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NOMENCLATURE

CSF	CSV + full $FSAA$ motion capability
CSI	baseline cueing system which includes flight instruments, controls, and sound simulation
CSM	CSI + restrained motion simulation
$CSMV$	CSM + visual scene simulation
CSV	CSI + visual scene simulation
F	standard statistical ratio of mean squares
N_{COL}	number of column control reversals; defined as movement out of a local deadband of 1.27 cm
N_{CR}	sum of control reversals N_{COL}, N_{WHL}, and N_{PED}
N_{PED}	number of rudder pedal control reversals; defined as movement out of a local deadband of 1.27 cm
N_{WHL}	number of wheel control reversals; defined as movement out of a local deadband of 0.25°
PRI	total integrated roll and yaw activity, deg
p_B	aircraft body-axis roll rate, deg/sec
r_B	aircraft body-axis yaw rate, deg/sec
t	time from the beginning of a run, sec
t_f	time of engine failure, sec
t_{IR}	initial reaction time $(t_{\delta_r} - t_f)$, sec
t_{LO}	time at which "lift-off" occurred, sec
t_{δ_r}	time at which the rudder deflection exceeded 5° following an engine failure, sec
t_{500}	time of attaining 152.4 m altitude, sec

Y_{LO}	"lift-off" point ($\lvert y_{cg} \rvert$ at t_{LO}), m
y_{cg}	location of the aircraft center of gravity with respect to the runway centerline (positive right), m
$\psi_{\max}$	maximum yaw angle for $t_f \leqslant t \leqslant t_{500}$, deg

EFFECTS OF VISUAL AND MOTION SIMULATION CUEING SYSTEMS ON PILOT PERFORMANCE DURING TAKEOFFS WITH ENGINE FAILURES

Benton L. Parris and Anthony M. Cook

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SUMMARY

Data are presented that show the effects of visual and motion cueing on pilot performance during takeoffs with engine failures. Four groups of USAF pilots flew a simulated KC-135 using four different cueing systems. The most basic of these systems was of the instrument-only type. Visual scene simulation and/or motion simulation was added to produce the other systems. Learning curves, mean performance, and subjective data are examined. These data show that the addition of visual cueing results in significant improvement in pilot performance, but the combined use of visual and motion cueing results in far better performance.

INTRODUCTION

The purpose of this investigation was to determine the relative values of visual and motion cueing systems for application in flight training simulators. The study is part of a joint NASA/USAF program to evaluate the possible modification of existing USAF KC-135 simulators. Concern had been expressed within the Air Force as to the adequacy of pilot training for hazardous flight conditions. One such condition is the failure of an engine during or immediately following takeoff. Engine failures, simulated in the aircraft while on the runway, are not permitted in the SAC Manual for KC-135 Aircrew Training. This type of training is, however, conducted in the existing KC-135 simulators which have no visual scene or motion systems.

The investigation was conducted using the NASA/Ames Flight Simulator for Advanced Aircraft (FSAA), a six-degree-of-freedom motion system, complete with visual scene and audio cueing. The potential value of a motion system and a comparison of the effects of visual and motion cueing on pilot performance during engine failure conditions were considered as additional objectives of the study.

The authors wish to acknowledge the contributions of those United States Air Force personnel whose collaboration and wholehearted cooperation made this investigation possible. Major Oak H. Deberg and Capt. Thomas W. Showalter, of the Aeronautical Systems Division of the Air Force Systems Command, were responsible for test development and planning. Lt. Col. Jonathan Dayton, Maj. Richard K. Runkle, and Capt. Harold Fiedler, all SAC KC-135 instructor pilots, were responsible for evaluating and refining the validity of the simulation; they also participated as observer pilots throughout the investigation.

SIMULATION EQUIPMENT

Motion System

The primary facility used was the six-degree-of-freedom Flight Simulator for Advanced Aircraft (FSAA) in the Flight and Guidance Simulation Laboratory at the Ames Research Center (fig. 1). The FSAA motion cue generation capabilities are presented in table 1. The roll, yaw, and lateral capabilities of the FSAA are well-suited to the requirements for simulating engine failures.

TABLE 1.– FSAA MOTION CAPABILITIES

Axis	Excursion	Acceleration
Roll	±45°	4 rad/sec^2
Pitch	±22°	2 rad/sec^2
Yaw	±30°	2 rad/sec^2
Longitudinal	±1.219 m	3.048 m/sec^2
Lateral	±15.24 m	4.572 m/sec^2
Vertical	±1.524 m	4.572 m/sec^2

The motion system was operated in two distinct configurations described as follows:

1. Full motion: In this configuration, the gains and time constants of the motion drive program were set at values considered to result in the most realistic representation of the motion of a large four-engine transport aircraft.

2. Restrained motion: In this configuration, the gains and time constants of the motion drive program were set at values to limit the excursion of the simulator to an approximate 1.22-m cube. This configuration was used to approximate the motion cueing capability that might be provided by a typical commercially available, six-legged synergistic motion system. No attempt was made to precisely model the synergism of such a system.

Visual System

Visual scene simulation was provided by the Ames Visual Flight Attachment-07 (VFA-07). This is a six-degree-of-freedom Redifon-type system wherein a color television camera is mounted on a gantry which moves in relation to a fixed scene model (fig. 2). The operating envelope and performance information for this system are presented in table 2. A collimated color image is presented on monitors at the pilot and co-pilot stations in the FSAA cab. The VFA-07 also

TABLE 2.– VFA-07 OPERATING ENVELOPE AND PERFORMANCE

Axis	Travel	Resolution	Max. velocity	Max. acceleration
Roll	±180°	0.80°	315 deg/sec	5000 deg/sec^2
Pitch	±25°	.02°	143 deg/sec	1200 deg/sec^2
Yaw	360° (continuous)	.02°	200 deg/sec	1700 deg/sec^2
Longitudinal	±10.923 m	±.218 cm	20.73 cm/sec	30.48 cm/sec^2
Lateral	±2.286 m	±.05 cm	27.43 cm/sec	30.48 cm/sec^2
Vertical	±0.6096 m	±.013 cm	42.67 cm/sec	54.86 cm/sec^2

Note: All dimensions are unscaled. A scale factor of 900:1 was used for this study.

incorporated a fog-generation system within the television signal link to simulate various cloud base conditions.

Cockpit Instruments and Controls

The FSAA cab was configured with representative flight instruments and controls (fig. 3), including wheel, column, and rudder pedals with programmed force-feel characteristics designed to resemble those of the KC-135A.

Sound System

The sound simulator at Ames Research Center, manufactured by Conductron-Missouri Company, was used to provide audio cues to the pilot through stereo speakers located at the right and left rear of the simulator cab. The sound generation was based on real-time information from the digital computer; it included thrust levels for each of the four engines, airspeed, and landing gear discrete event information. The sound system simulated turbojet engine sound for each of the four engines which, in the engine failure event, provided the pilot with an engine spool-down cue. Additional audio cueing included airspeed sound, gear up/down thumps, and weight-on-wheels thump.

Aircraft and Flight Dynamics Model

The aircraft model and associated equations of motion were implemented on a Xerox Sigma 8 digital computer. The aircraft aerodynamics and control system models were derived from information contained in Boeing Aircraft Document D3-9090, Rev. A, 12 October 1973.[1] The model of the engines was constructed from data contained in Boeing Aircraft Document D-16906, Rev. 5 October 1956,[2] and in USAF T.O. IC-135(K)A-1, 10 August 1974.[3] The landing gear characteristics and a portion of the control dynamics data were obtained from Boeing Aircraft Document D6-5599, 1 December 1964.[4] Refinements to the simulation, such as engine spool times, special cockpit instruments, and control force-feel characteristics, were established empirically with the aid of USAF instructor pilots who had considerable KC-135A experience.

The equations of motion for the aircraft were modeled in the standard structure for real-time aircraft simulations at Ames. This model is described in detail in reference 1.

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[1] Summary of the Stability, Control, and Flying Qualities Information for All the -135 Series Airplanes. Boeing Doc. No. D3-9090-Rev. A, October 12, 1973.

[2] Specification Engine Performance for Use in Airplane Performance Determination – J57-P-43W (JT3C-2), J57-P-43WA, -43WB and -59W Engine. Boeing Doc. No. D-16906, May 9, 1955, last revision on October 5, 1956.

[3] USAF Series KC-135 Aircraft Flight Manual. T.O. 1C-135(K)A-1 – last change No. 28, August 10, 1974.

[4] Substantiating Data Report for the KC-135A Flight Manual. Boeing Doc. No. D6-5599 – last revision on December 1, 1964.

TEST SUBJECTS

Thirty-six SAC aircraft commanders served as test subjects; approximately one-quarter of them were instructor pilots. On the average, these pilots had 1500 hr of KC-135A flight experience of which 680 hr was as aircraft commander; 45 hr of the experience was gained during the 2 months prior to this experiment. These pilots also had an average of 170 hr experience in the standard KC-135A instrument-only flight simulators.

TEST PROCEDURE

The investigation required 12 days of testing in which various combinations of cueing systems were used to quantitatively determine what amount of training would transfer to a real engine failure situation. Three pilots were tested each day and all subjects progressed through the following three phases of testing.

Phase I – Orientation

This phase began with a briefing on the experiment and on the operating procedures of the FSAA. Then each subject pilot flew a series of eight landings with full FSAA motion and visual capability (*CSF*) and varying visibility and wind conditions. Each subject pilot was rated on his general ability to handle the aircraft. This assessment was used as the basis for assigning the subject to one of four groups with the object of producing groups with similar mean ability.

Phase II – Training

Each group of nine subject pilots was assigned one of the cueing systems described in table 3. Each individual pilot flew two 13-run sessions for a total of 26 takeoff trials using only the cueing system to which his group was assigned.

TABLE 3.– CUEING SYSTEM ASSIGNMENTS FOR PHASE II

Subject group	Cueing system	Cockpit instruments	Audio system	Visual system	Motion system (restricted)	Representation
1	*CSI*	Yes	Yes	No	No	Current SAC KC-135 trainers
2	*CSV*	Yes	Yes	Yes	No	Potential improvement to current trainers
3	*CSM*	Yes	Yes	No	Yes	Commercially available 6-post motion system (approximation)
4	*CSMV*	Yes	Yes	Yes	Yes	Commercially available 6-post motion (approximation) and visual system

The failure condition for each trial was randomized to preclude subject anticipation of any particular failures. Table 4 summarizes the number of trials the subject performed for each type of failure. Takeoff conditions were: 113,398 kg gross weight, 15° C (59° F) day, flaps at 20°, and wet thrust. The failures prior to lift-off occurred at 277.8 km/hr (150 KCAS, between decision and rotation speeds). The airborne failures occurred at a wheel height of 10.67 m. The failures were also divided equally between port and starboard engines.

TABLE 4.- ENGINE FAILURE SUMMARY FOR PHASE II

Type of failure	Number of trials
None	6
Outboard engine prior to lift-off	8
Outboard engine after lift-off	8
Inboard engine prior to lift-off	2
Inboard engine after lift-off	2

Phase III – Evaluation

In the third and final phase of the investigation, each subject pilot performed a series of 10 takeoff trials with full FSAA system capability (*CSF*) to simulate transfer to the actual flight vehicle. As in Phase II, the failure condition for each trial was randomized. Table 5 summarizes the number of trials each subject performed for each type of failure.

Since outboard engine failures were of primary interest, only one inboard failure was given during Phase III. The outboard failures were divided equally between port and starboard engines.

TABLE 5.– ENGINE FAILURE SUMMARY FOR PHASE III

Type of failure	Number of trials
None	1
Outboard engine prior to lift-off	4
Outboard engine after lift-off	4
Inboard engine after lift-off	1

Subject Questionnaire

Following each phase of the investigation, the subjects completed questionnaires concerning the quality of the simulation, the sufficiency of cues, and comparisons between Phase II and Phase III cueing. Sample questionnaires are presented in appendix A. These questionnaires were designed to yield general subjective comments in addition to qualitative ratings.

Data Collection and Analysis

Time histories for a predetermined set of 45 aircraft control and flight condition parameters were recorded on strip charts and digital magnetic tape during all phases of the investigation. Due to a tape data system problem, data for seven of the 36 subjects were not recorded on magnetic tape. However, data for all subjects was recorded on strip charts. Because the desired post-test analysis would have required an unreasonable amount of manual data reduction using strip chart data as a base, and because the ability ratings of the 29 subjects whose data were recorded on magnetic tape showed adequate group means, the analysis presented in this report is based solely on the data recorded on magnetic tape. It should be noted that the strip chart recordings for the seven subjects mentioned above were examined briefly by USAF personnel and were judged not to have a significant effect on the overall outcome of the investigation.

A preliminary analysis of the data showed that of the numerous performance parameters considered, only five showed meaningful trends. These five parameters are defined as follows:

t_{IR}	initial reaction time $(t_{\delta_r} - t_f)$, sec
N_{CR}	sum of control reversals $N_{COL} + N_{WHL} + N_{PED}$
Y_{LO}	"lift-off" point ($\lvert y_{cg} \rvert$ at t_{LO}), m
PRI	total integrated roll and yaw activity, $\int_{t_f}^{t_{500}} (\lvert p_B \rvert + \lvert r_B \rvert) dt$, deg
$\psi_{\max}$	maximum yaw angle, $\lvert \psi \rvert_{\max}$ for $t_f \leqslant t \leqslant t_{500}$, deg

The performance data were analyzed from the standpoint of "learning" (i.e., variation of performance with number of trials) and from the standpoint of overall performance. The data presented in this report are divided into these two categories and into the subcategories of engine failures prior to and after lift-off.

For the analysis of learning, the average subject performance was plotted versus number of trials (see figs. 4–23). The average subject performance is defined as

$$\overline{PP}_k(m,cs) \triangleq \frac{\sum_{i=1}^{N} PP_{k_i}(m,cs)}{N}$$

where $PP_{k_i}(m,cs)$ is the performance parameter k for subject i, trial m, in cueing system (cs); and N is the total number of subjects in cs.

For the analysis of overall performance, the mean (AV), mean plus one-half standard deviation (SD), and mean minus one-half SD for all subjects and all trials in a particular cueing system were plotted versus cueing system (see figs. 24–53). The mean and standard deviation are defined as follows:

$$\text{Mean} = AV_k(cs) \triangleq \frac{\sum_{m=1}^{M} PP_{k_i}(m,cs)}{M}$$

$$\text{Standard deviation} = SD_k(cs) \triangleq \sqrt{\left| \frac{\sum_{m=1}^{M} PP_{k_i}^2(m,cs)}{M} - AV_k^2(cs) \right|}$$

where M is the total number of trials for all subjects in cs.

To determine the statistical significance of cueing system effects for outboard engine failures during Phase II (training), two analyses of variance were performed for each of the five performance parameters, one for failures prior to lift-off and one for failures after lift-off. These analyses were based on the average subject performance $\overline{PP}_k(m,cs)$ data, defined above, regarding cueing systems (cs) as treatments and trials (m) as samples within treatments. The results of these analyses are presented in appendix B.

RESULTS AND DISCUSSION

Analysis of Subjective Data

The overall opinion of the subject pilots was that the quality of the simulation with respect to resembling the flying qualities of the aircraft was between good and excellent when the full FSAA capability (*CSF*) was employed (see table 6). Note the shift in ratings to good and excellent with the Phase I to Phase III transition. Most of the subject pilots had heretofore flown only fixed-base, nonvisual, KC-135 simulators of the "procedures trainer" only type. In spite of initial briefings and assurances that this investigation was not an evaluation of each subject's piloting skill, there still appeared to be an understandable natural apprehension during Phase I regarding individual performance under data-taking scrutiny. These concerns were probably dispersed as the investigation was carried into Phase II. Many subjects' comments indicated that the simulation exhibited roll (aileron) sensitivity higher than that of the aircraft. "Over-sensitive controls" is a common observation among pilots with little simulator experience, in spite of efforts to calibrate and reproduce control force-feel characteristics.

TABLE 6.– SUBJECTIVE RATING OF FULL FSAA CAPABILITY (*CSF*)

Rating	Number of subject pilots	
	Phase I	Phase III
Excellent	3	22
Good	28	14
Fair	4	---
Poor	1	---
Very poor	---	---

Results of the subjective evaluations of the cueing systems made after Phase II of the investigation are presented in tables 7 and 8.

TABLE 7.– PHASE II – SUFFICIENCY OF CUES TO ENABLE NEGOTIATION OF ENGINE FAILURES

Rating	Number of subject pilots			
	CSI	*CSV*	*CSM*	*CSMV*
Very sufficient	2	6	2	8
Sufficient	6	3	4	1
Occasionally sufficient	1	---	3	---
Insufficient	---	---	---	---
Very insufficient	---	---	---	---

TABLE 8.– PHASE II – RATING OF CUEING SYSTEMS AS A TRAINING DEVICE FOR OUTBOARD ENGINE FAILURES

Rating	Number of subject pilots			
	CSI	*CSV*	*CSM*	*CSMV*
Excellent	1	9	2	8
Good	3	---	3	1
Fair	3	---	2	---
Poor	1	---	2	---
Very poor	1	---	---	---

As can be seen in these data, the cueing systems, which included a visual system (*CSV* and *CSMV*), were considered superior to others in terms of sufficiency of cues and as training devices. It is interesting to note that although *CSMV* received higher ratings than *CSV* in terms of sufficiency, the *CSV* system was considered to be a somewhat better training device. None of the cueing systems were considered to provide insufficient cues for negotiating an engine failure.

Results of the subjective evaluations made following Phase III of the investigation are presented in tables 9 and 10.

A comparison of the sufficiency evaluations of Phase II and Phase III shows the most marked improvement in cueing for those subjects trained in the *CSI* system. A similar improvement, but not

TABLE 9.– PHASE III – SUFFICIENCY OF CUES TO ENABLE NEGOTIATION OF ENGINE FAILURES (*CSF*)

Rating	Number of subject pilots			
	Training group			
	1(*CSI*)	2(*CSV*)	3(*CSM*)	4(*CSMV*)
Very sufficient	9	7	6	8
Sufficient	---	2	3	1
Occasionally sufficient	---	---	---	---
Insufficient	---	---	---	---
Very insufficient	---	---	---	---

TABLE 10.– PHASE III – RATING OF CUEING SYSTEM USED IN PHASE II AS TRAINING DEVICE FOR PHASE III (*CSF*)

Rating	Number of subject pilots			
	CSI	*CSV*	*CSM*	*CSMV*
Strong positive relation	1	7	1	9
Positive relation	3	2	4	---
Neutral relation	4	---	4	---
Negative relation	1	---	---	---
Strong negative relation	---	---	---	---

as significant, was that shown for the subjects trained in the *CSM* system. There was only a slight improvement for the subjects trained in the *CSV* system and no difference in terms of sufficiency for the *CSMV* group of subjects. These data appear to indicate that the addition of visual cues (with *CSF*) was the primary improvement in cueing and that motion cueing was an improvement but to a lesser degree.

The evaluations of the Phase II systems as training devices for Phase III indicate the best training to have occurred in the system with both visual and motion cueing (*CSMV*). However, the *CSV* system was rated as having positive to strong positive relation (good to excellent training) to Phase III.

The subjective comments secured from the questionnaires may be summarized by the following general statements. The visual scene simulation was considered to be the most useful cue in that it evoked the quickest and most consistently accurate response to an engine failure. The motion cues, when used in conjunction with the visual system, were considered to be quite useful in reinforcing the subject's judgment as to whether or not his response to the engine failure was adequate. Use of motion cues, without accompanying outside visual reference, often led to confusion as to direction and amount of control response required to recover from an engine failure and forced a heavier reliance on cockpit instruments. The use of cockpit instruments alone was considered to be inadequate for negotiating engine failures during takeoff. The cockpit instruments were believed to be better suited as backup and cross-check references once initial corrective measures had been taken.

Review of the comments of the subjects trained in the *CSMV* system revealed no shortcomings of the restrained motion as compared to full motion. Interestingly, many of these subjects stated that they could not detect significant differences between the two motion systems.

Analysis of Performance

Phase II learning curves for engine failures prior to lift-off– The average learning curves of subjects tested during Phase II for outboard engine failures prior to lift-off are presented in figures 4 through 8. The average learning curves of all subjects in *CSF* during Phase III are included for comparison as assumed task asymptotes. It should be noted that the jump in the curves after the fourth run is probably due to the two-session method used for testing in Phase II. However, this jump is evident only for subjects in *CSI* and *CSM* and primarily for those in *CSI*.

The initial time response (t_{IR}) of subjects (fig. 4) shows the most pronounced conditioning (about 1.5 sec) for those subjects in *CSI*. However, the response of these subjects does not reach the level of those in the other cueing systems. The subjects in *CSM* show a slight initial negative conditioning (degradation of performance) of about 0.5 sec but quickly settle to a response time slightly less than the subjects in *CSI*. Subjects in *CSV* show very slight positive time response conditioning (improved performance) in the initial portion of Phase II and a definite negative conditioning of about 0.7 sec in the latter portion of Phase II. Subjects in *CSMV* show only slight conditioning of time response and settle to a level that is about 0.3 sec faster than those in *CSV* and that is very near the Phase III final values. Very little time response conditioning is seen in Phase III results (*CSF*). This is probably due to extensive conditioning in Phase II and the fact that the subjects knew they would receive mostly outboard engine failures during Phase III. It should be noted that the resolution of time response is ±0.048 sec.

