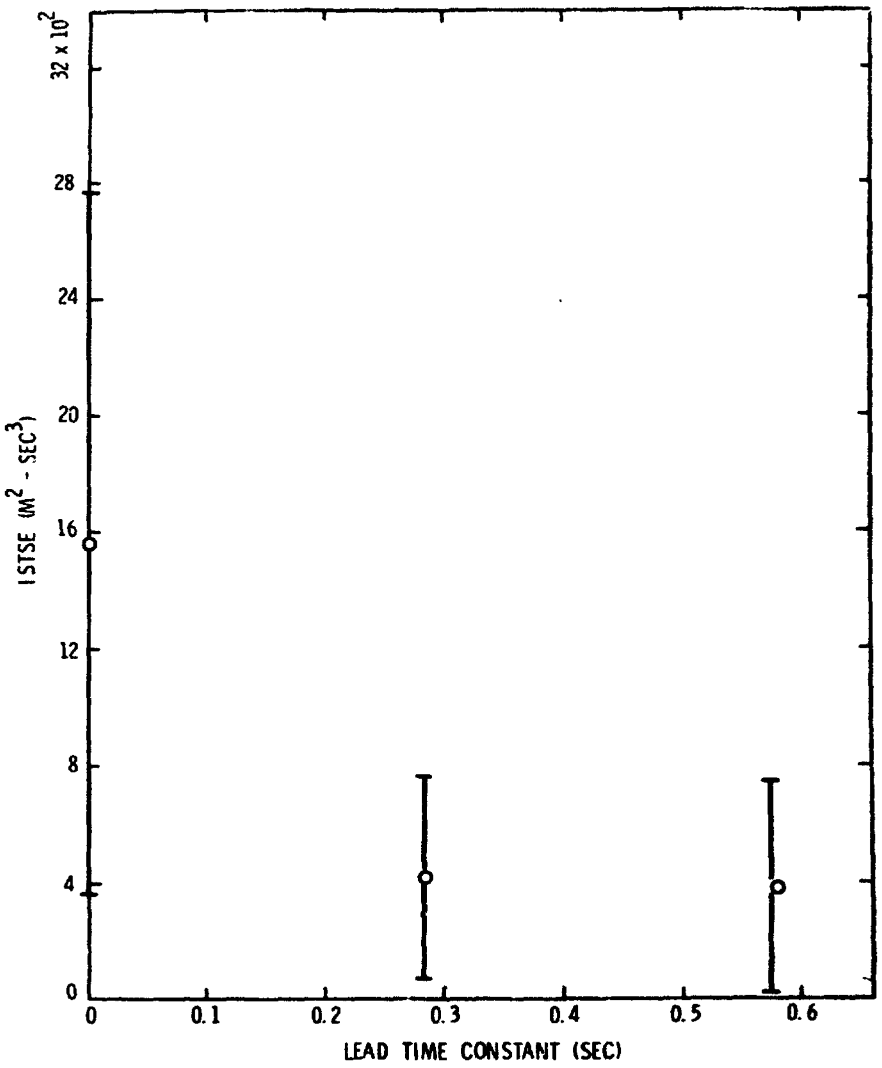


FIG. 10a EFFECT OF LEAD TIME CONSTANT ON STEP GUST PERFORMANCE WITH LATERAL POSITION AS THE ERROR

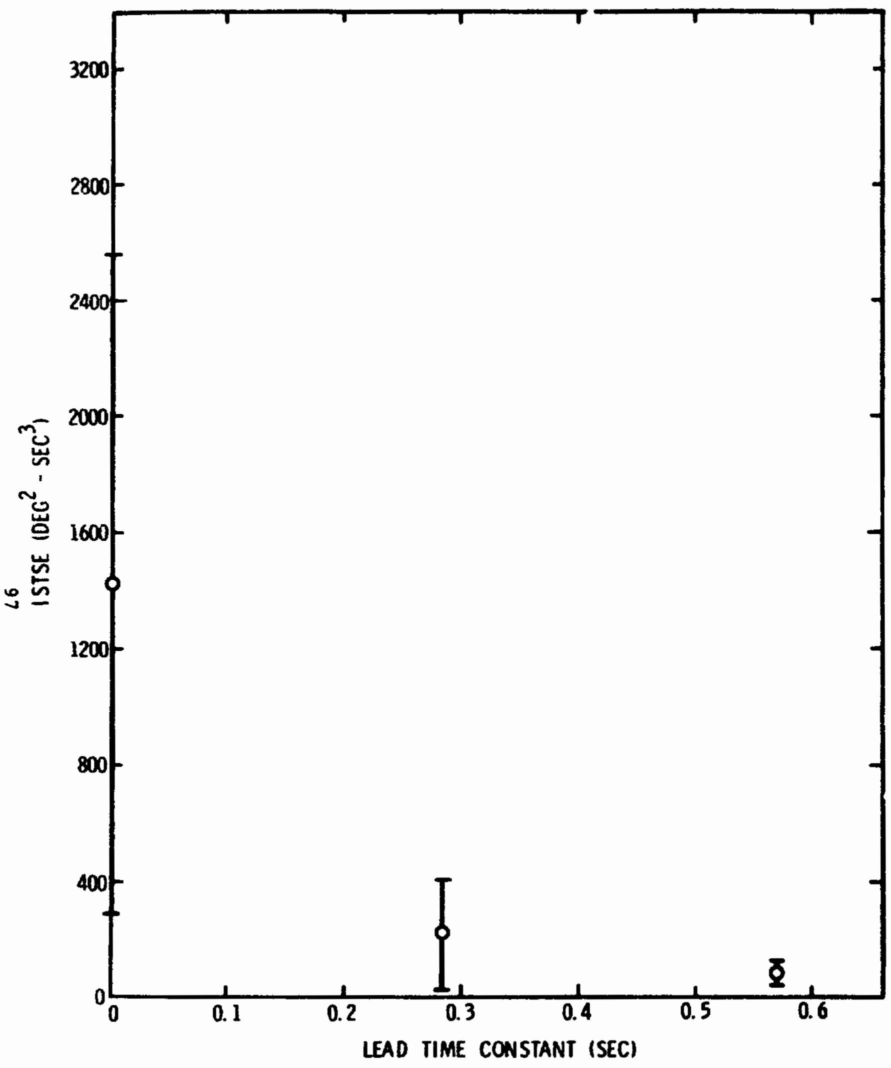