The amount of control activity (N_{CR}) for engine failures prior to lift-off (fig. 5) was greatest for subjects in *CSV*. Subjects in *CSMV* exhibited similar control activity but at a somewhat lower level. The subjects in cueing systems with visual cueing exhibited a much higher level of control activity than those without visual cueing. All subjects seem to exhibit a smooth conditioning toward less activity and the subjects in *CSMV* approach a minimum of control activity more rapidly than the others. It is interesting to note that subjects in *CSI* exhibit control activity conditioning very similar to those in *CSM* and that the rate of conditioning is similar for those subjects with anything less than a full set of cues.

The displacement from runway center at the time of lift-off (Y_{LO}) for engine failures prior to lift-off (fig. 6) varied over a wide range and did not settle to an acceptable level of performance for subjects in *CSI* and *CSM* (no visual cueing); however, those subjects in *CSV* and *CSMV* and all subjects in Phase III (*CSF*) displayed consistent acceptable performance in this respect. These data demonstrate the importance of visual cueing for holding the runway with an on-the-ground outboard engine failure. Note that trials without visual cueing were off the runway edge by wide margins at lift-off, even without engine failures prior to lift-off (fig. 11).

The amount of aircraft roll and yaw activity (*PRI*) is a reasonably good indication of how well a pilot controls the aircraft following an engine failure. The improvement in this respect for outboard engine failures prior to lift-off appears to be most pronounced for subjects in *CSV* (fig. 7). If one considers the Phase III results (*CSF*) as an indication of the task asymptote, the subjects in *CSMV* appear to have required little or no training to attain and hold this level of performance. The subjects in *CSI* show an initial performance in this respect that is about halfway between that of subjects in *CSV* and *CSMV*; they also exhibit a continuous conditioning toward the task asymptote, when considering the two-session method of Phase II. However, the jump in performance from the first session (runs 1–4) and the second session (runs 5–8) is only evident here for subjects in *CSI* and indicates the impermanence of the conditioning obtained in that cueing system. The subjects in *CSM* exhibit *PRI* performance consistently near the task asymptote but show a somewhat erratic conditioning tendency.

Considering the maximum yaw angle reached ($\psi_{\max}$) in the aircraft flight path after an outboard engine failure prior to lift-off (fig. 8), the subjects in *CSI* exhibit continuous conditioning in the first and second sessions of Phase II, but the jump in performance between the two sessions is evident. The subjects in *CSV*, however, exhibit a continuous positive conditioning throughout Phase II and approach a value of $\psi_{\max}$ which is nearer the task asymptote. The subjects in *CSM* exhibit positive conditioning across the two sessions of Phase II and achieve values of $\psi_{\max}$ similar to those of the *CSV* subjects, but the erratic nature of their conditioning is also evident. As with *PRI*, the subjects in *CSMV* appear to have required very little training to attain and hold the task asymptotic value of $\psi_{\max}$.

Phase II learning curves for engine failures after lift-off– The average learning curves for engine failures after lift-off are presented in figures 9 through 13.

The initial time response (t_{IR}, fig. 9) was slowest for subjects in *CSI*. These subjects also exhibit very erratic time response conditioning. The conditioning of subjects in *CSV* and *CSM* is surprisingly similar and is much less erratic than that of the *CSI* group, but it does not approach the considered task asymptote (Phase III, *CSF*). The subjects in *CSMV* exhibit quicker response than the other groups but still display erratic conditioning similar to the *CSV* and *CSM* groups. The *CSMV* group was the only one to attain response times near the task asymptote. Comparing the time response curves for outboard engine failures prior to lift-off (fig. 4) with those for failures after lift-off (fig. 9), only those subjects with visual cueing had markedly different time responses for the two tasks. This might be an indication of regimes of effectiveness for visual cueing.

The amount of control activity (N_{CR}, fig. 10) for subjects with visual cueing was nearly twice the amount for subjects without. Again, subjects in *CSI* and *CSM* exhibit a certain amount of reconditioning after the transition from the first to second sessions. However, these subjects as well as those in *CSV* and *CSMV* exhibit a conditioning toward a lower amount of activity and this tendency seems to be correlated with an improved performance as shown in *PRI*, figure 12.

The displacement from runway center at the time of lift-off (Y_{LO}, fig. 11) for subjects without visual cueing again indicates the need for visual cueing during takeoff. It should be noted that these data were recorded prior to the engine failure.

The subjects in *CSI* showed erratic conditioning and a tendency to converge on a value of aircraft roll and yaw activity (*PRI*, fig. 12) much greater than the task asymptote. The subjects in *CSV* showed a similar erratic nature of conditioning during the first session of Phase II, but exhibited a steady trend toward the task asymptote during the second session. The subjects in *CSM* started near the task asymptote and tended to diverge from that value during the first session of Phase II; however, they reversed this trend during the second session. The subjects in *CSMV* had the best performance with respect to *PRI*, but displayed some erratic conditioning. It appears that if more trials had been given, subjects in *CSV*, *CSM*, and *CSMV* would have converged on the task asymptote.

Considering the maximum yaw angle excursion of the aircraft after an outboard engine failure after lift-off ($\psi_{\max}$, fig. 13), the subjects in *CSI* exhibited extremely erratic performance and displayed definite negative conditioning. The subjects in *CSV* and *CSM* also had erratic performance but did tend toward some positive conditioning. Comparing *PRI* (fig. 12) and $\psi_{\max}$ (fig. 13), it is interesting to note that subjects in *CSV* produced higher levels of aircraft roll and yaw activity (*PRI*) but lower maximum yaw excursion ($\psi_{\max}$); subjects in *CSM* showed the opposite trend. The $\psi_{\max}$ performance of subjects in *CSMV* was again better than that of any of the other groups and shows trends similar to the *PRI* performance. Again, it appears that more trials in any of the cueing systems would have led to a better definition of the task asymptote for that cueing system.

Phase III learning curves for engine failures prior to lift-off– The average Phase III learning curves of the separate test groups for outboard engine failures prior to lift-off are presented in figures 14 through 18.

The initial time response conditioning (t_{IR}, fig. 14) shows a maximum difference between any two groups of about 0.25 sec. Differences in t_{IR} between groups could be considered insignificant for the task.

The amount of control activity (N_{CR}, fig. 15) shows similar conditioning for groups trained without visual cueing. The *CSI* group converges to the lowest amount of activity and the *CSV* group converges to a level of activity which is approximately five control reversals more than the *CSI* group.

All groups exhibited almost no conditioning with respect to Y_{LO} (fig. 16), with values for all groups differing by only as much as 11 m.

The *PRI* learning curves (fig. 17) were similar for the *CSV* and *CSM* groups. The *CSI* and *CSMV* groups exhibited a level of *PRI* approximately 25° lower than the other groups.

The differences in $\psi_{\max}$ (fig. 18) were so small (on the order of 4°) that they should be considered insignificant. Therefore, no meaningful comparison can be made between groups on the basis of this parameter for this task.

Phase III learning curves for engine failures after lift-off– The average Phase III learning curves of the separate test groups for outboard engine failures after lift-off are presented on figures 19 through 23.

Very little time response conditioning (fig. 19) was exhibited by the test groups and all groups had about the same level of time response (1.2 sec). The *CSI* group deviated from this level only for the first trial and then only by about 0.2 sec. Again, differences in t_{IR} between groups could be considered insignificant for this task.

For all groups, the amount of control activity for this task (fig. 20) began at a much lower level than for the failures prior to lift-off (fig. 15) and showed a continuous decrease as more trials were given. The *CSI* group displayed a slightly higher rate of conditioning on N_{CR} than the other groups, but all groups tended to level-off at about the same value of N_{CR}.

The maximum difference between groups of Y_{LO} was about 3 m (fig. 21). These results are definitely insignificant, which was expected, since the failure task did not occur until after lift-off.

The aircraft roll and yaw activity learning curves have two forms (fig. 22). One form being characteristic of the *CSMV* group and the other form characteristic of *CSI*, *CSV*, and *CSM* groups. The *CSMV* group exhibited a lower rate of learning, but reached a lower final value of *PRI*. It appears that the *CSMV* group adapted to *CSF* better than the other groups in terms of *PRI*.

The maximum difference in $\psi_{\max}$ between groups for the task was approximately 3° (fig. 23). Therefore, no significant comparison of $\psi_{\max}$ learning curves during Phase III can be made for this task.

The data of figures 14 through 23 are included for completeness. They do not show any significant conditioning occurring during Phase III. The conclusion is that all the significant training occurred during Phase II which is illustrated in figures 4 through 13.

Overall performance– The results described in the following paragraphs are based on statistics for all runs in a particular cueing system and therefore include the entire learning process. Different results might have been obtained if these statistics had been based solely on established asymptotes for the cueing systems. Since it was not possible to solidly establish these asymptotes, the method of including all data was chosen.

The Phase III (*CSF*) data presented on figures 24 through 33 are based on all subjects in Phase III, regardless of which Phase II group they were in, and is included for comparison as merely another cueing system. The Phase III data presented in figures 34 through 53 are segregated into results for the separate test groups.

Phase II and Phase III results for outboard engine failures prior to lift-off– The initial time response data for this task (fig. 24) indicate that cueing systems with a visual scene induce response that is about 1.25 sec (average) faster than *CSI* but only 0.5 sec faster than *CSM*. These data also indicate a gradual improvement in response as the level of motion cueing added to the visual scene is increased. The variance, however, continuously decreases as the cueing system moves from *CSI* to *CSMV*, but is approximately the same for *CSMV* and *CSF*. These data indicate that the addition of motion achieves improvement mainly by reducing the variance rather than the mean value of time response.

The control activity data for this task (fig. 25) indicate that, in the mean, subjects with visual cueing exert more control effort toward performance of the task than do subjects without visual cueing, and that this effort is gradually reduced with the addition of increasing amounts of motion cueing. The variance in control activity increases sharply when visual cueing is added whether or not motion cueing was initially present. The means and variance of control activity for subjects in cueing systems without visual cueing are very nearly identical.

The Y_{LO} data (fig. 26) show more distinctly the obvious importance of visual cueing to allow the subjects to hold the runway after an engine failure prior to lift-off.

The aircraft roll and yaw activity data for this task (fig. 27) indicate that motion cueing is the primary aid to controlling the aircraft after an on-the-ground failure. It is interesting to note that *CSV* produced a higher mean and variance in *PRI* than did *CSI* for this task.

The statistics for maximum yaw angle for this task (fig. 28) indicate that both motion and visual cues are needed to hold the yaw excursion of the aircraft to a minimum.

Phase II and Phase III results for outboard engine failures after lift-off– The initial time response for this task (fig. 29) is not improved by the addition of visual cueing as significantly as it was for engine failures prior to lift-off (fig. 24). However, the addition of motion-only cueing (*CSM*) does not improve the time response as well as the addition of visual cueing (*CSV*). The real improvement is seen when both motion and visual cueing are used (*CSMV*). Increasing the amount of motion cueing (*CSF*) also tends to improve the time response. It is interesting to note that the variance in time response for this task is nearly identical for systems with visual cueing.

The overall level of control activity for this task (fig. 30) is slightly lower than for on-the-ground engine failures (fig. 25), but the trends in effects of types of cueing are nearly identical. That is, subjects with visual cueing exhibit higher means and wider variance in control activity than subjects without visual cueing.

The statistics for Y_{LO} (fig. 31) merely amplify the results noted in the learning curve analysis. That is, visual cueing is obviously necessary for keeping the aircraft centered on the runway, regardless of engine failures.

As with on-the-ground failures (fig. 27), aircraft roll and yaw activity for this task (fig. 32) is minimized primarily by motion cueing. However, the visual without motion cueing (*CSV*) did yield improvement in the mean *PRI* performance for this task as opposed to the adverse effect for on-the-ground failures.

The statistics for maximum yaw angle for this task (fig. 33) again show that both motion and visual cueing are needed to minimize $\psi_{\max}$. However, as with *PRI*, *CSV* appears to offer more improvement in $\psi_{\max}$ performance for this task than for on-the-ground failures.

Phase III results for outboard engine failures prior to lift-off– During Phase III, the maximum difference in mean time response between any of the groups was about 0.1 sec (fig. 34) and the variance was nearly the same for all groups. Therefore, no significant effects of cueing systems on time response for this task in Phase III are evident.

The only significant trend in the control activity data (fig. 35) is that the higher level of control activity exhibited by the *CSV* group seems to have carried over from Phase II to Phase III.

The *CSM* group exhibited the most difficulty in holding runway center after engine failure during Phase III (fig. 36). The *CSV* system appears to be best for training the subjects to hold runway center for this task.

The aircraft roll and yaw activity data (fig. 37) indicate that *CSMV* is best for training subjects to control the aircraft after an on-the-ground failure. A surprising indication is that *CSI* appears to be a better training system for this task than either *CSV* or *CSM*.

The $\psi_{\max}$ data (fig. 38) show the same trends as the *PRI* data for this task. However, *CSV* appears to be better training for minimizing yaw excursion than *CSM*.

Phase III results for outboard engine failures after lift-off– Only insignificant differences in time response (maximum of 0.2 sec) are evident for this task in Phase III (fig. 39).

Although differences are small, the higher level of control activity exhibited by subjects with visual cueing appears to have carried over to Phase III for this task (fig. 40).

The maximum difference in Y_{LO} means between any of the groups in Phase III was about 0.8 m (fig. 41) and the variance was nearly the same for all groups. Therefore, no significant trends are evident in the Y_{LO} data for this task during Phase III.

Similar to on-the-ground failures (fig. 37), the *PRI* data (fig. 42) indicate that *CSMV* is best for training subjects to control the aircraft after an engine failure following lift-off.

Although differences in $\psi_{\max}$ data are small (fig 43), these data exhibit the same trends as the *PRI* data (fig. 42) for this task.

Comparison of Phase II (Training) and Phase III (Evaluation) means for engine failures prior to lift-off– The means of time response for this task (fig. 44) more clearly indicate the significant improvement achieved by visual cueing and the marginal improvement achieved by adding motion to visual.

If one considers an optimum level of control activity for this task to be near the Phase III mean for $CSMV$ (fig. 45), this optimum appears to be approached from the high side by cueing system groups with visual cueing, and from the low side by groups without visual cueing.

The necessity of visual cueing for holding runway center after an on-the-ground engine failure is again illustrated by the Y_{LO} means presented in figure 46.

The PRI means presented in figure 47 support the view that motion with visual cueing is the primary aid to controlling the aircraft for this task.

The $\psi_{\max}$ means presented on figure 48 illustrate the value of combined motion and visual cueing with respect to keeping yaw excursion to a minimum.

Comparison of Phase II (Training) and Phase III (Evaluation) means for engine failures after lift-off– The t_{IR} means presented in figure 49 clearly indicate the importance of combining visual and motion cueing to achieve minimum response times for this task.

The amount of control activity for this task (fig. 50) shows trends similar to the on-the-ground failures in that the groups trained in systems with visual cueing exhibit a higher level of control activity.

The Y_{LO} means presented in figure 51 again illustrate the need for visual cueing to hold the runway center regardless of engine failures.

The roll and yaw activity means (fig. 52) indicate that the motion cueing is the primary aid for controlling the aircraft for this task, and that the combination of visual and motion cueing seems to provide the best training.

As with the on-the-ground failures, the $\psi_{\max}$ means presented in figure 53 support the need for combined visual and motion cueing with respect to keeping yaw excursion to a minimum.

SUMMARY OF RESULTS

An investigation of the effects of visual scene and motion simulation on the ability of a pilot to perform the task of controlling a large four-engine transport aircraft following an outboard engine failure during takeoff has indicated the following:

1. The use of cockpit instruments only or cockpit instruments in conjunction with limited motion is inadequate for negotiating engine failures during takeoff and offer poor training for this task.

2. The visual cueing is mandatory for keeping the aircraft on the runway during takeoff regardless of engine failures.

3. The visual cueing added to cockpit instruments offers significant improvement with respect to detecting the onset of an engine failure, but motion is highly desired to achieve high overall task performance.

4. The visual scene offers an improvement with respect to training, but visual and motion cueing far exceed the visual-alone capabilities.

Both performance measures and subjective opinion indicated the results stated above. However, further studies should be conducted to evaluate the effects of various levels of motion cueing on performance for a wide range of aircraft and tasks.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif. 94035, Feb. 21, 1978

APPENDIX A

SAMPLE SUBJECT QUESTIONNAIRES

The following questionnaires were used to obtain subjective data during the various phases of this study.

PERSONAL DATA

Questionnaire

1. Name:
2. Rank:
3. Age:
4. Years In Service:
5. Office Address:
6. Commanding Officer and Address:
7. Flying Data

A. Time Flown (by type)

I. Tankers	Hours
a) KC-135A___	____
b) ____	____
c) ____	____
II. Bombers	
a) ____	____
b) ____	____
c) ____	____

III. Cargo/Transport

a)_____ ______

b)_____ ______

c)_____ ______

IV. Fighters/Attack

a)_____ ______

b)_____ ______

c)_____ ______

V. Trainers

a)_____ ______

b)_____ ______

c)_____ ______

B. Currency

I. Number of hours flying time on KC-135 during past two (2) months. ______

II. Date you were appointed as KC-135 aircraft commander ______

III. Number of hours as a KC-135 aircraft commander ______

8. Simulator Data

A. Approximately how much total simulator time do you have? ______

B. How many hours do you have in a simulator with a "motion system"? ______

C. How many hours do you have in a simulator with a visual system? ______

KC-135 ENGINE-OUT STUDY

Phase I

Name: ____________

Subject Number: __________

1. Rate the quality of the simulation during Phase I.

______1.) Excellent Simulator flew like the aircraft.

______2.) Good Simulator flying qualities closely resemble those of the aircraft.

______3.) Fair Simulator flying qualities are similar to those of the aircraft.

______4.) Poor Simulator flying qualities poorly resemble those of the aircraft.

______5.) Very Poor Simulator flying qualities do not resemble KC-135 aircraft.

Please discuss.

2. Other comments.

KC-135 ENGINE-OUT STUDY

Phase II

Name:____________________

Subject Number:_____________

1. What cues did you use to detect when an engine failure had occurred? Please discuss.

2. What cues did you use to discriminate between outboard and inboard engine failures? Please discuss.

3. Rate how sufficiently these cues enabled you to negotiate engine failures.

_____a) Very sufficient Cues consistently permitted a prompt and proper reaction.

_____b) Sufficient Cues usually permitted a prompt and proper reaction.

_____c) Occasionally Sufficient Cues occasionally permitted a prompt and proper reaction.

_____d) Insufficient Cues rarely permitted prompt and proper reaction.

_____e) Very Insufficient Cues were inadequate to permit a prompt and proper reaction.
Please discuss.

4. Rate this cueing system as a training device for outboard engine failures in actual aircraft.

_____a) Excellent

_____b) Good

_____c) Fair

_____d) Poor

_____e) Very poor

Please discuss.

KC-135 ENGINE-OUT STUDY

Phase III

Name: __________

Subject Number: __________

1. Rate the quality of the simulation during Phase III.

_____a) Excellent Simulator flew like the aircraft.

_____b) Good Simulator flying qualities closely resemble those of the aircraft.

_____c) Fair Simulator flying qualities similar to those of the aircraft.

_____d) Poor Simulator flying qualities resembles poorly those of the aircraft.

_____e) Very Poor Simulator flying qualities do not resemble KC-135 aircraft.

Please discuss.

2. What cues did you use to detect an engine failure? Please discuss.

3. What cues did you use to discriminate between outboard and inboard engine failures? Please discuss.

4. Rate how sufficiently these cues enabled you to negotiate an engine failure.

_____a) Very Sufficient Cues consistently permitted a prompt and proper reaction.

_____b) Sufficient Cues usually permitted a prompt and proper reaction.

_____c) Occasionally Sufficient Cues occasionally did permit a prompt and proper reaction.

_____d) Insufficient Cues rarely permitted prompt and proper reactions.

_____e) Very Insufficient Cues were inadequate to permit a prompt and proper reaction.

Please discuss.

5. Describe the relationship between the cueing system you used in Phase II and your performance in Phase III.

_____a) Strong Positive Relationship Experience with Phase II cueing system was excellent training for Phase III.

_____b) Positive Relationship Experience with Phase II cueing system was good training for Phase III.

_____c) Neutral Relationship Experience with Phase II cueing system was of little value in Phase III.

_____d) Negative Relationship Experience with Phase II cueing system led to some improper reactions in Phase III.

_____e) Strong Negative Relationship Experience with Phase II cueing system led to many improper reactions in Phase III.

Please discuss.

APPENDIX B

PHASE II ANALYSIS OF VARIANCE

The following tables present the results of the analysis of variance performed on the group mean performance data for Phase II of this study.

TABLE 11.–PHASE II ANALYSIS OF VARIANCE FOR OUTBOARD ENGINE FAILURES PRIOR TO LIFT-OFF

(a) Initial reaction time, t_{IR} (sec)

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	7.34	3	2.45	21.37
Within cueing systems	2.40	21	.11	
Total	9.74	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	3.04	1.28	1.40	0.84
2	2.28	.89	2.00	1.03
3	1.73	.84	1.40	1.06
4	1.80	1.06	1.56	1.19
5	2.61	.75	1.54	.95
6	2.50	1.24	1.31	1.14
7	1.98	1.43	1.68	.90
8	1.94	1.41	1.37	1.08

(b) Sum of control reversals, N_{CR}

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	654.00	3	218.00	11.74
Within cueing systems	389.99	21	18.57	
Total	1043.99	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	11.29	23.57	10.29	22.63
2	8.29	20.86	7.71	16.13
3	7.86	19.00	6.29	12.25
4	4.86	18.14	5.86	13:13
5	7.43	15.57	4.14	10.38
6	6.29	11.29	7.43	11.63
7	3.00	11.14	2.86	10.00
8	2.17	14.17	3.71	8.00

(c) Lift-off point, Y_{LO} (m)

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	82378.88	3	27459.63	20.85
Within cueing systems	27655.63	21	1316.93	
Total	110034.50	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	132.15	19.71	154.38	27.90
2	118.27	20.42	119.09	7.56
3	72.31	9.30	140.84	9.81
4	85.91	15.75	91.67	13.16
5	40.93	7.45	60.86	11.59
6	197.83	16.07	140.67	18.14
7	107.46	8.14	67.64	11.30
8	154.91	5.63	154.70	14.38

(d) Integrated roll and yaw activity, *PRI* (deg)

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	22045.69	3	7348.56	5.92
Within cueing systems	26083.06	21	1242.05	
Total	48128.75	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	150.38	251.40	92.19	88.94
2	102.90	159.76	80.19	81.13
3	107.71	143.46	83.31	77.87
4	81.49	130.73	58.42	75.97
5	126.66	114.40	64.75	72.39
6	83.71	116.95	99.10	87.46
7	69.33	90.47	59.05	59.70
8	65.33	110.11	68.90	56.93

---

[a] DF = degrees of freedom.

[b] F is significant with $\alpha = 0.005$.

TABLE 11.– CONCLUDED

(e) Maximum yaw angle, ψ_{max} (deg)

Source	Sum of squares	DF^a	Mean squares	F^c
Cueing systems	238.26	3	79.42	3.30
Within cueing systems	505.10	21	24.05	
Total	743.35	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	22.76	18.65	16.31	7.30
2	12.23	21.58	13.25	6.84
3	11.25	10.78	13.88	4.90
4	8.31	7.75	8.48	5.89
5	17.19	7.61	7.95	6.99
6	14.92	8.76	17.96	6.97
7	9.88	7.35	7.36	5.37
8	11.14	6.67	9.64	4.99

[a] DF = degrees of freedom.

[c] F is significant with $\alpha = 0.050$.

TABLE 12.–PHASE II ANALYSIS OF VARIANCE FOR OUTBOARD ENGINE FAILURES AFTER LIFT-OFF

(a) Initial reaction time, t_{IR} (sec)

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	2.42	3	0.81	10.19
Within cueing systems	1.66	21	.08	
Total	4.08	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	2.32	2.27	2.20	1.61
2	2.37	1.73	1.73	1.28
3	2.00	1.58	1.62	1.34
4	2.22	1.80	1.82	1.58
5	1.80	1.89	1.99	1.29
6	2.60	1.67	1.78	1.12
7	2.45	1.81	1.69	1.43
8	1.59	1.64	2.11	1.53

(b) Sum of control reversals, N_{CR}

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	173.50	3	57.83	13.96
Within cueing systems	87.03	21	4.14	
Total	260.53	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	7.43	13.57	5.71	11.00
2	7.57	11.29	5.57	10.63
3	4.57	13.57	5.71	9.25
4	5.00	9.43	5.14	10.75
5	7.57	14.00	7.14	6.50
6	5.29	9.00	5.00	8.00
7	6.86	9.33	3.00	9.14
8	4.83	7.40	3.60	7.83

(c) Lift-off point, Y_{LO} (m)

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	8935.39	3	2978.46	25.46
Within cueing systems	2457.12	21	117.01	
Total	11392.51	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	36.62	3.55	31.74	3.61
2	35.77	3.40	38.20	4.14
3	68.99	4.17	20.86	3.80
4	28.37	3.04	18.21	3.76
5	49.10	4.31	43.20	3.41
6	44.58	3.55	42.67	1.95
7	48.15	2.52	30.44	1.86
8	18.96	2.39	15.28	2.32

(d) Integrated roll and yaw activity, *PRI* (deg)

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	75556.38	3	25185.46	19.65
Within cueing systems	26918.63	21	1281.84	
Total	102475.01	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	235.46	161.74	109.20	131.71
2	293.50	135.20	105.26	75.84
3	171.56	249.86	121.76	85.40
4	236.53	158.56	128.33	116.29
5	202.96	217.67	136.85	81.54
6	205.37	169.40	122.74	100.38
7	248.04	154.92	119.74	105.35
8	188.63	119.07	104.98	83.52

[a] *DF* = degrees of freedom.
[b] *F* is significant with $\alpha = 0.005$.

TABLE 12.– CONCLUDED

(e) Maximum yaw angle, ψ_{max} (deg)

Source	Sum of squares	DF^a	Mean squares	F^b
Cueing systems	469.57	3	156.52	8.22
Within cueing systems	399.75	21	19.04	
Total	869.32	24		

Group mean performance vs trials cueing systems

Trials	*CSI*	*CSV*	*CSM*	*CSMV*
1	16.54	11.67	17.96	12.49
2	27.41	10.74	17.39	9.53
3	15.14	20.07	14.42	8.87
4	16.41	8.27	23.24	14.19
5	19.31	12.47	18.95	6.76
6	18.03	10.89	17.42	9.12
7	28.45	18.14	18.49	10.91
8	17.48	9.06	14.77	10.75

[a] *DF* = degrees of freedom.
[b] *F* is significant with $\alpha = 0.005$.

REFERENCE

1. McFarland, Richard E.: A Standard Kinematic Model for Flight Simulation at NASA-Ames. NASA CR-2497, January 1975.

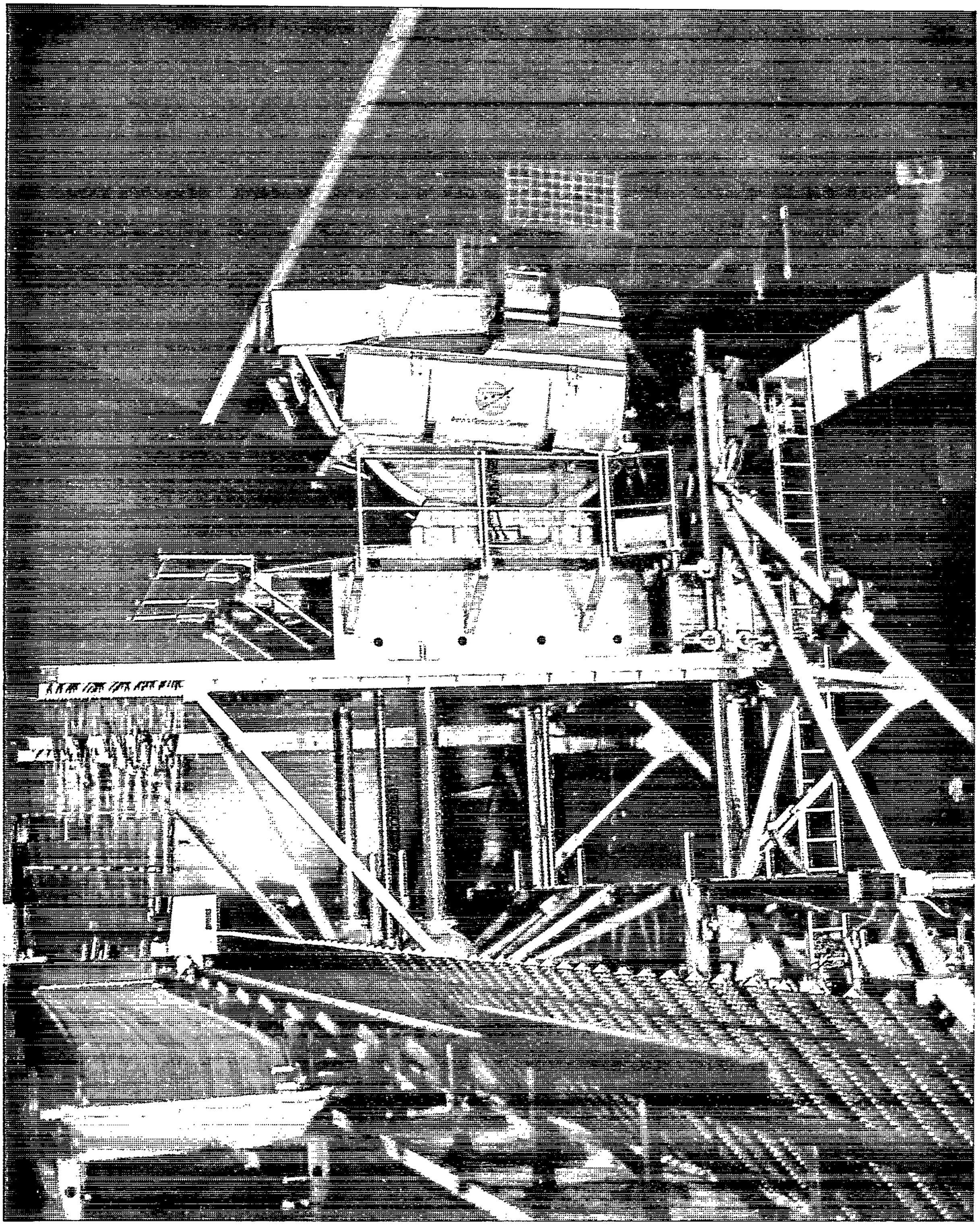

Figure 1.— The six-degree-of-freedom Flight Simulator for Advanced Aircraft (FSAA) at Ames Research Center.

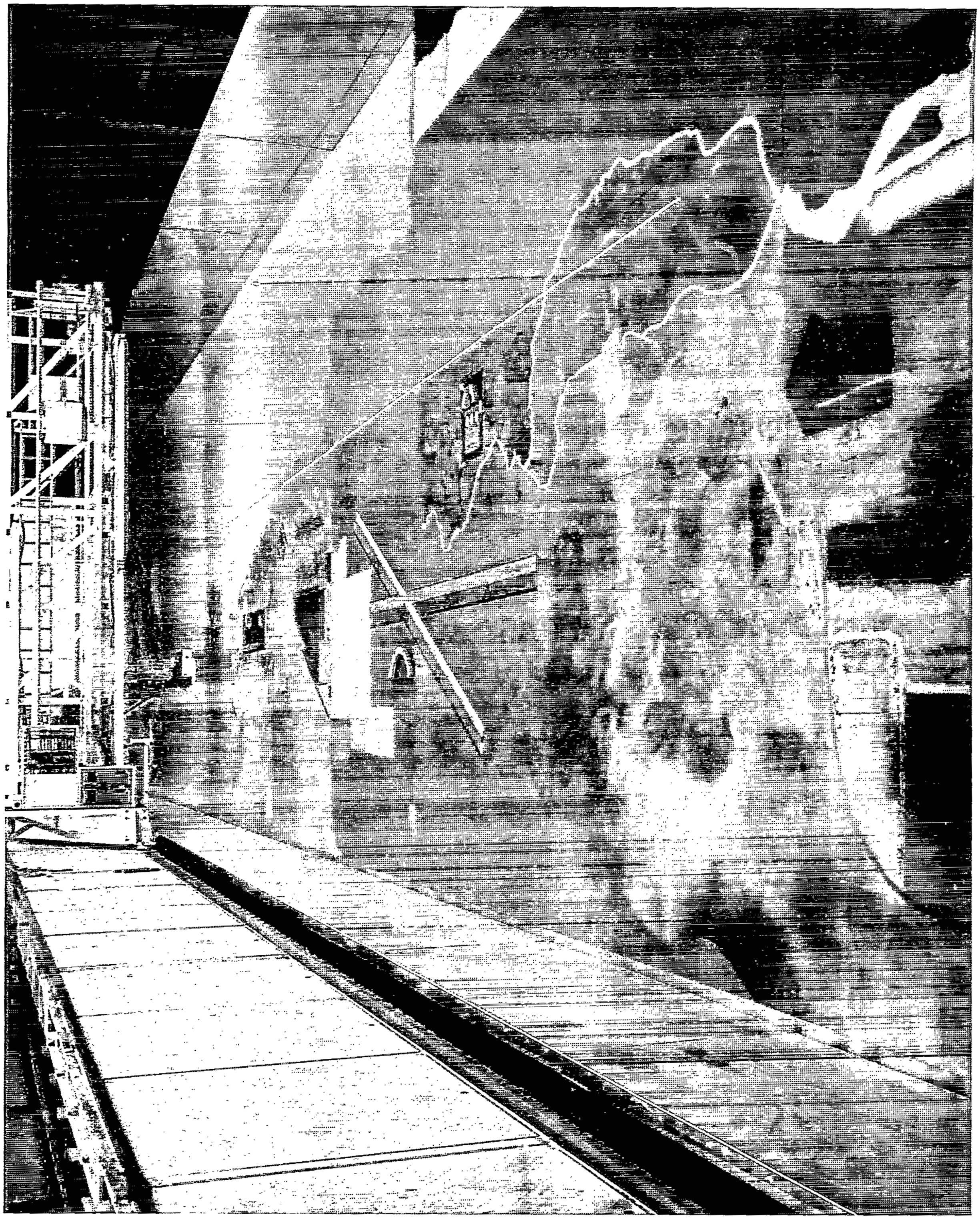

Figure 2.– The six-degree-of-freedom Visual Flight Attachment – 07 (VFA-07) at Ames Research Center.

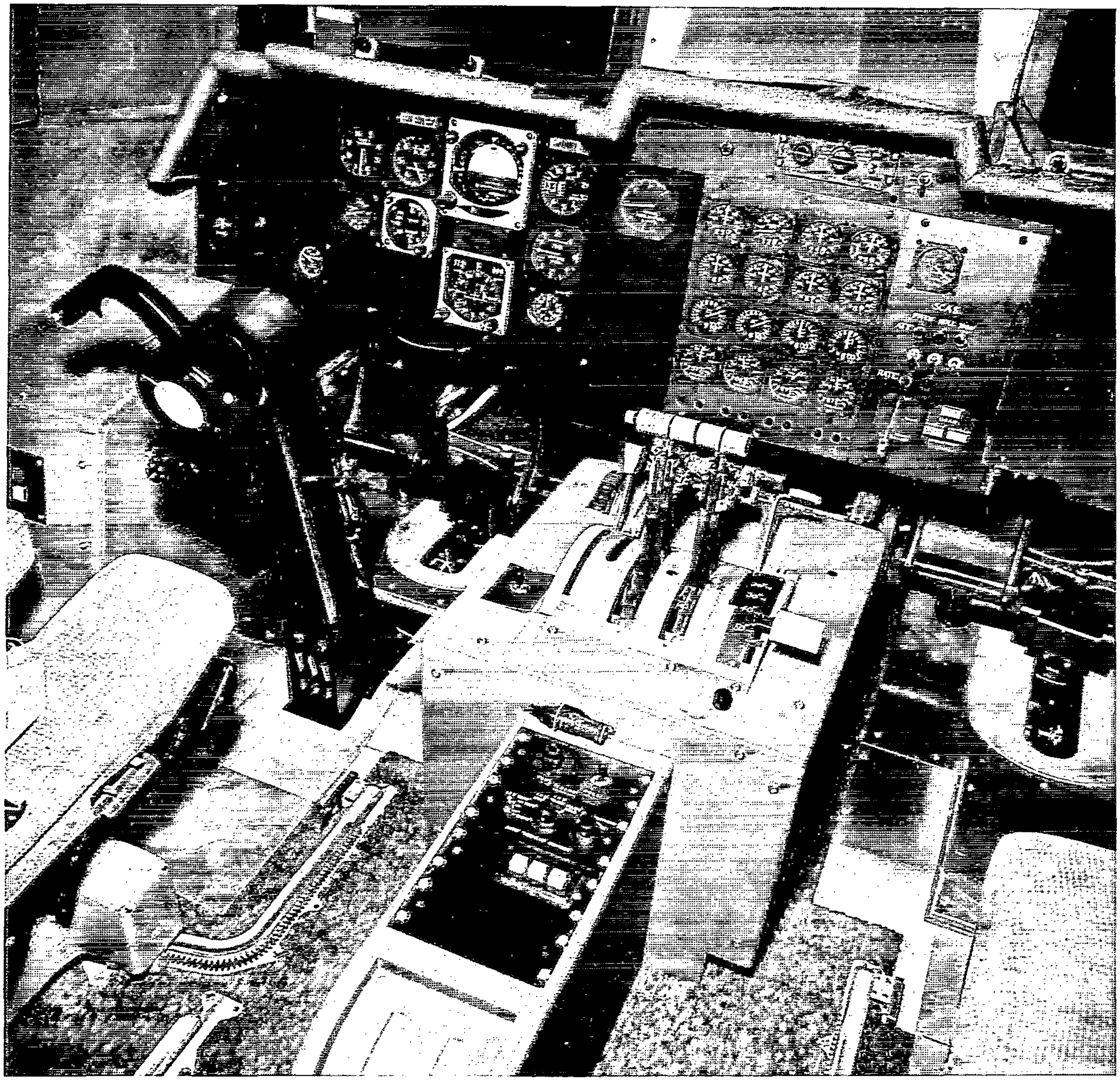

Figure 3.– The FSAA cab layout for the KC-135A simulation.

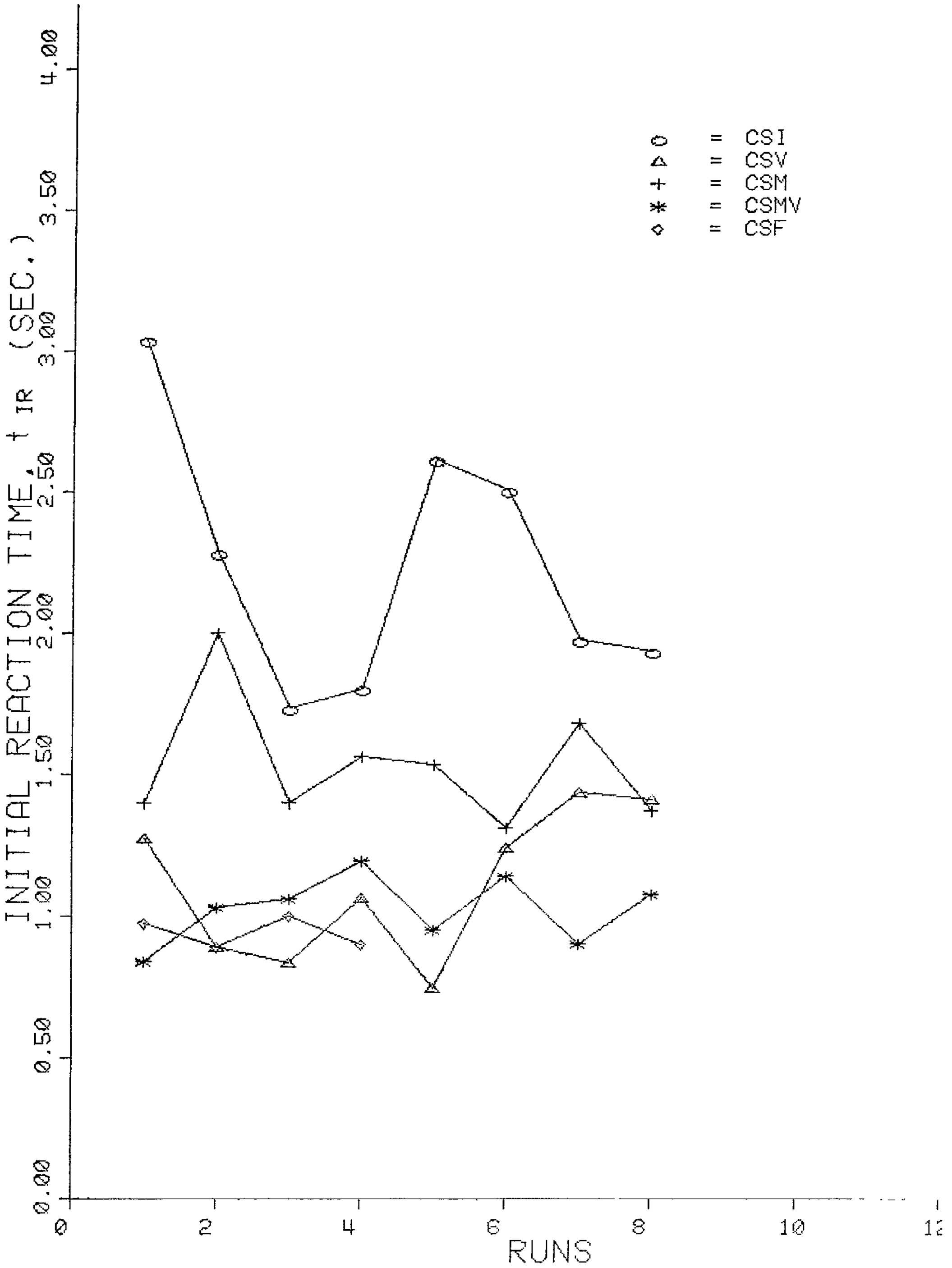

Figure 4.– Initial reaction time average Phase II learning for outboard engine failures prior to lift-off.