FIG. 10b EFFECT OF LEAD TIME CONSTANT ON STEP GUST PERFORMANCE WITH YAW ANGLE AS THE ERROR

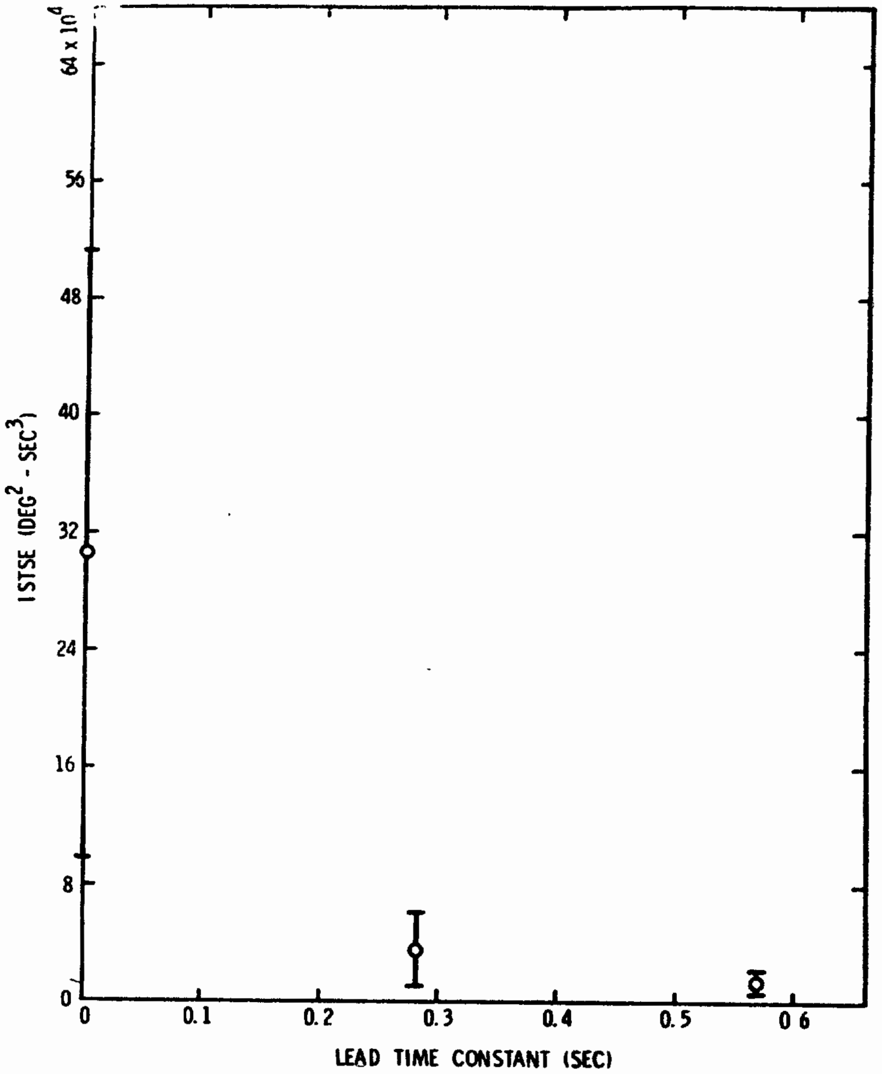


FIG. 10c EFFECT OF LEAD TIME CONSTANT ON STEP GUST PERFORMANCE WITH STEERING WHEEL ANGLE AS THE ERROR

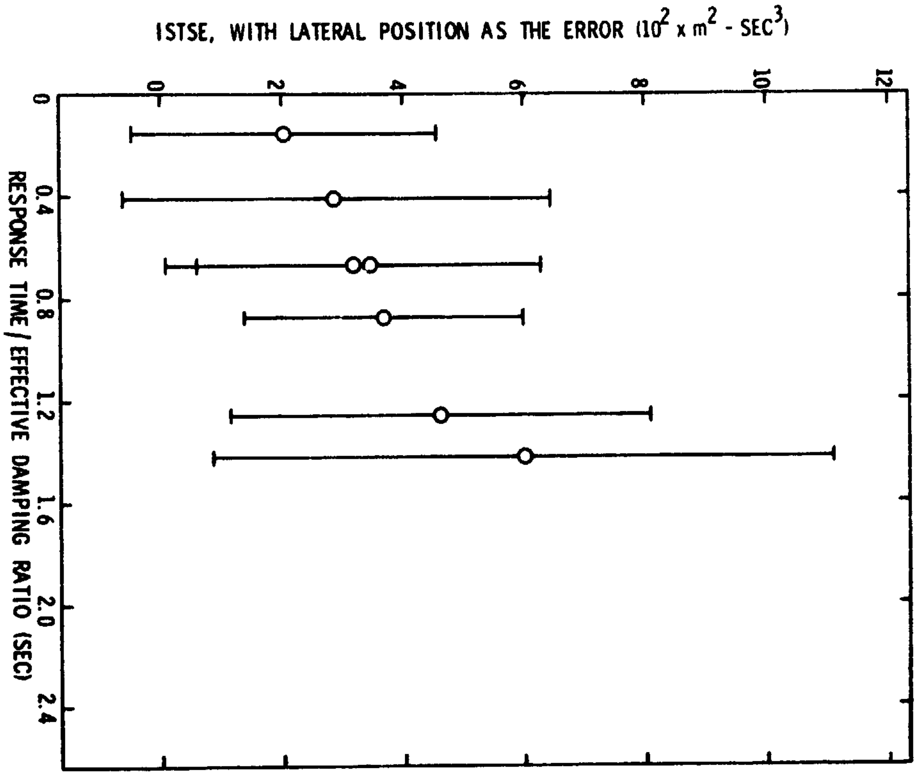


FIG. 11 PERFORMANCE DURING STEP GUST REGULATION TASK, WITH RESPONSE TIME DIVIDED BY EFFECTIVE DAMPING AS THE INDEPENDENT VARIABLE