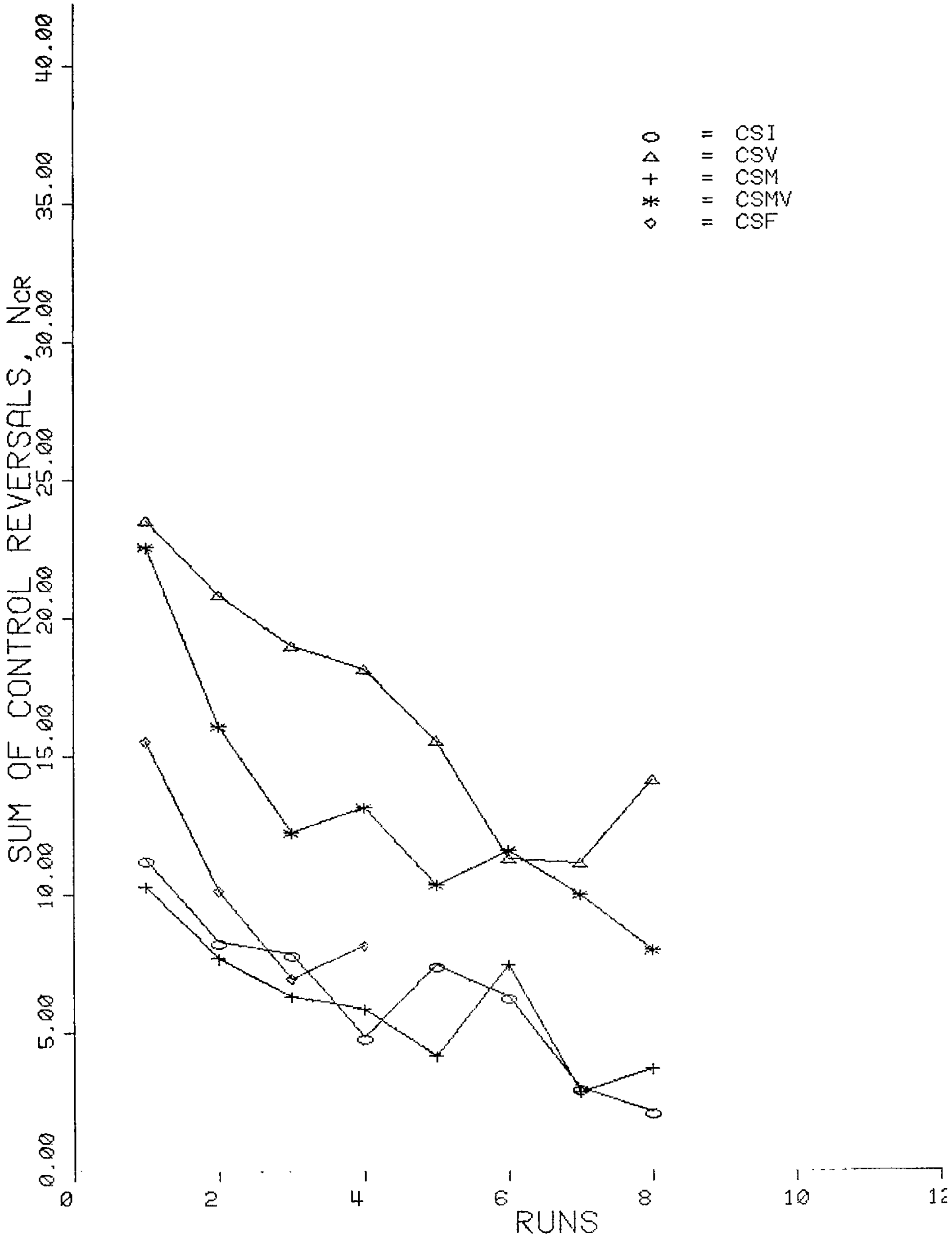

Figure 5.– Control reversal average Phase II learning for outboard engine failures prior to lift-off.

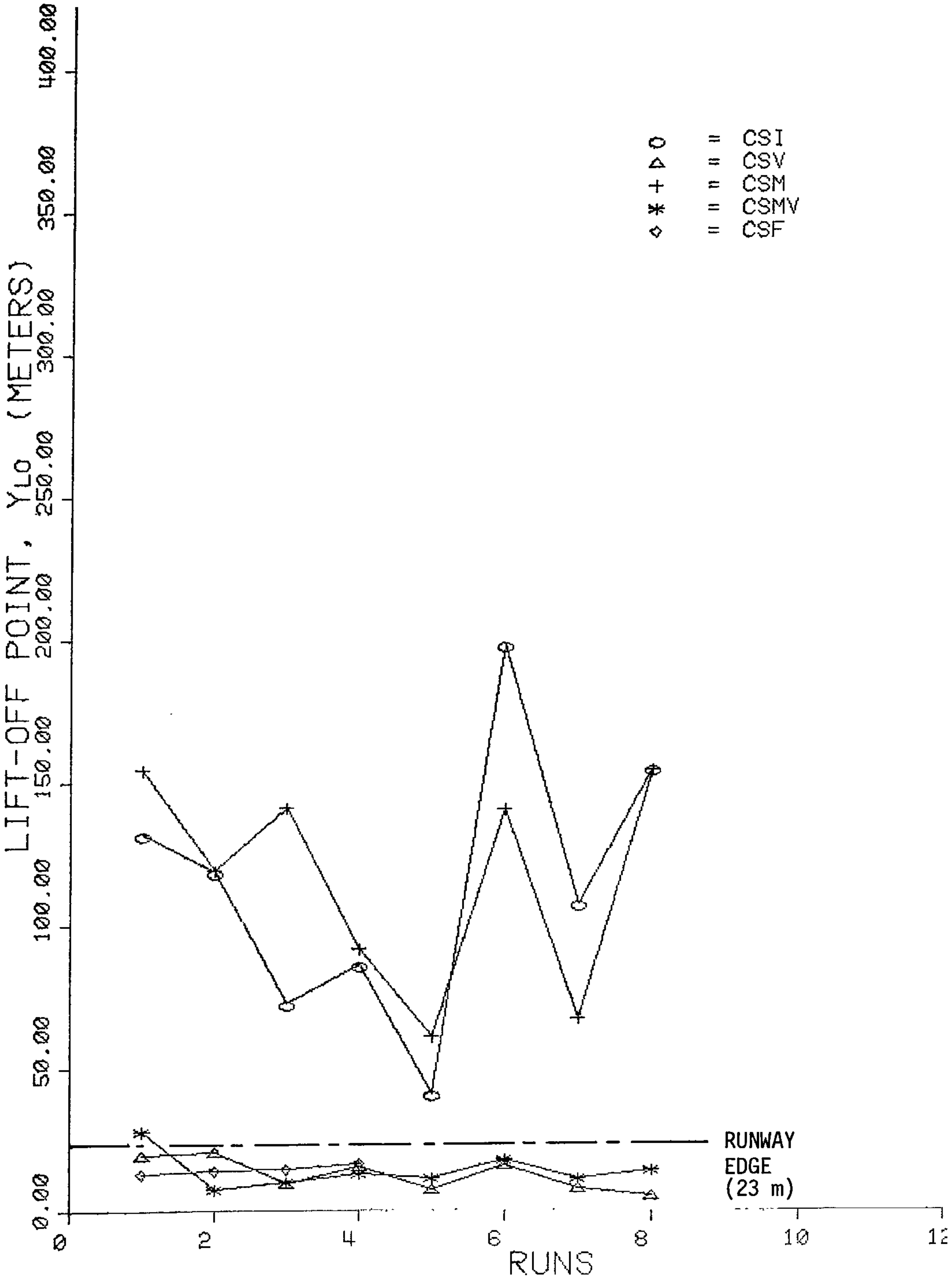

Figure 6.– Lift-off point average Phase II learning for outboard engine failures prior to lift-off.

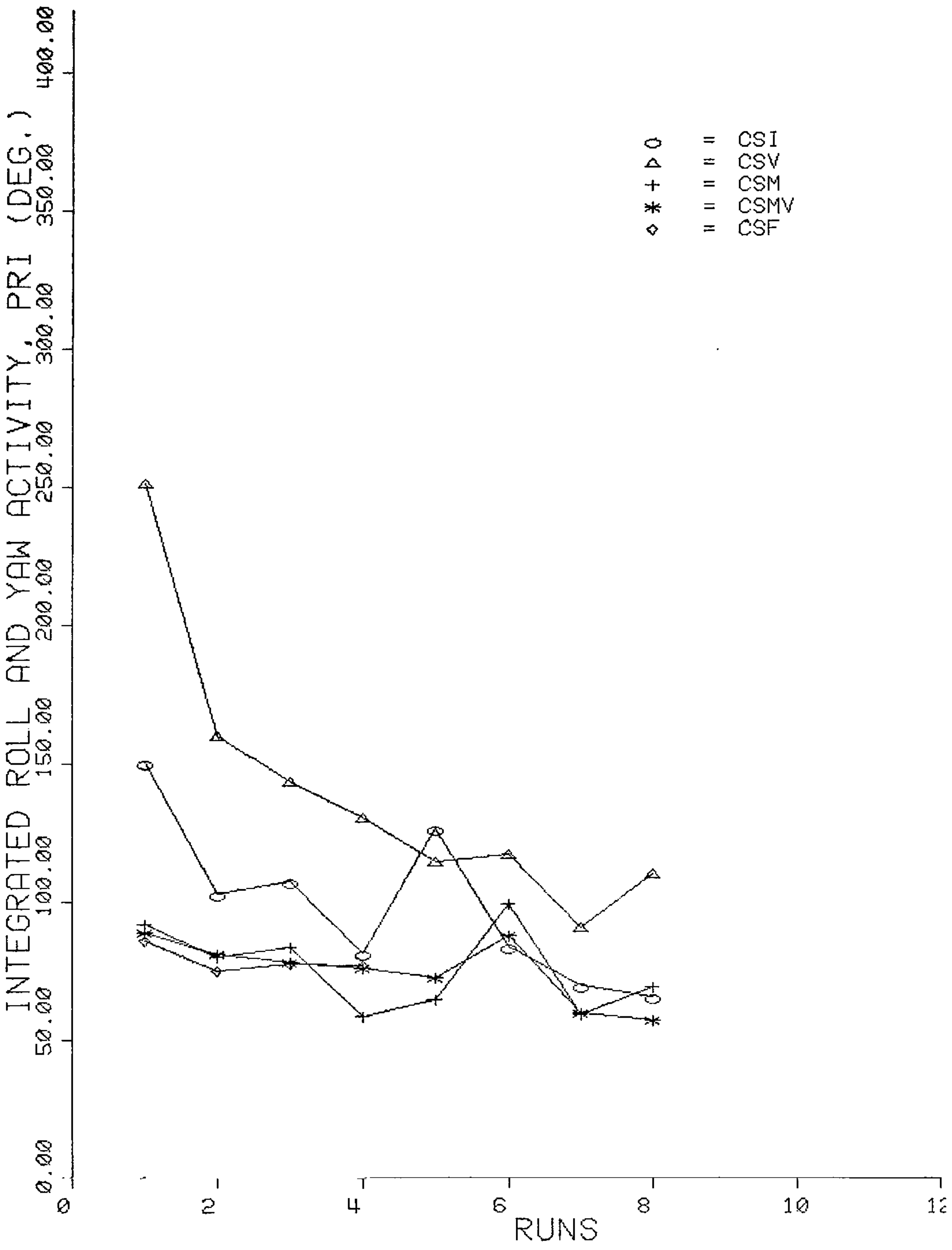

Figure 7.– Integrated roll and yaw activity average Phase II learning for outboard engine failures prior to lift-off.

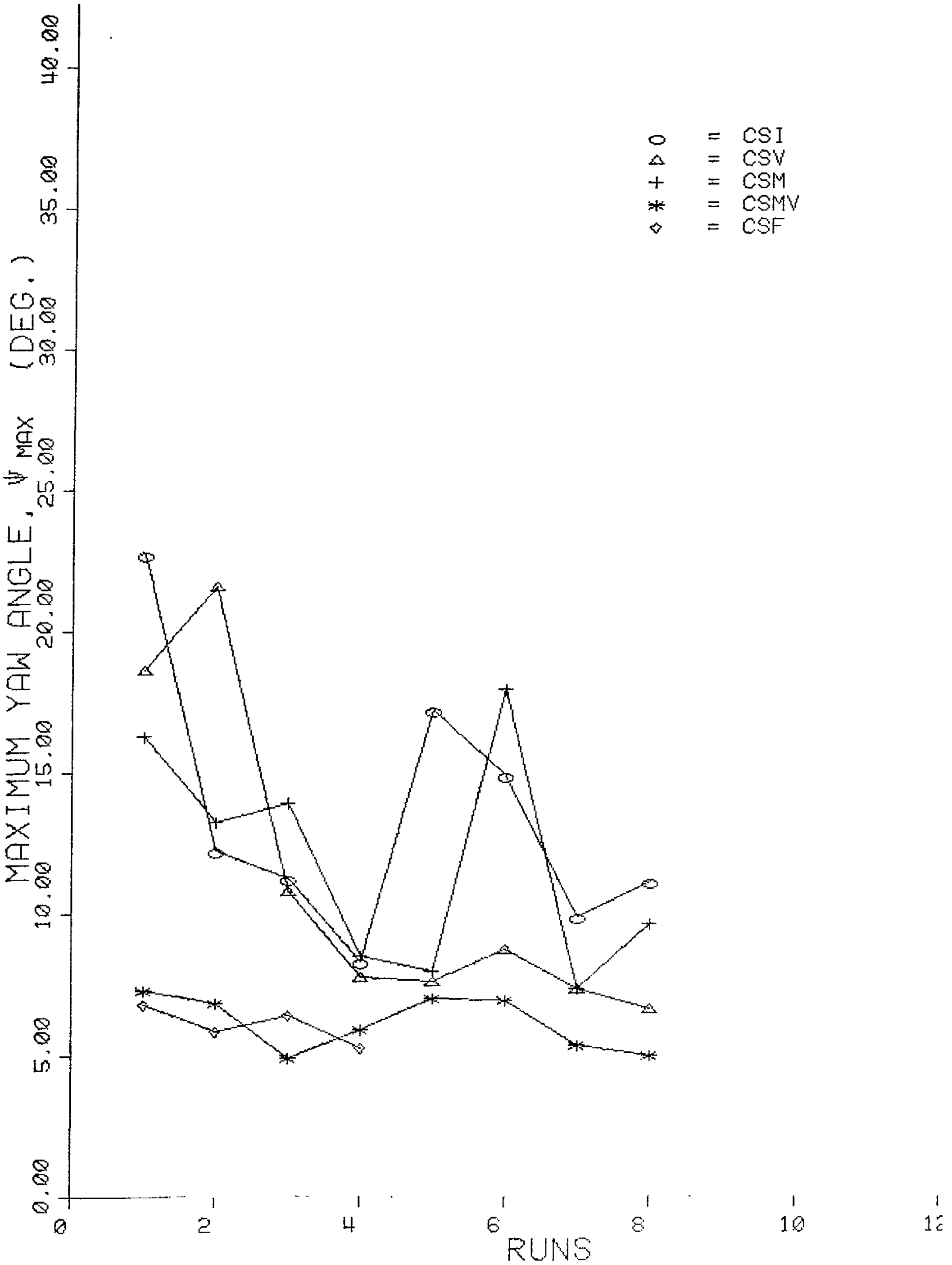

Figure 8.– Maximum yaw angle average Phase II learning for outboard engine failures prior to lift-off.

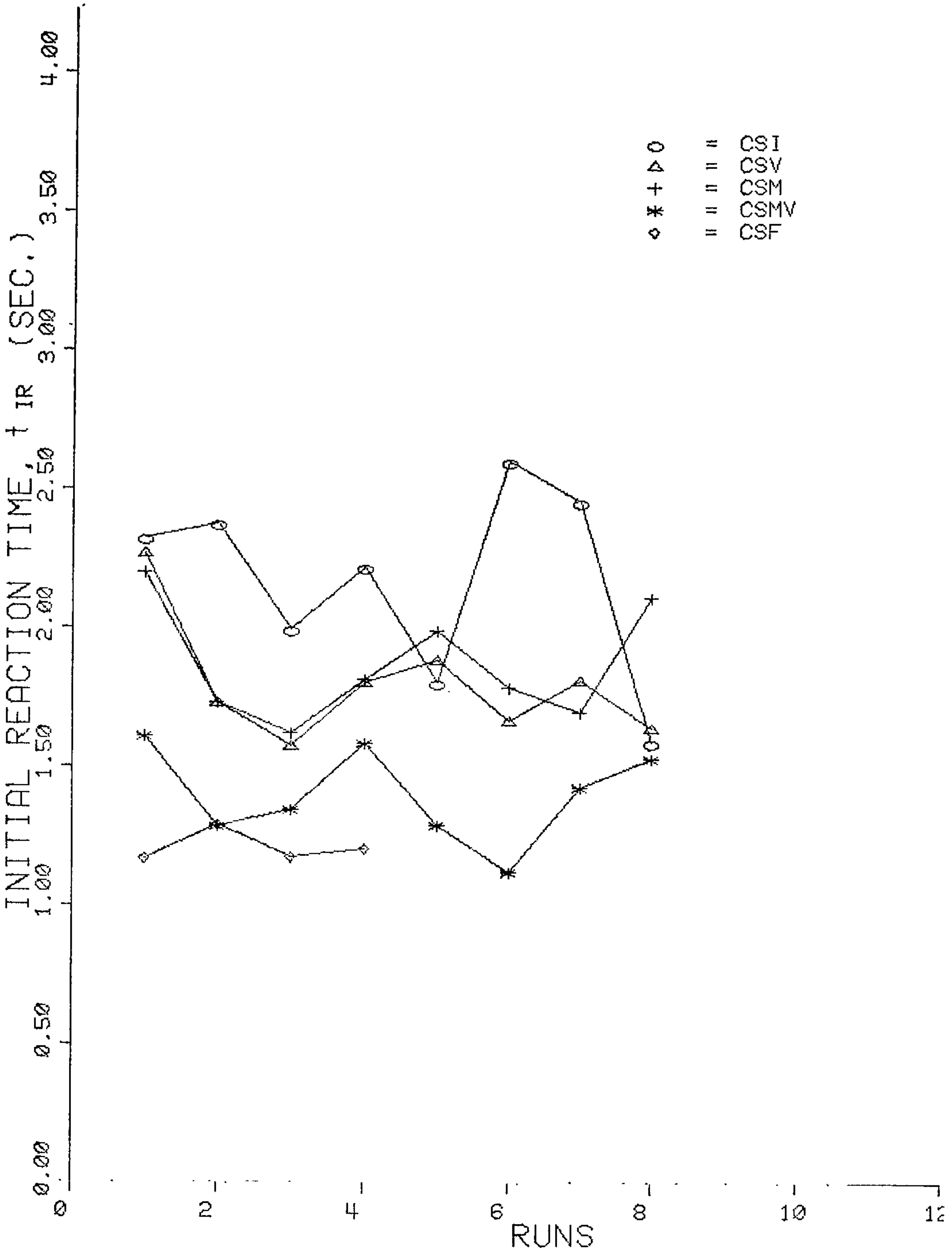

Figure 9.– Initial reaction time average Phase II learning for outboard engine failures after lift-off.