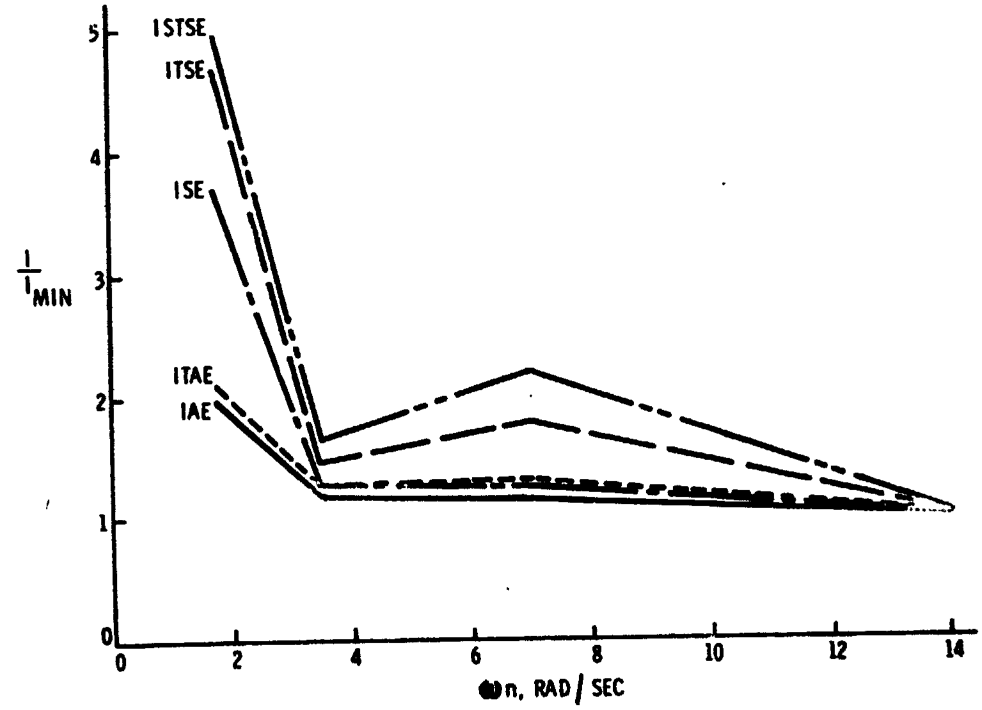


FIG. 12 COMPARISON OF PERFORMANCE CRITERIA AS A FUNCTION OF NATURAL FREQUENCY WITH STEERING WHEEL ANGLE AS THE ERROR (ARTIFICIAL LATERAL POSITION ERROR)

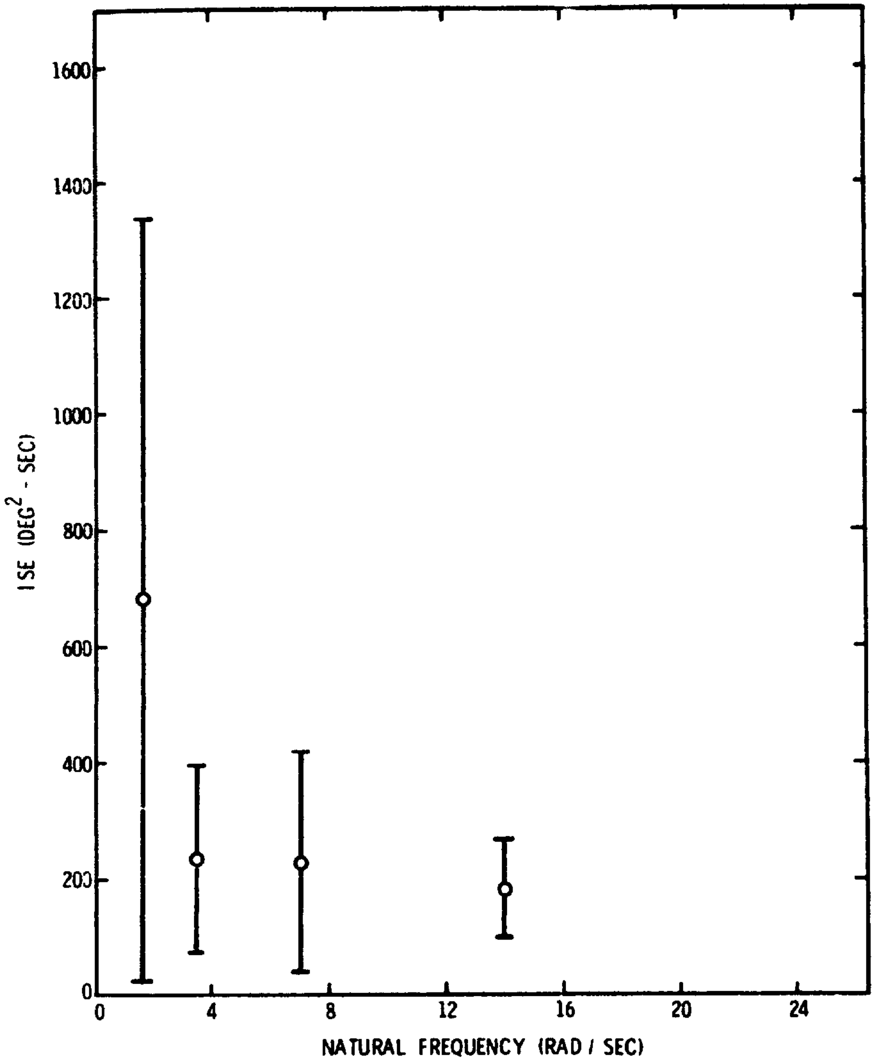


FIG. 13a EFFECT OF NATURAL FREQUENCY ON STEERING WHEEL BEHAVIOR FOLLOWING A STEP CHANGE IN LANE POSITION

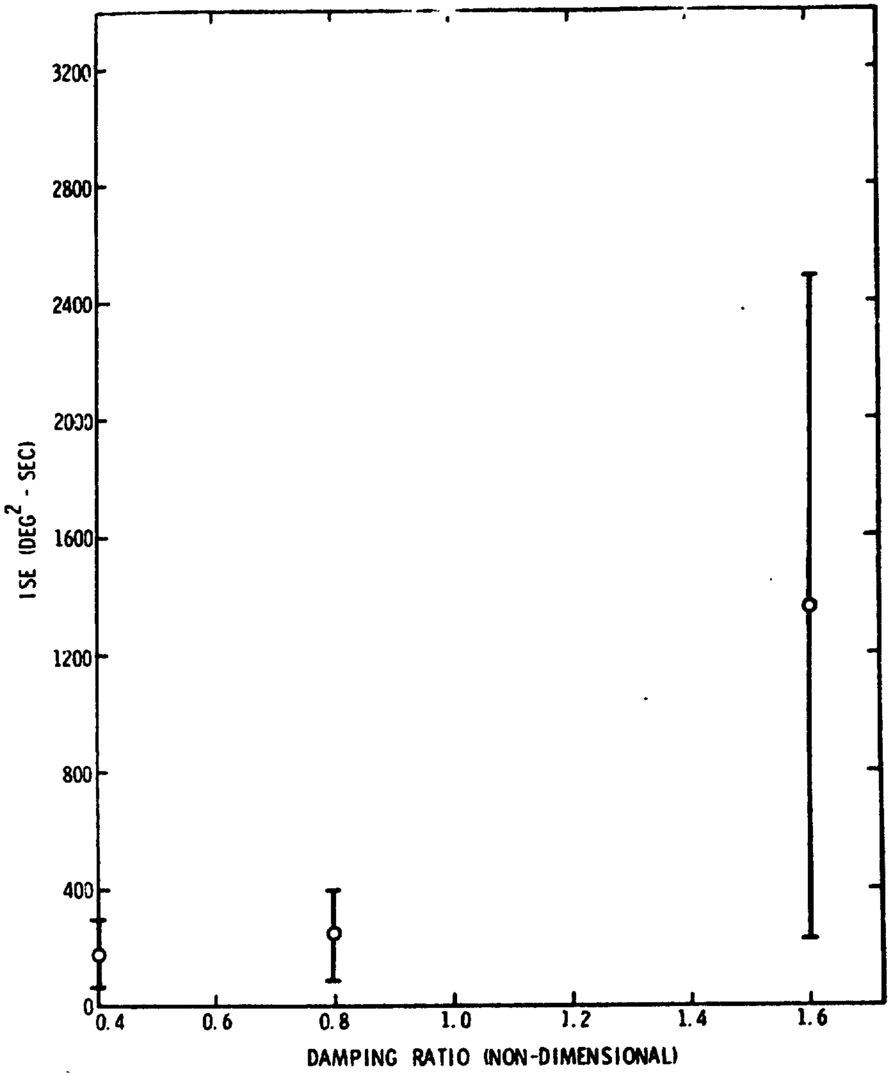