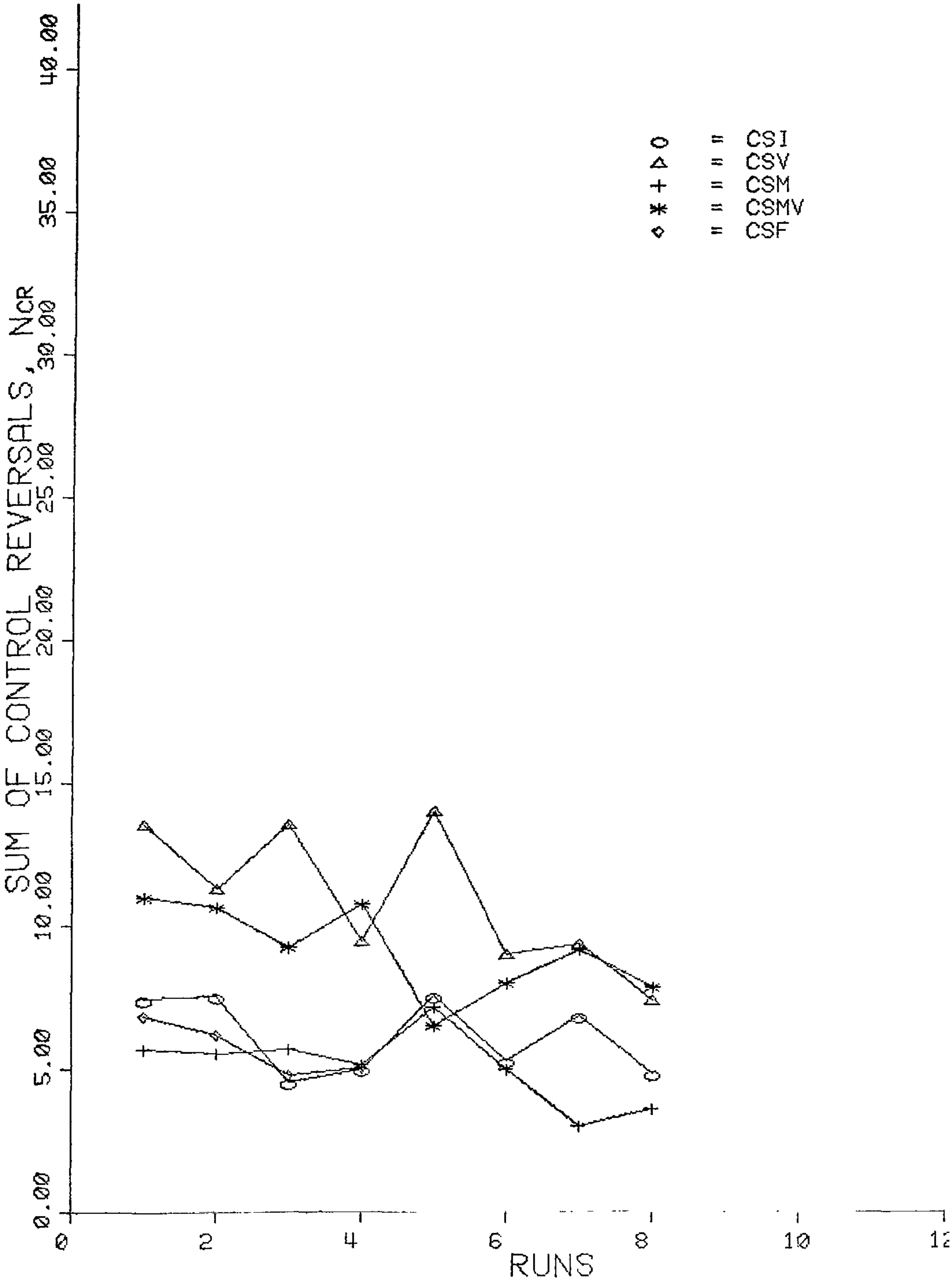

Figure 10.— Control reversal average Phase II learning for outboard engine failures after lift-off.

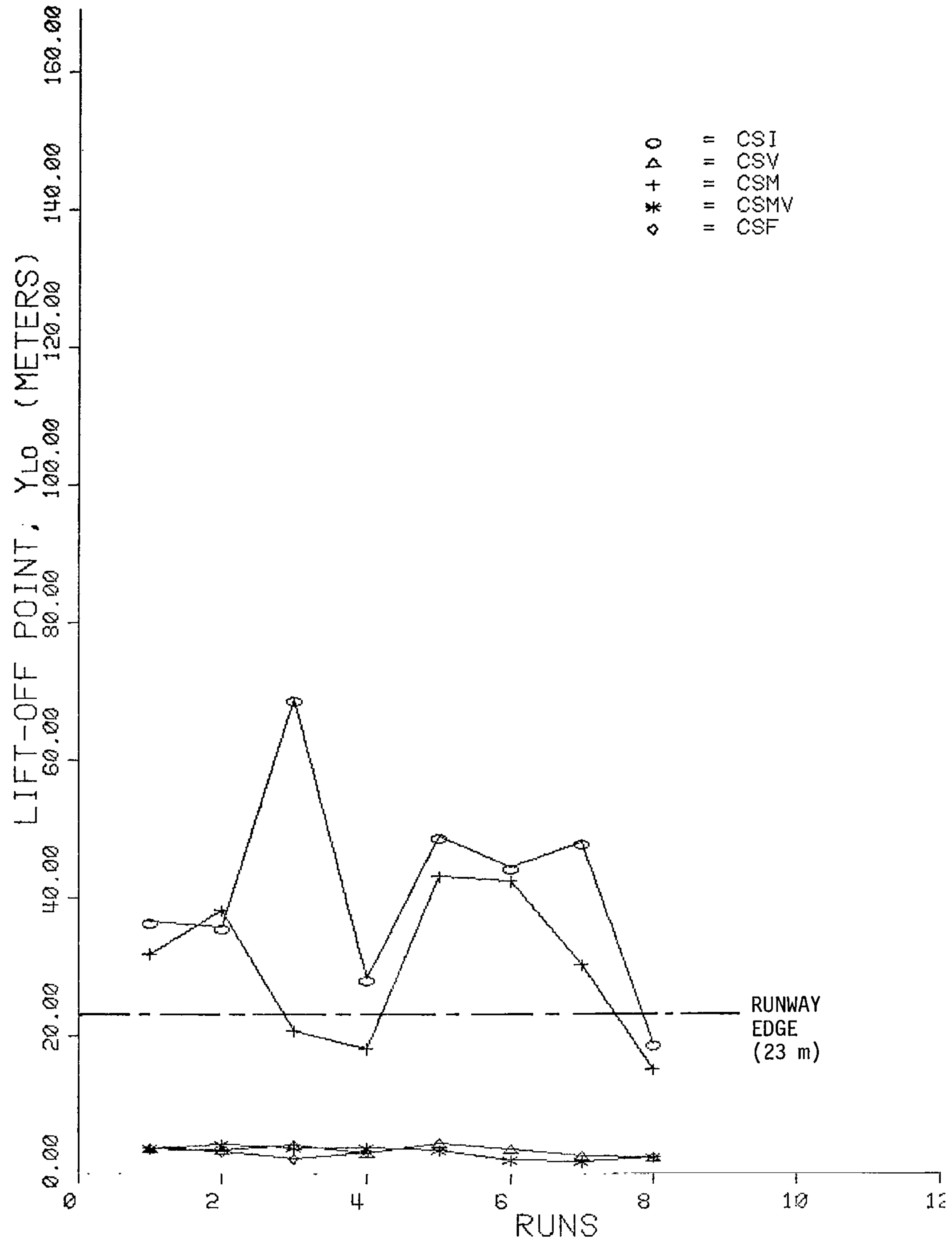

Figure 11.– Lift-off point average Phase II learning for outboard engine failures after lift-off.

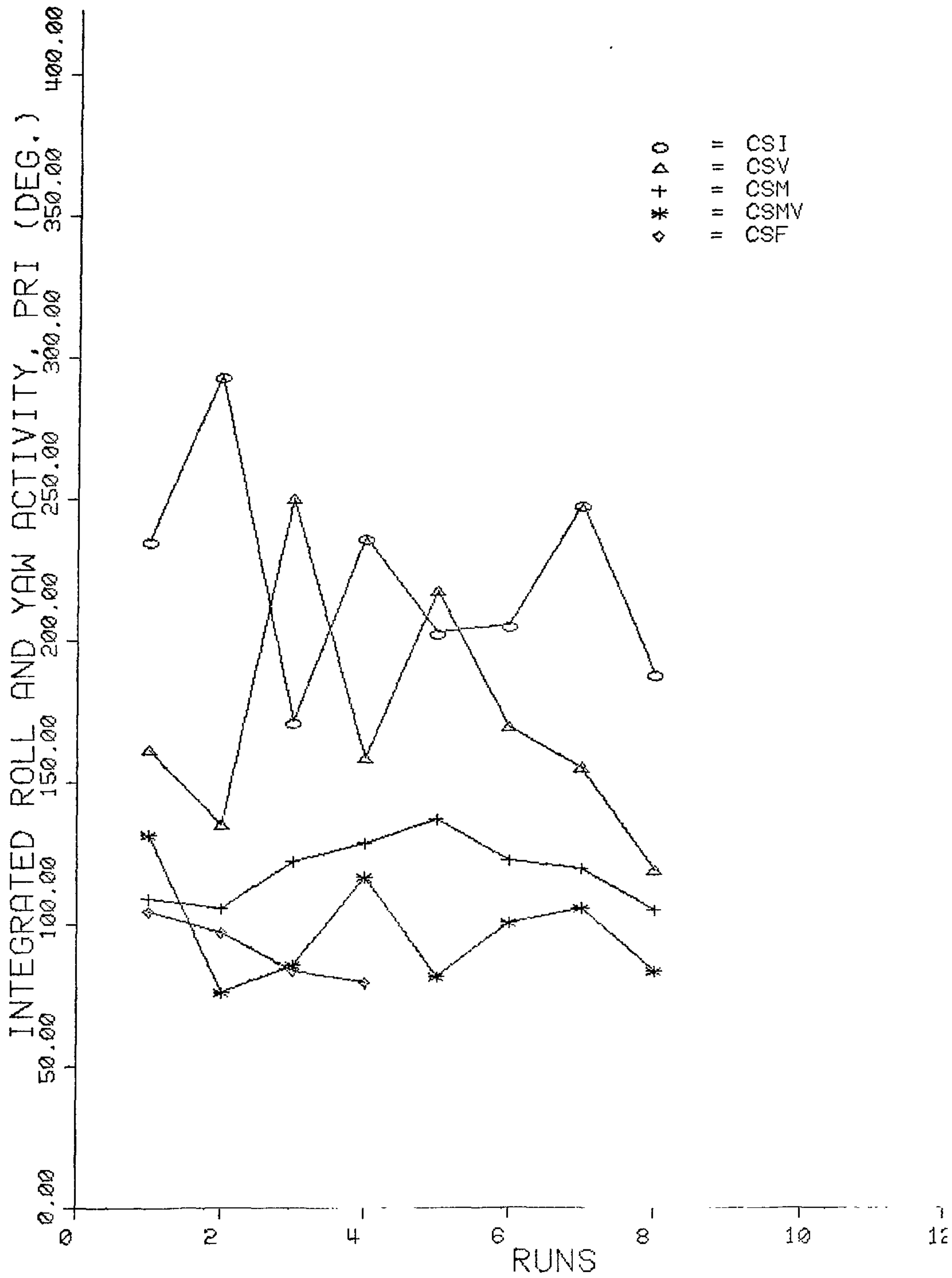

Figure 12.– Integrated roll and yaw activity average Phase II learning for outboard engine failures after lift-off.

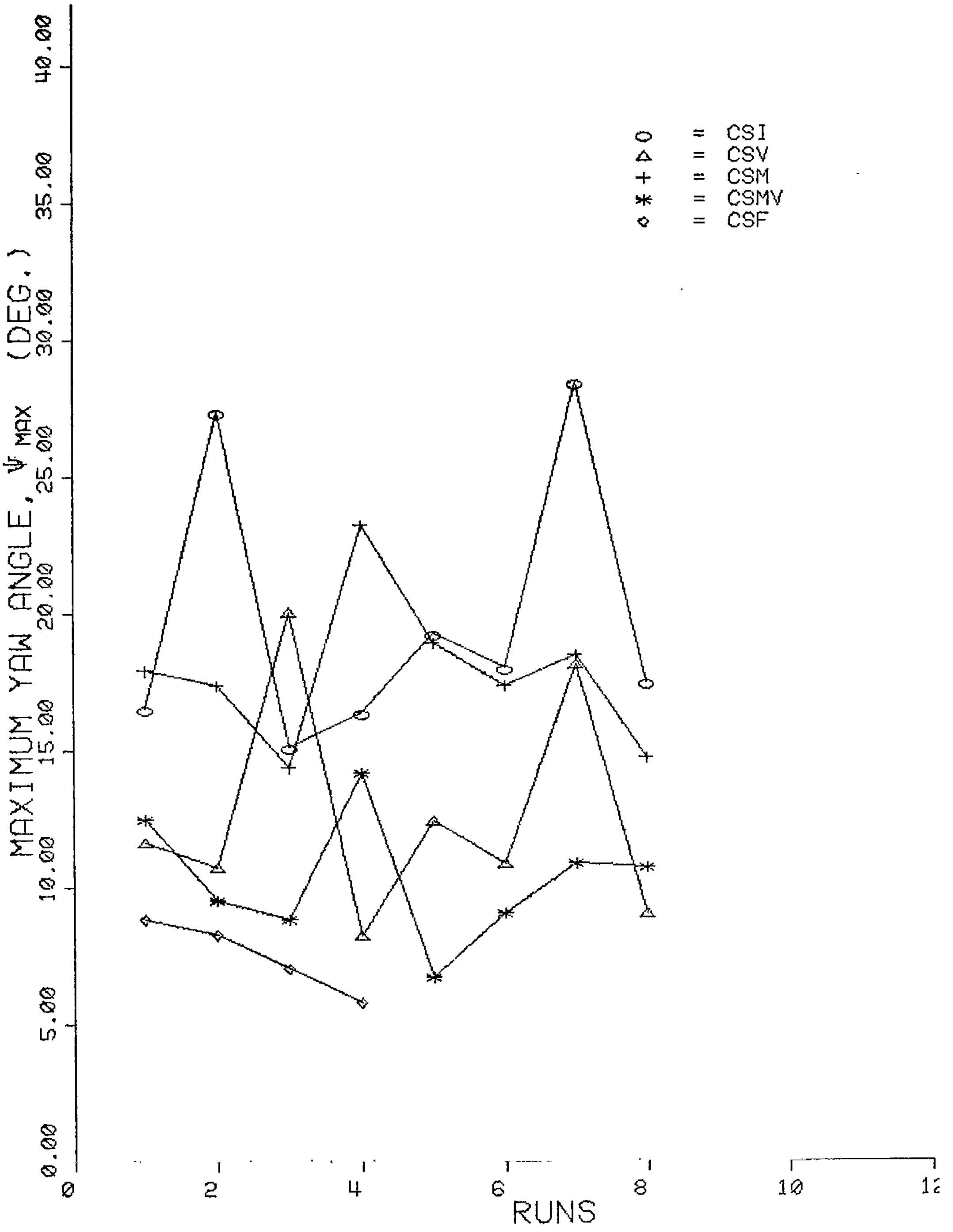

Figure 13.– Maximum yaw angle average Phase II learning for outboard engine failures after lift-off.

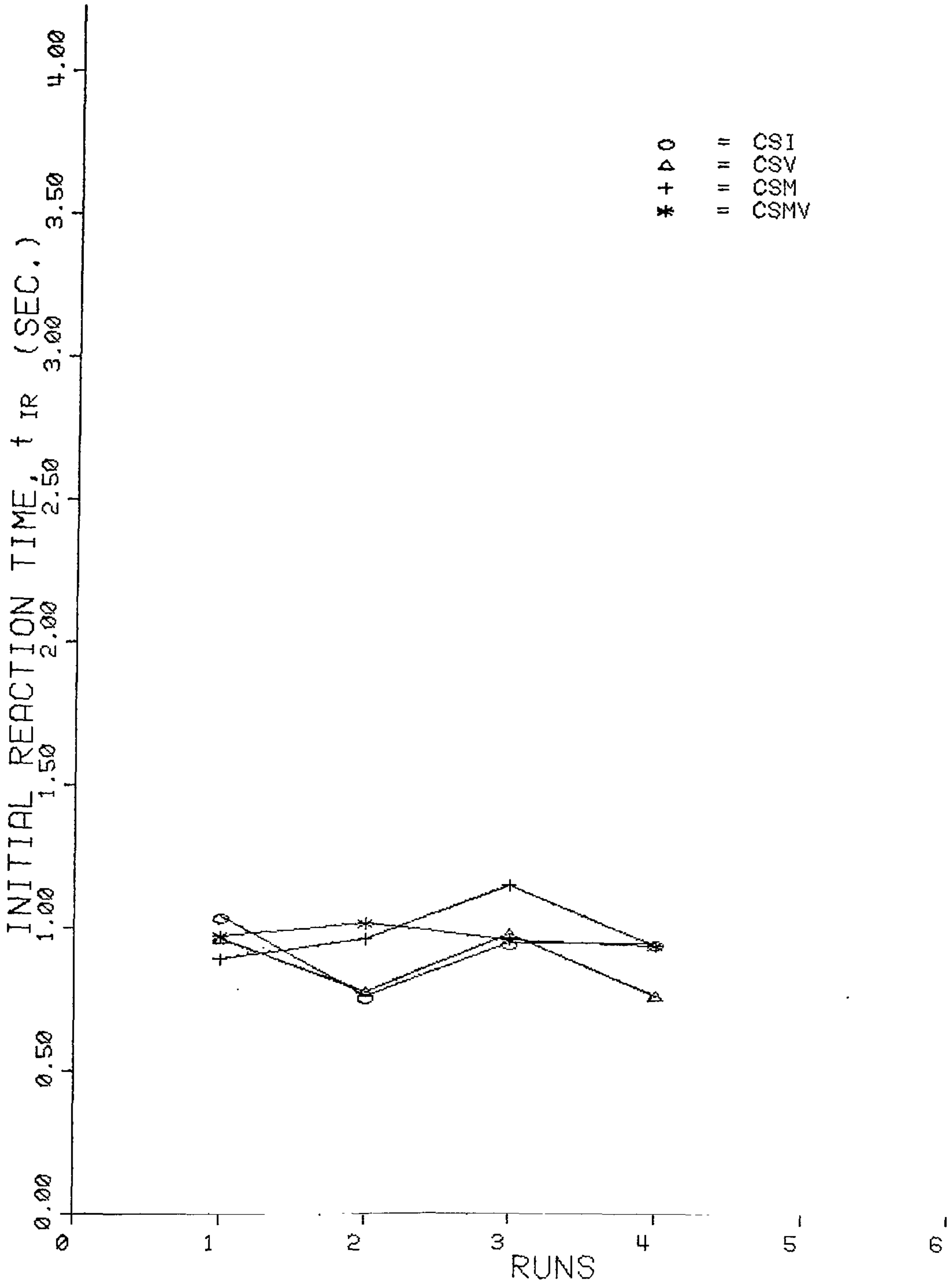

Figure 14.– Initial reaction time average Phase III learning for outboard engine failures prior to lift-off.

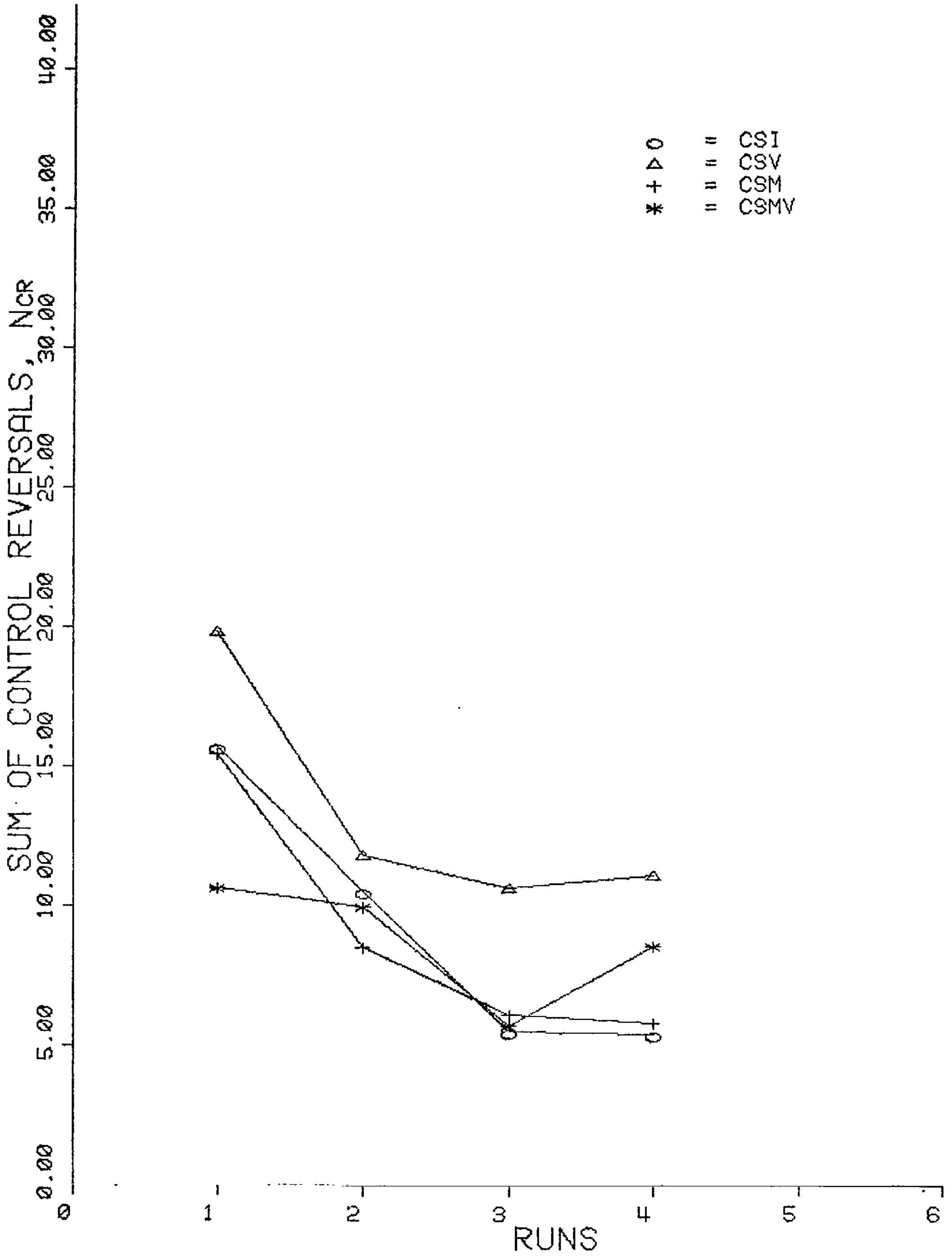

Figure 15.– Control reversal average Phase III learning for outboard engine failures prior to lift-off.

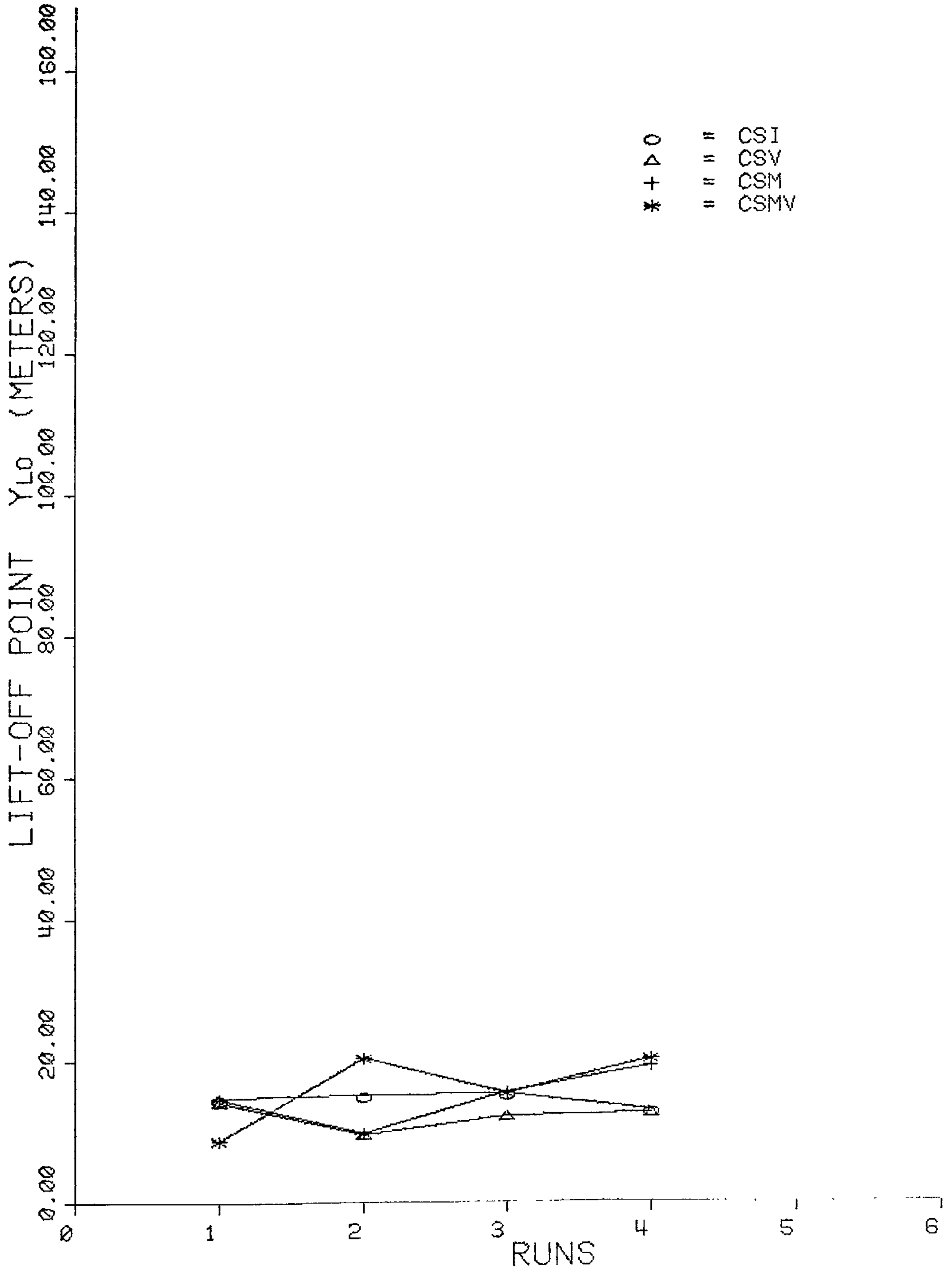

Figure 16.– Lift-off point average Phase III learning for outboard engine failures prior to lift-off.

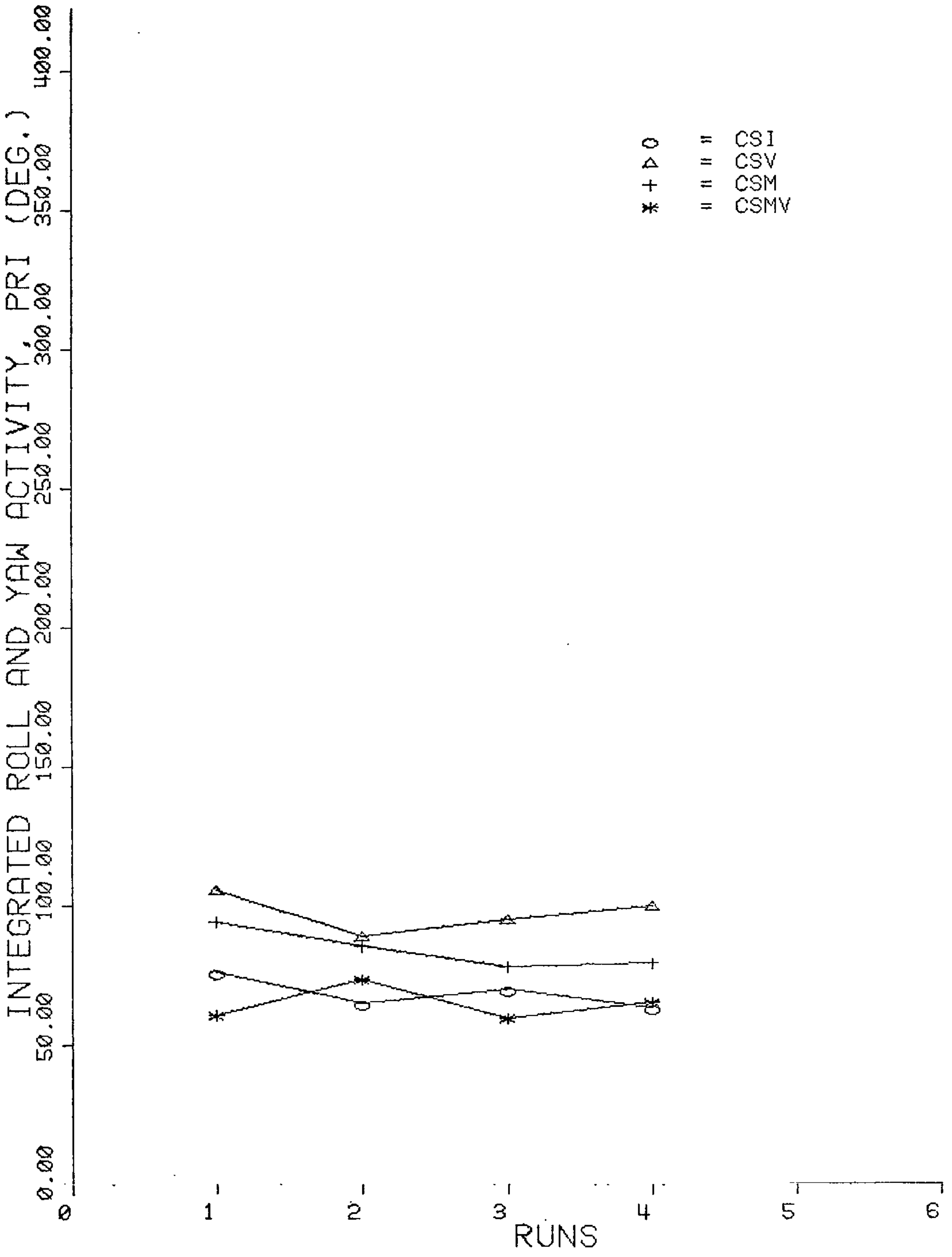

Figure 17.– Integrated roll and yaw activity average Phase III learning for outboard engine failures prior to lift-off.

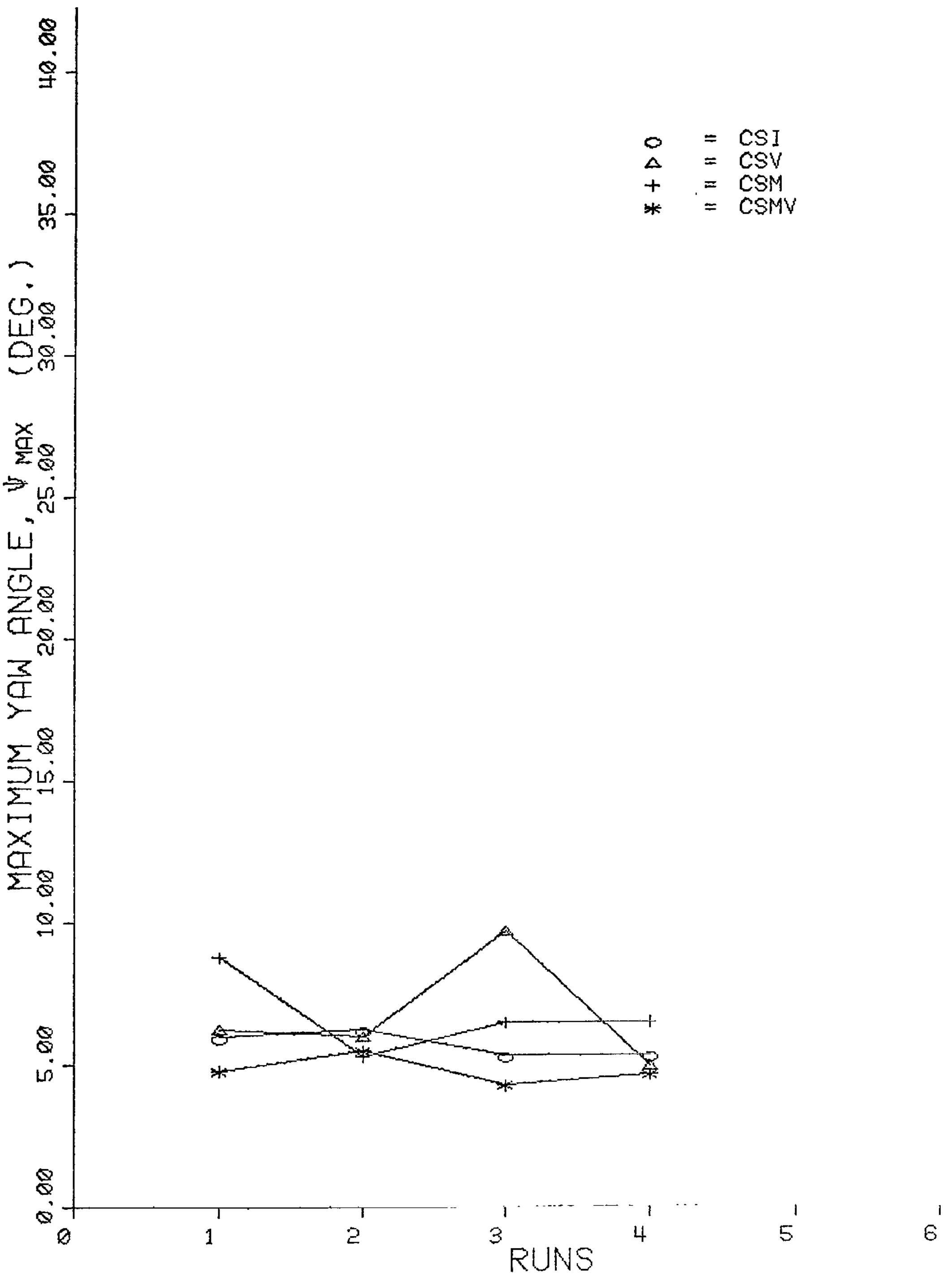

Figure 18.– Maximum yaw angle average Phase III learning for outboard engine failures prior to lift-off.

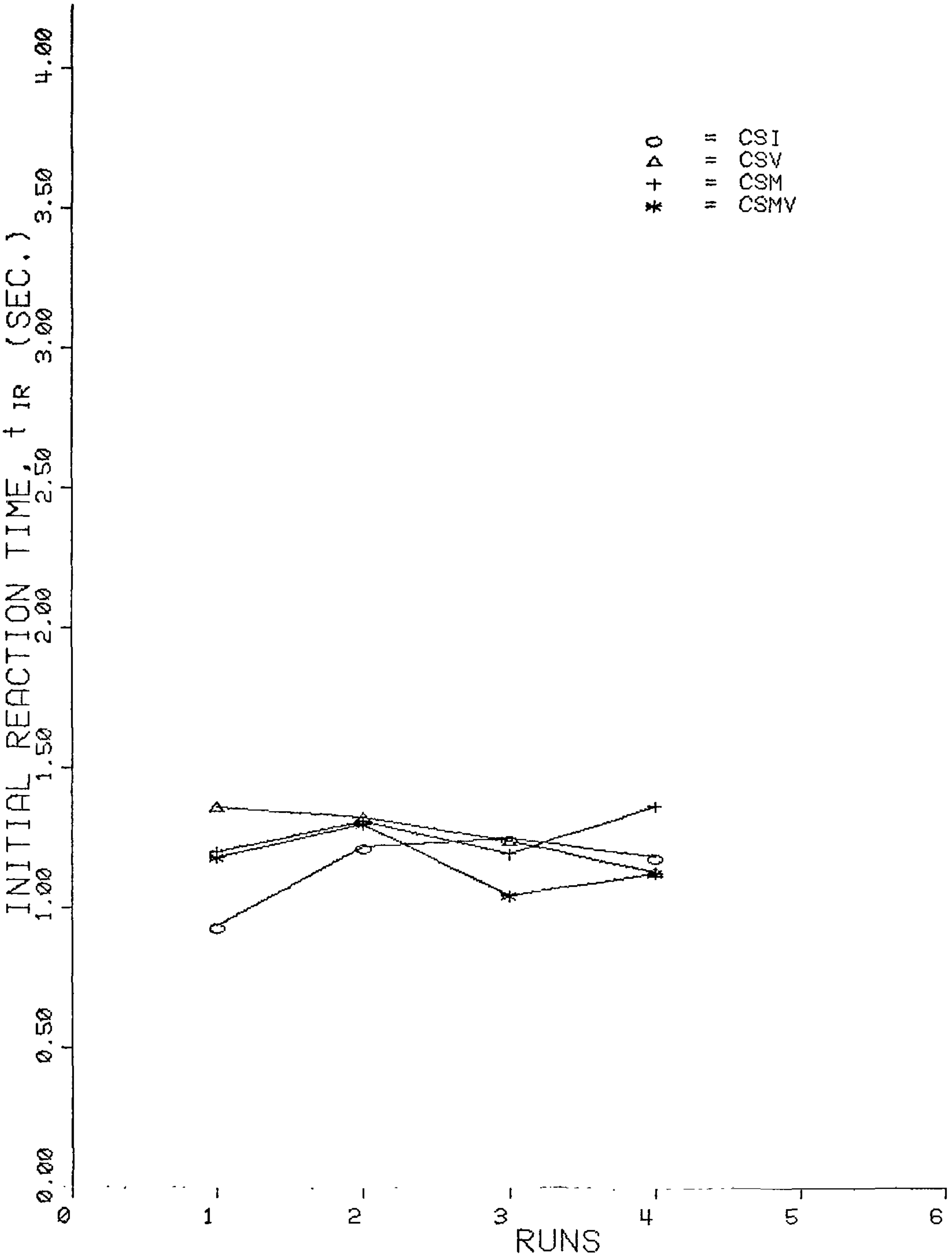

Figure 19.– Initial reaction time average Phase III learning for outboard engine failures after lift-off.

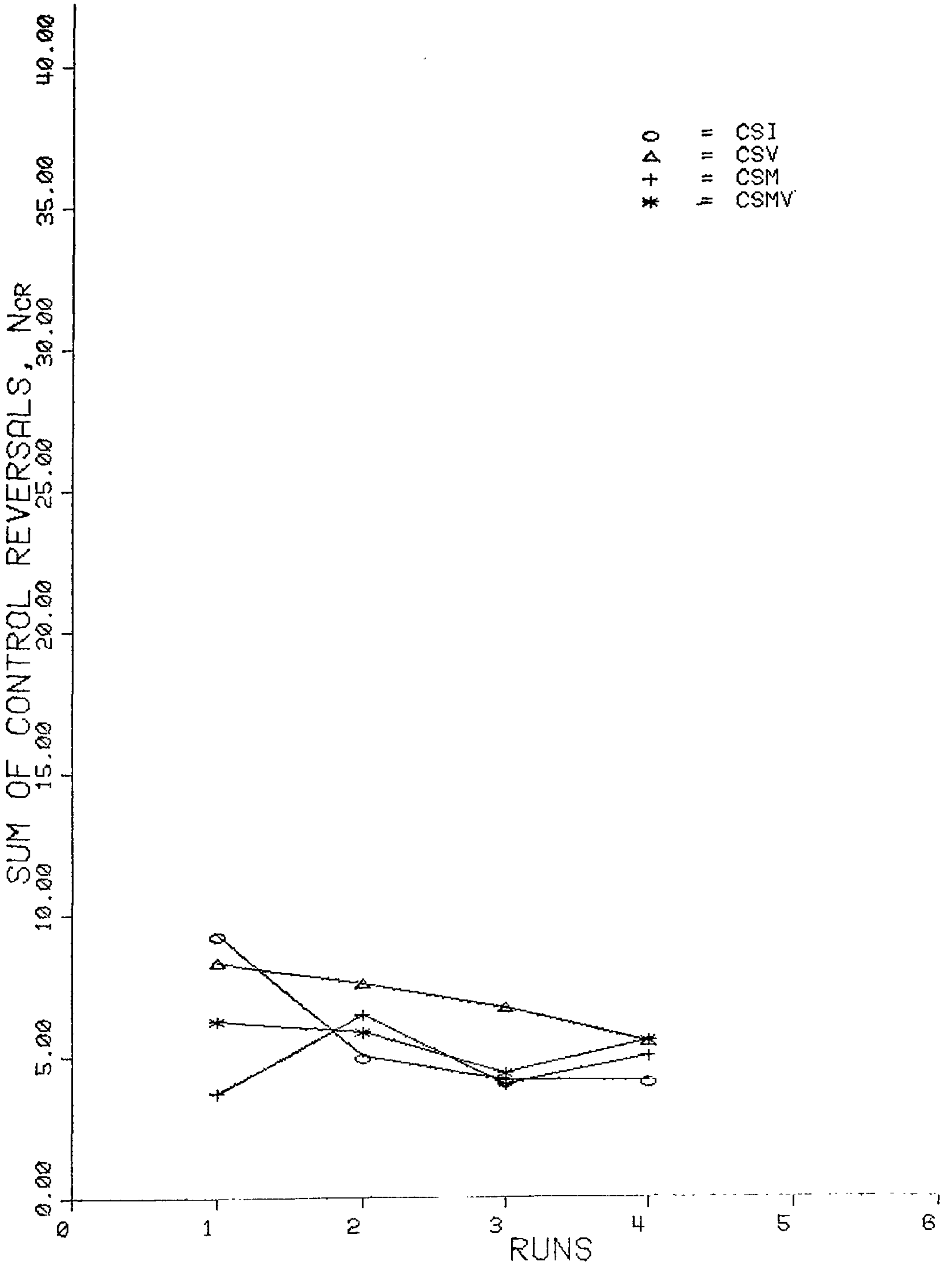

Figure 20.– Control reversal average Phase III learning for outboard engine failures after lift-off.