FIG. 13b EFFECT OF DAMPING RATIO ON STEERING WHEEL BEHAVIOR FOLLOWING A STEP CHANGE IN LANE POSITION

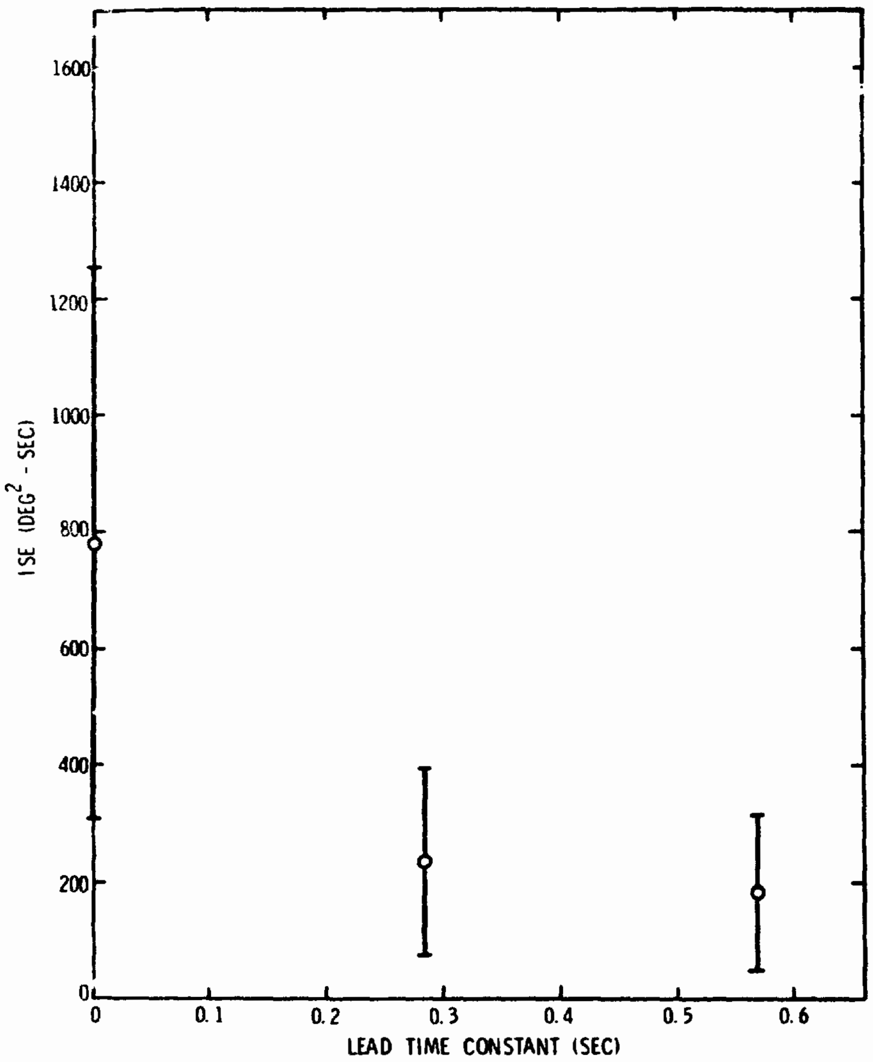


FIG. 13 C EFFECT OF LEAD TIME CONSTANT ON STEERING WHEEL BEHAVIOR FOLLOWING A STEP CHANGE IN LANE POSITION

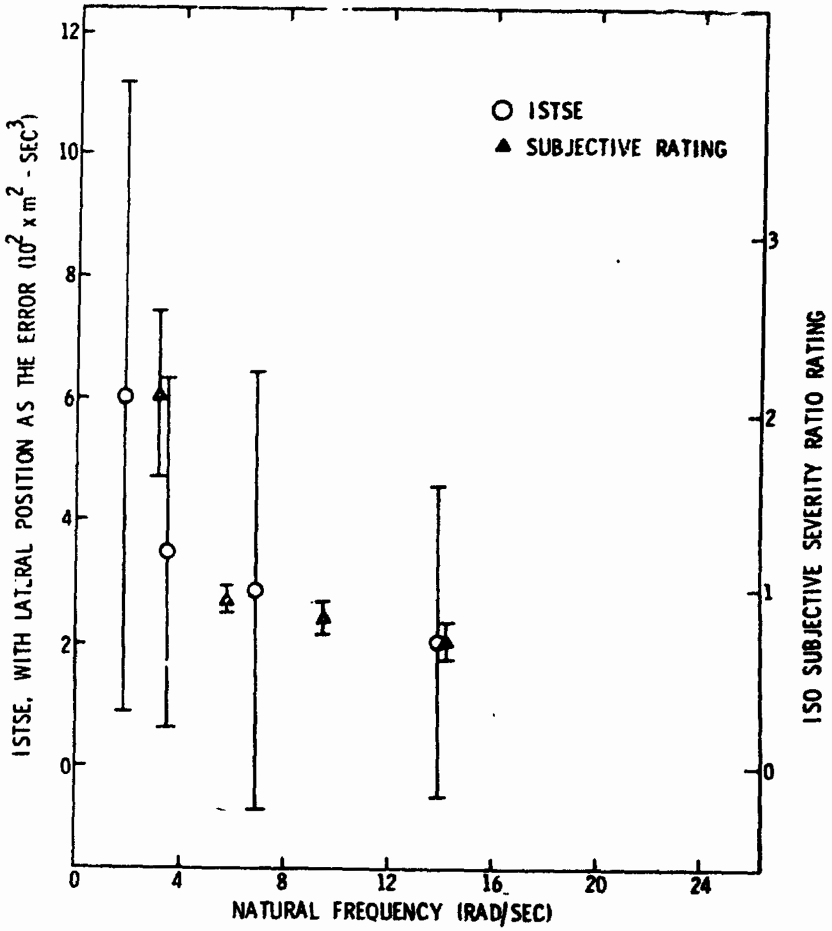


FIG. 14 EFFECT OF NATURAL FREQUENCY ON PERFORMANCE AND OPINION RATINGS DURING TRANSIENT MANEUVERS