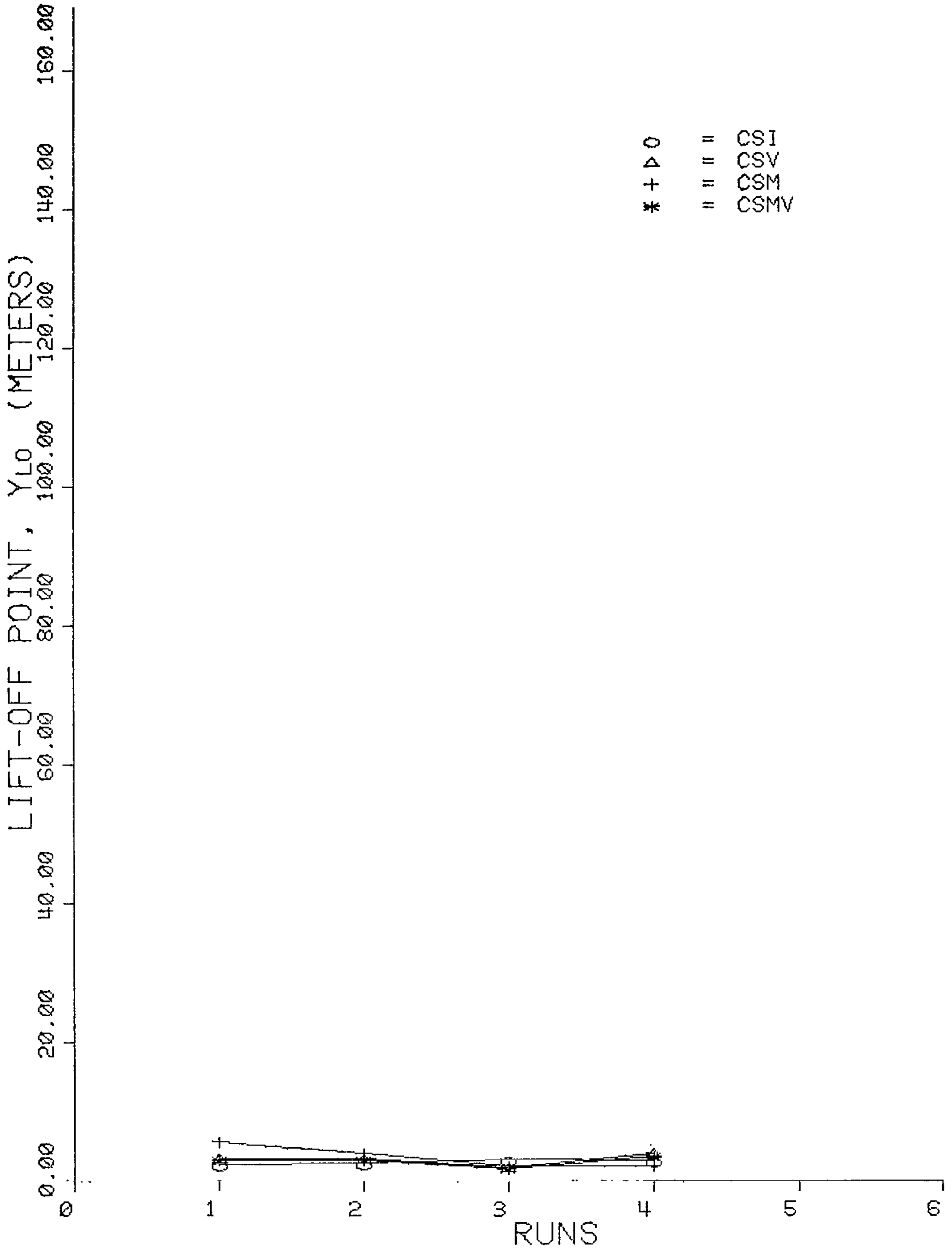

Figure 21.— Lift-point average Phase III learning for outboard engine failures after lift-off.

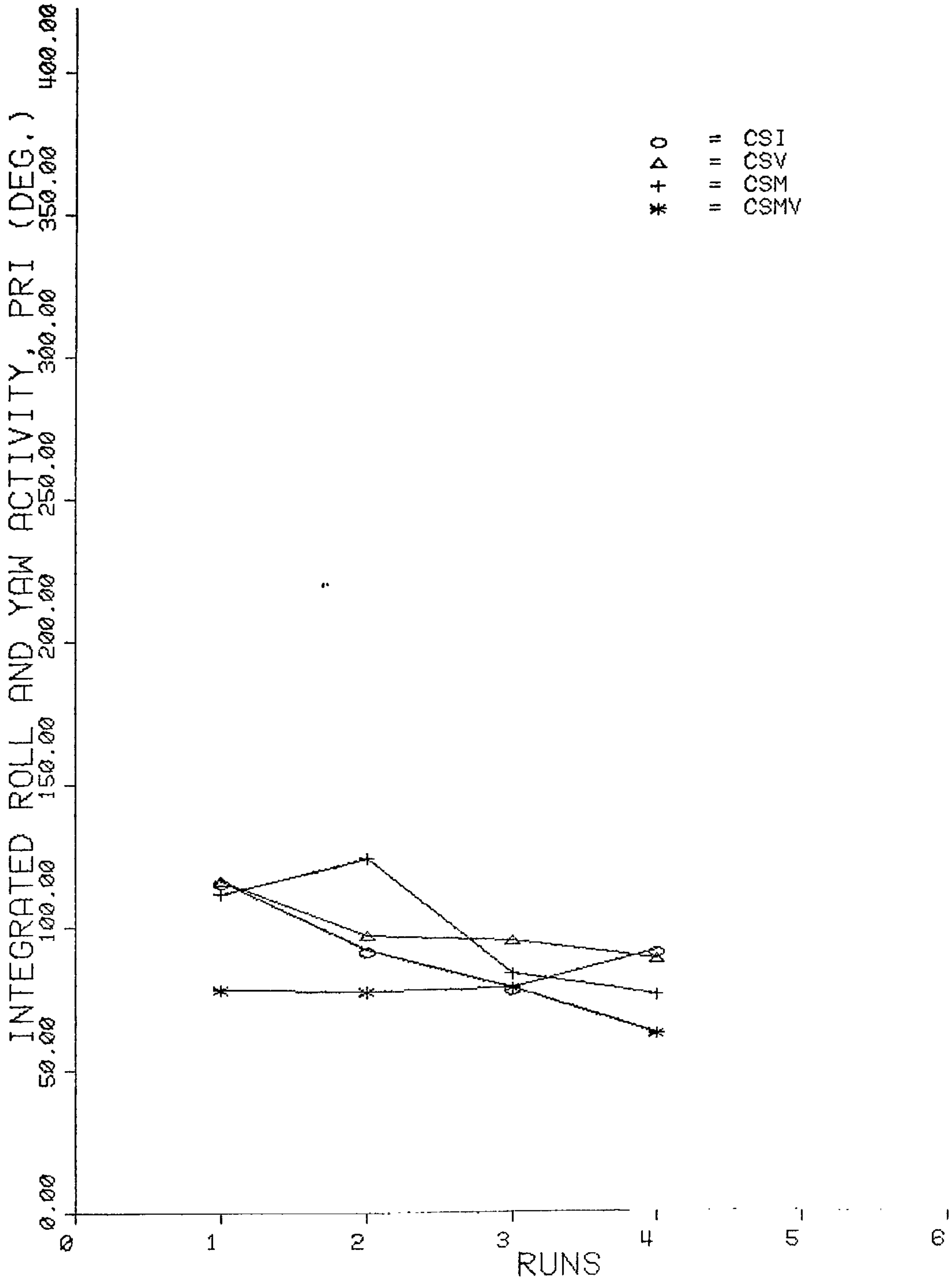

Figure 22.– Integrated roll and yaw activity average Phase III learning for outboard engine failures after lift-off.

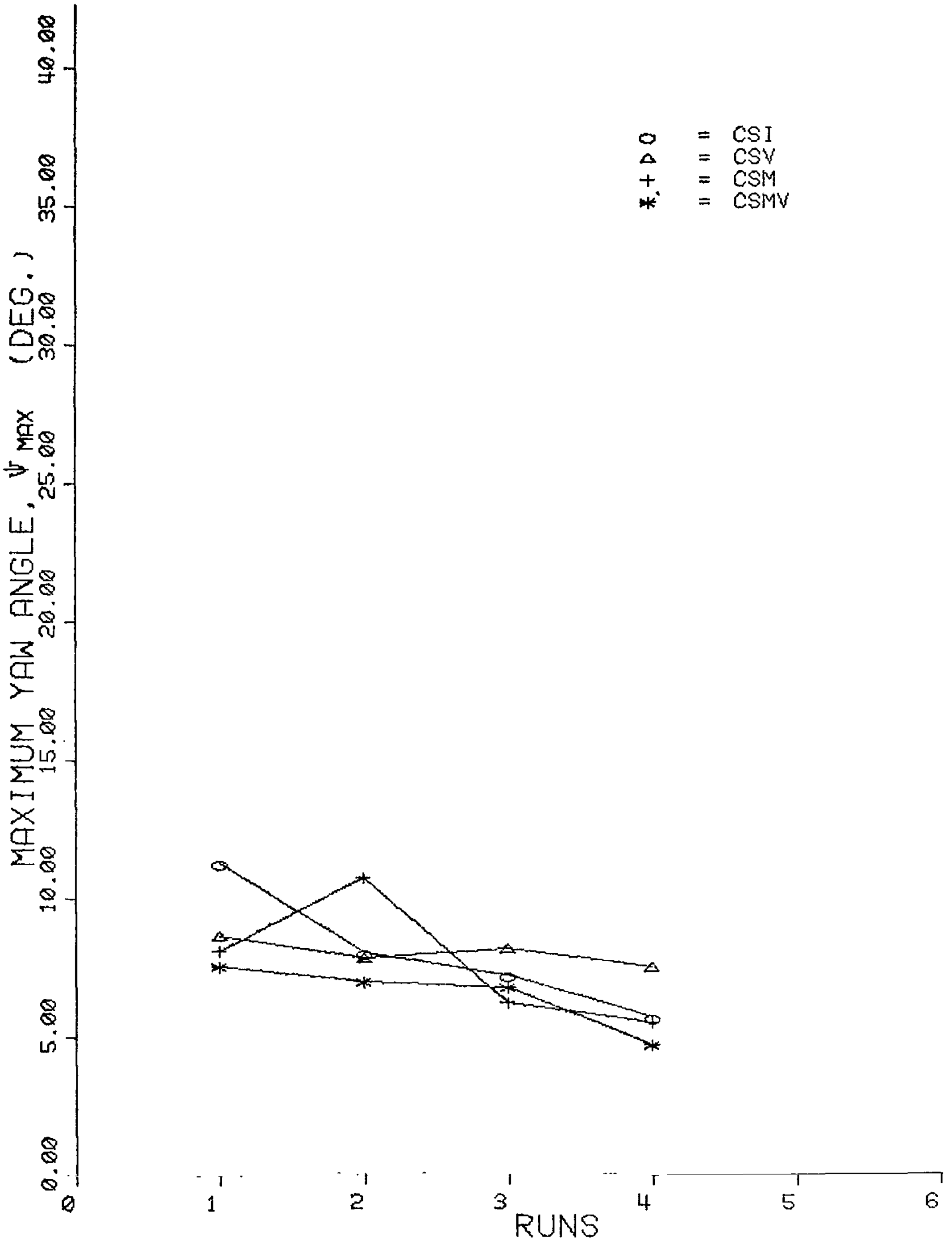

Figure 23.– Maximum yaw angle average Phase III learning for outboard engine failures after lift-off.

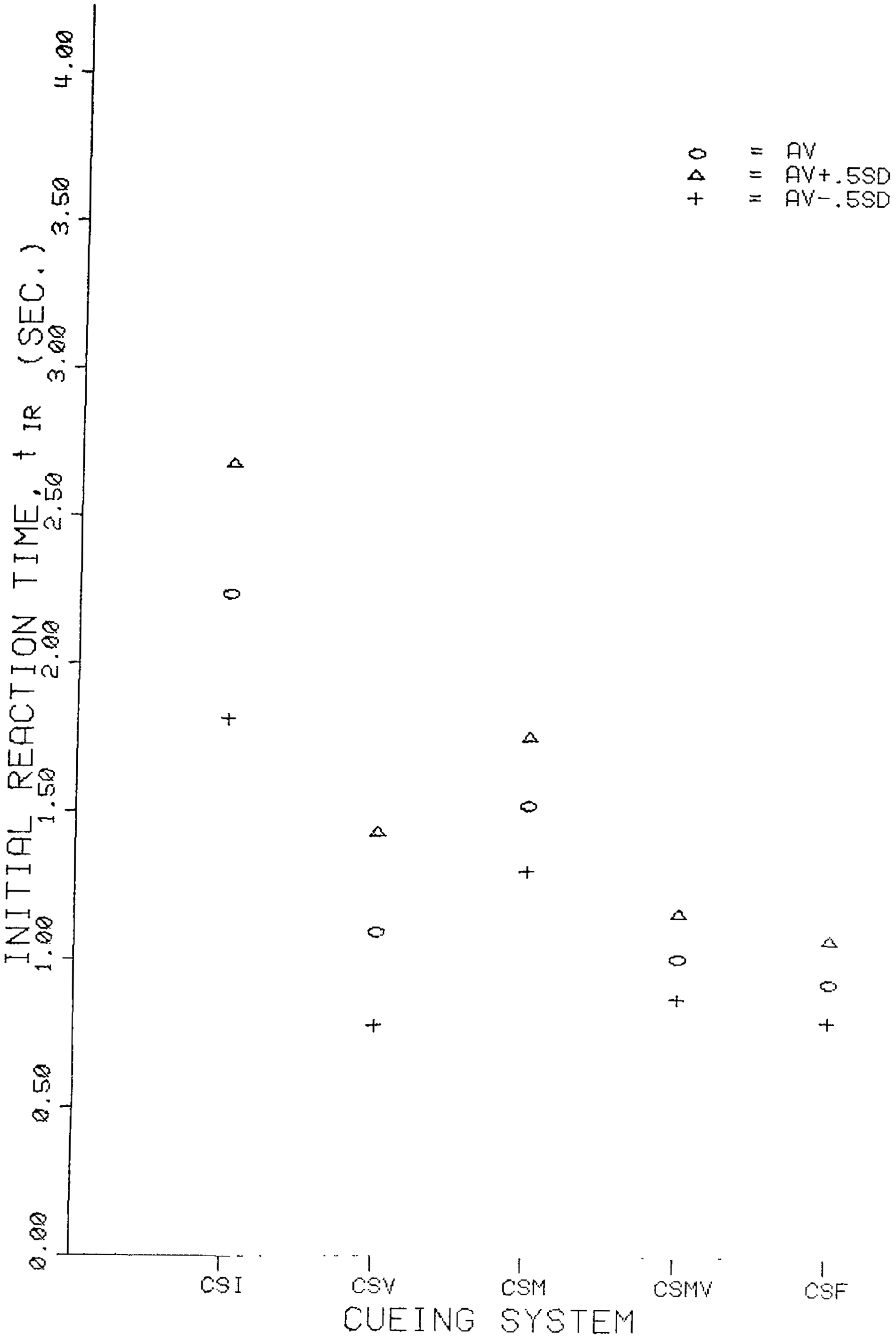

Figure 24.– Initial reaction time average group performance during Phase II for outboard engine failures prior to lift-off.

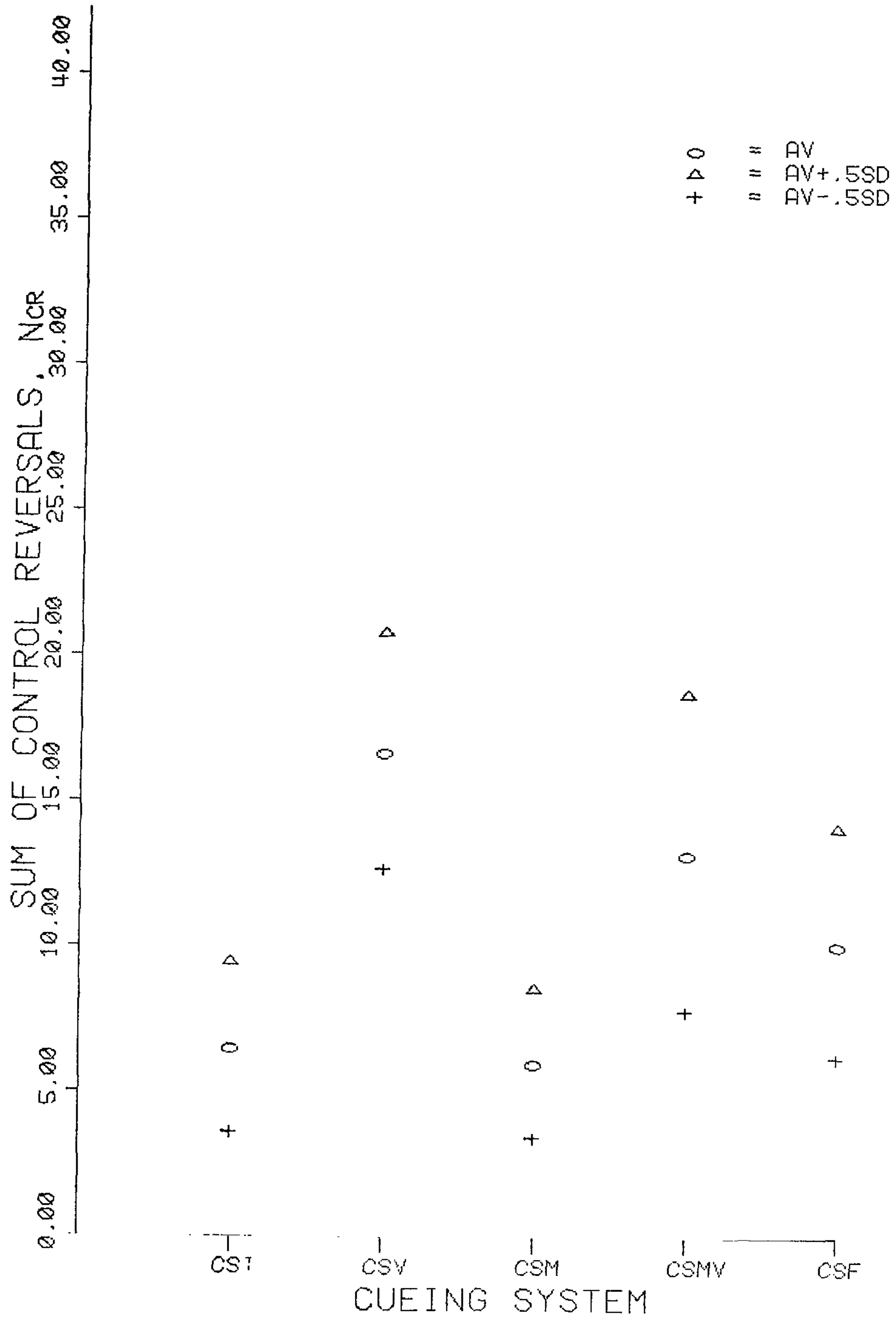

Figure 25.— Control reversal average group performance during Phase II for outboard engine failures prior to lift-off.

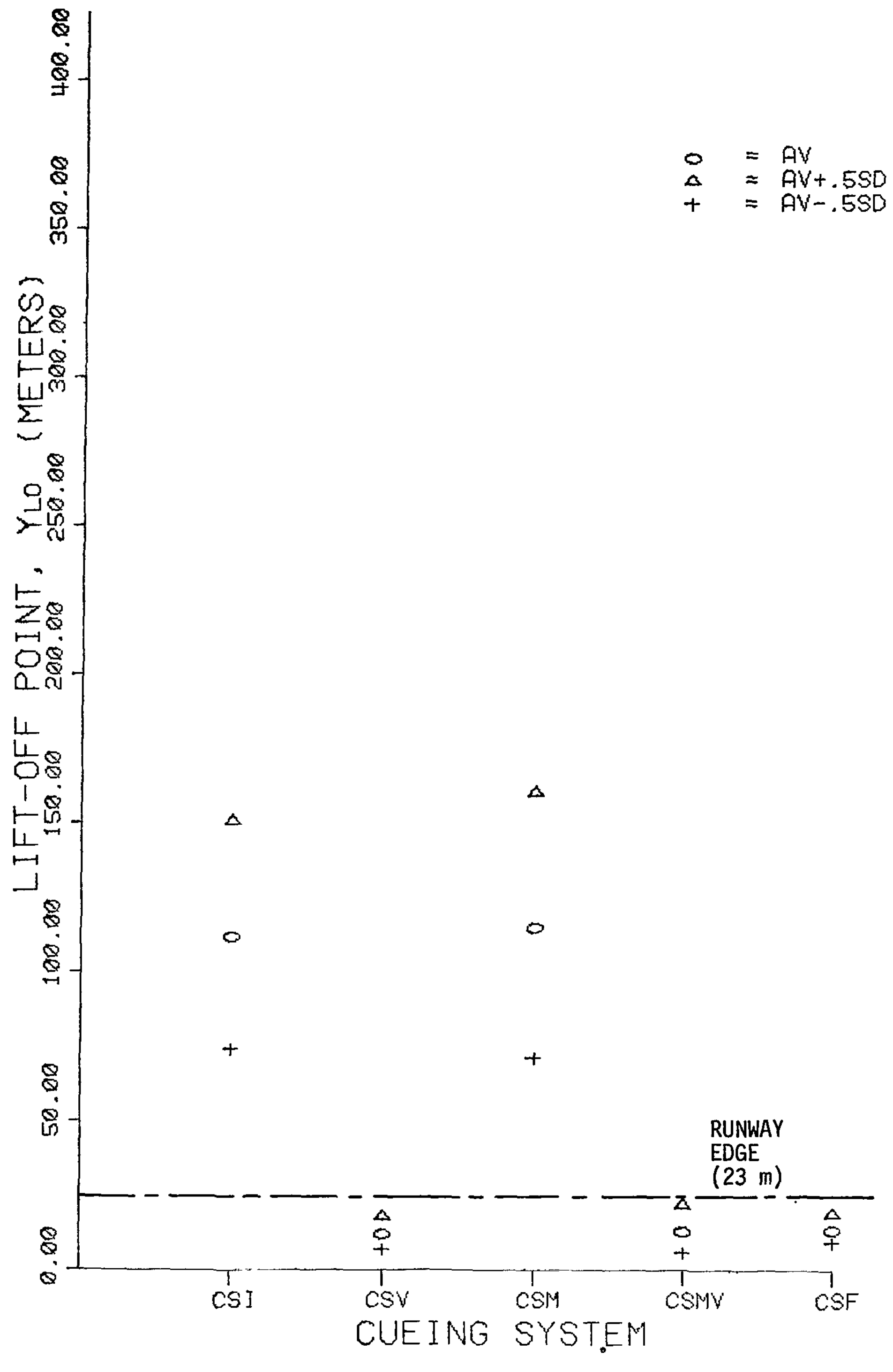

Figure 26.– Lift-off point average group performance during Phase II for outboard engine failures prior to lift-off.

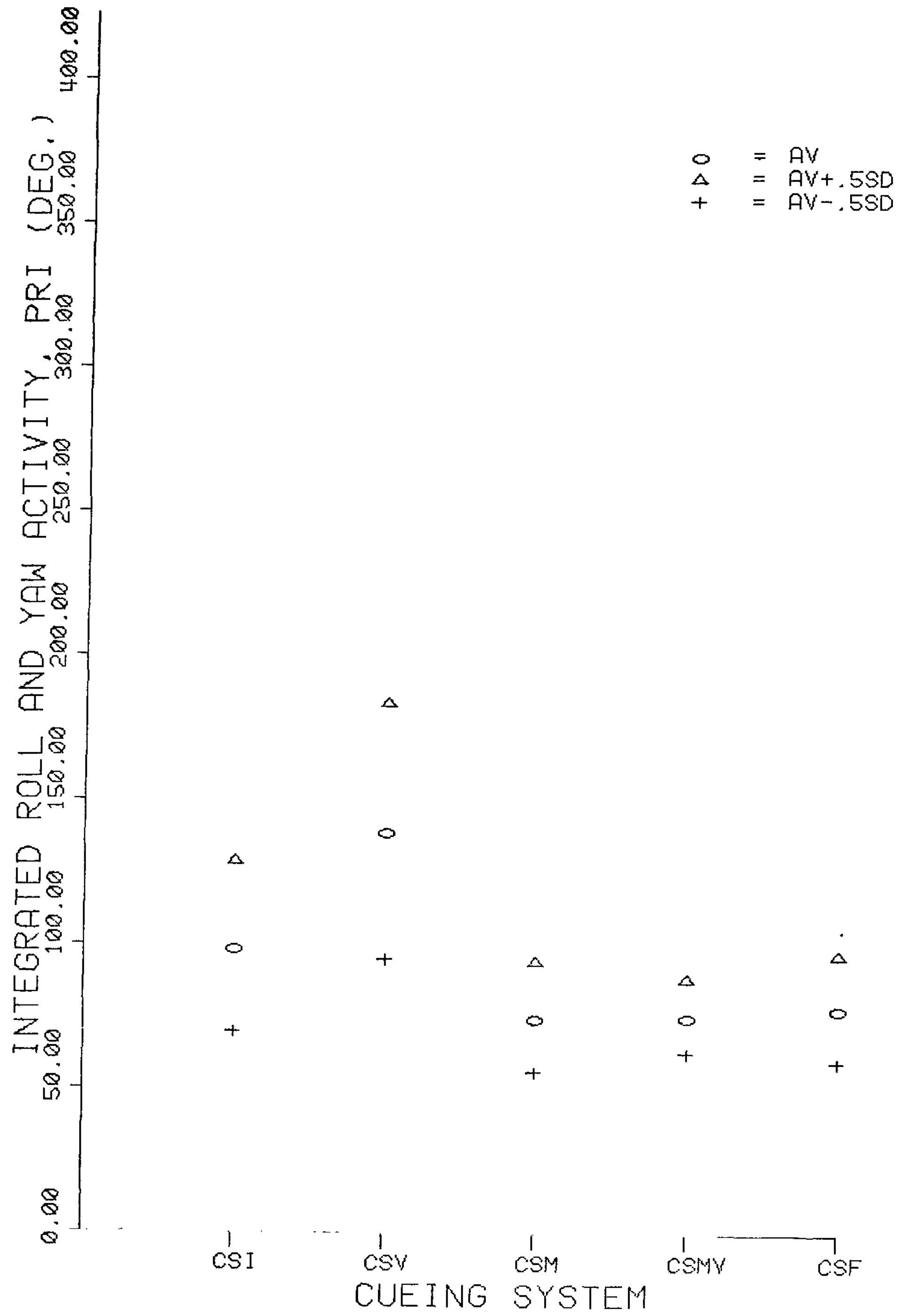

Figure 27.— Integrated roll and yaw activity average group performance during Phase II for outboard engine failures prior to lift-off.

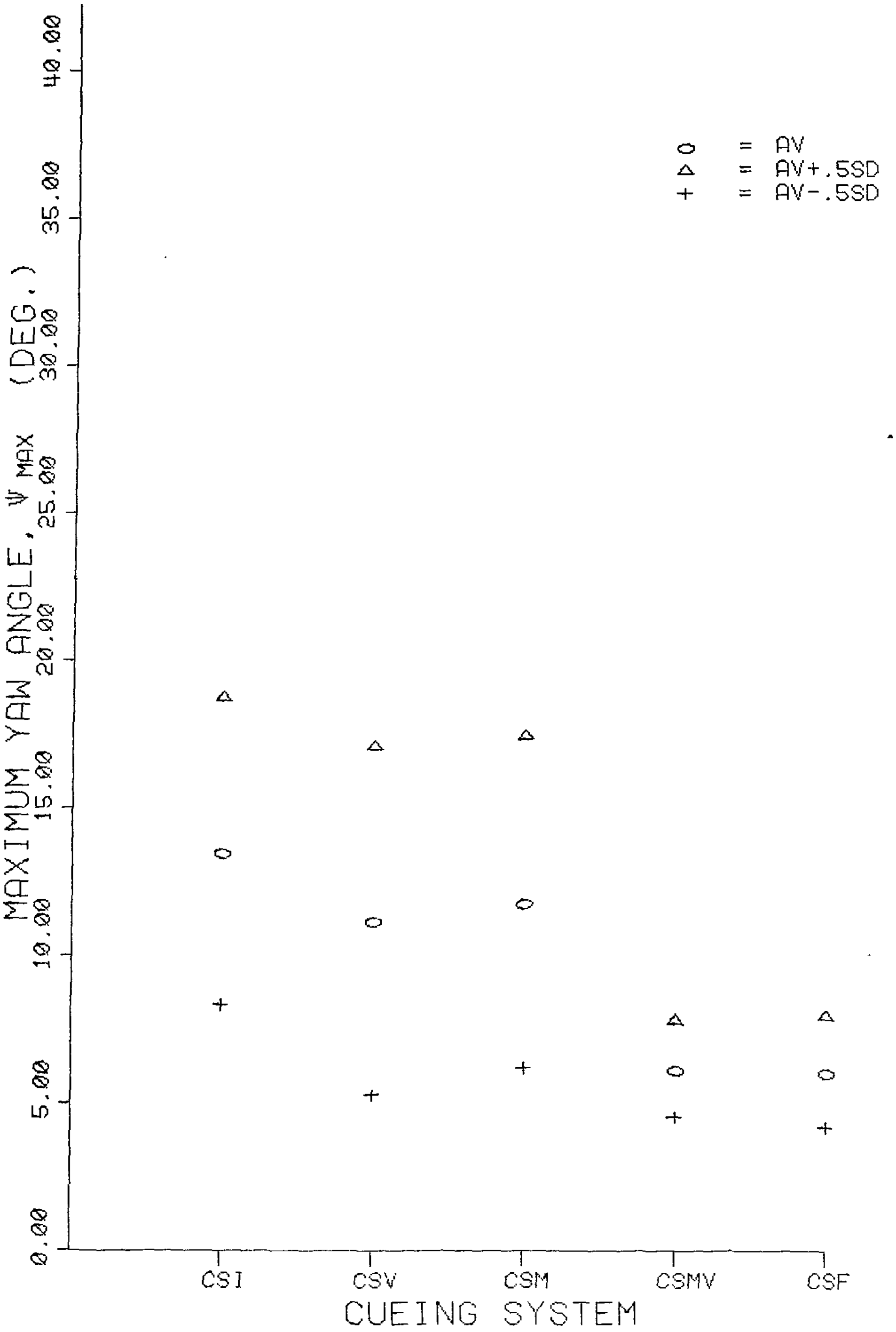

Figure 28.– Maximum yaw angle average group performance during Phase II for outboard engine failures prior to lift-off.

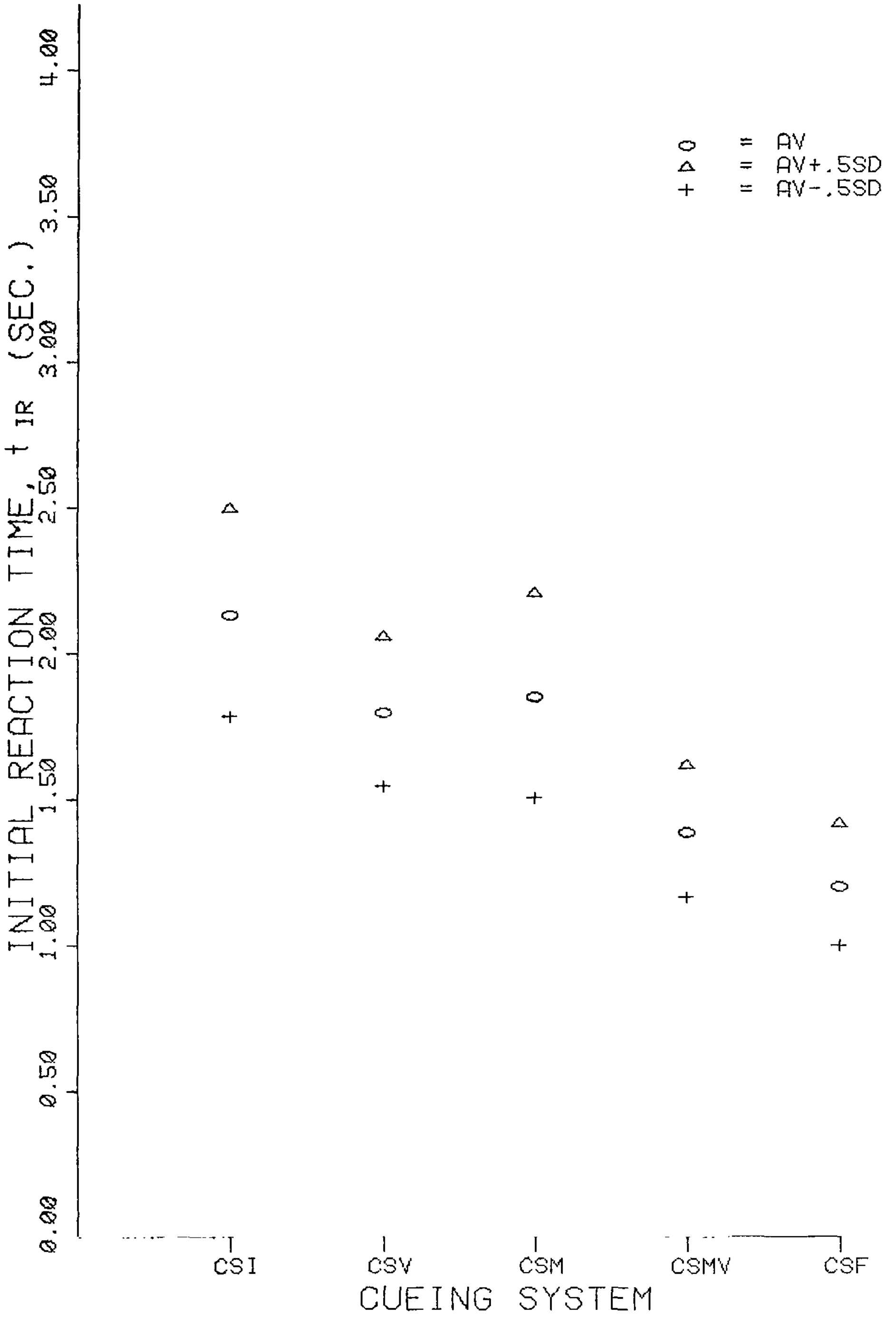

Figure 29.– Initial reaction time average group performance during Phase II for outboard engine failures after lift-off.

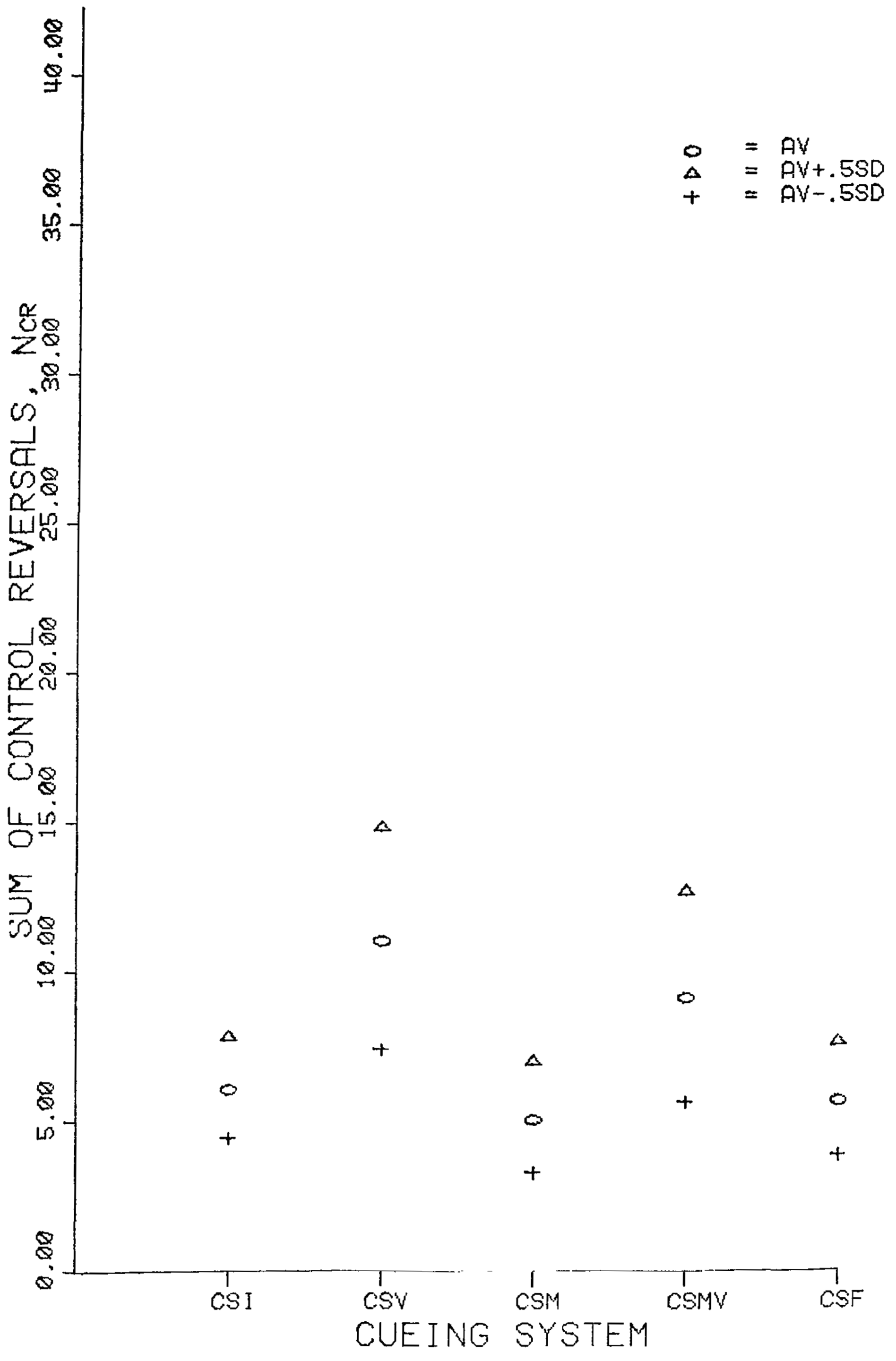

Figure 30.– Control reversal average group performance during Phase II for outboard engine failures after lift-off.

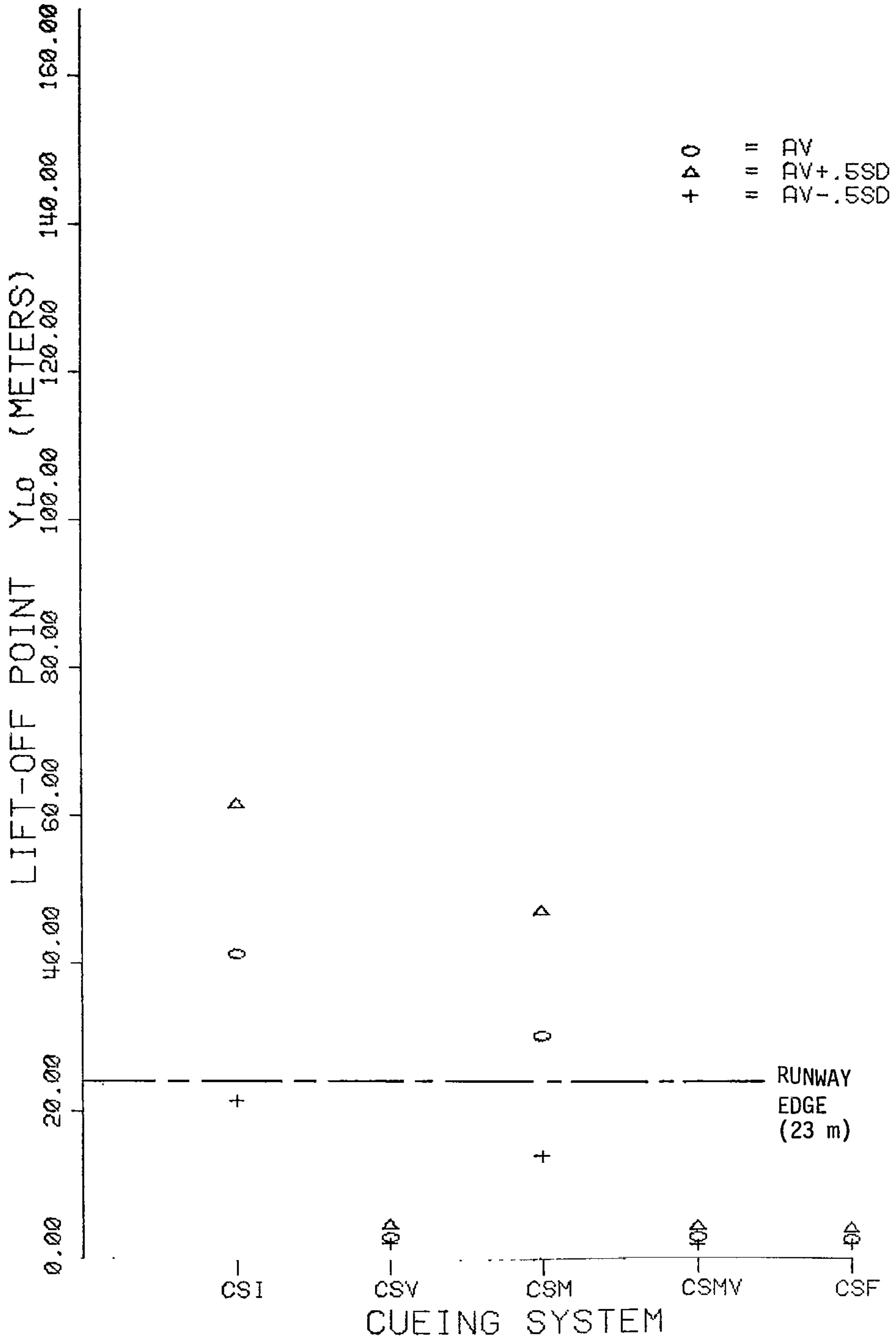

Figure 31.– Lift-off point average group performance during Phase II for outboard engine failures after lift-off.

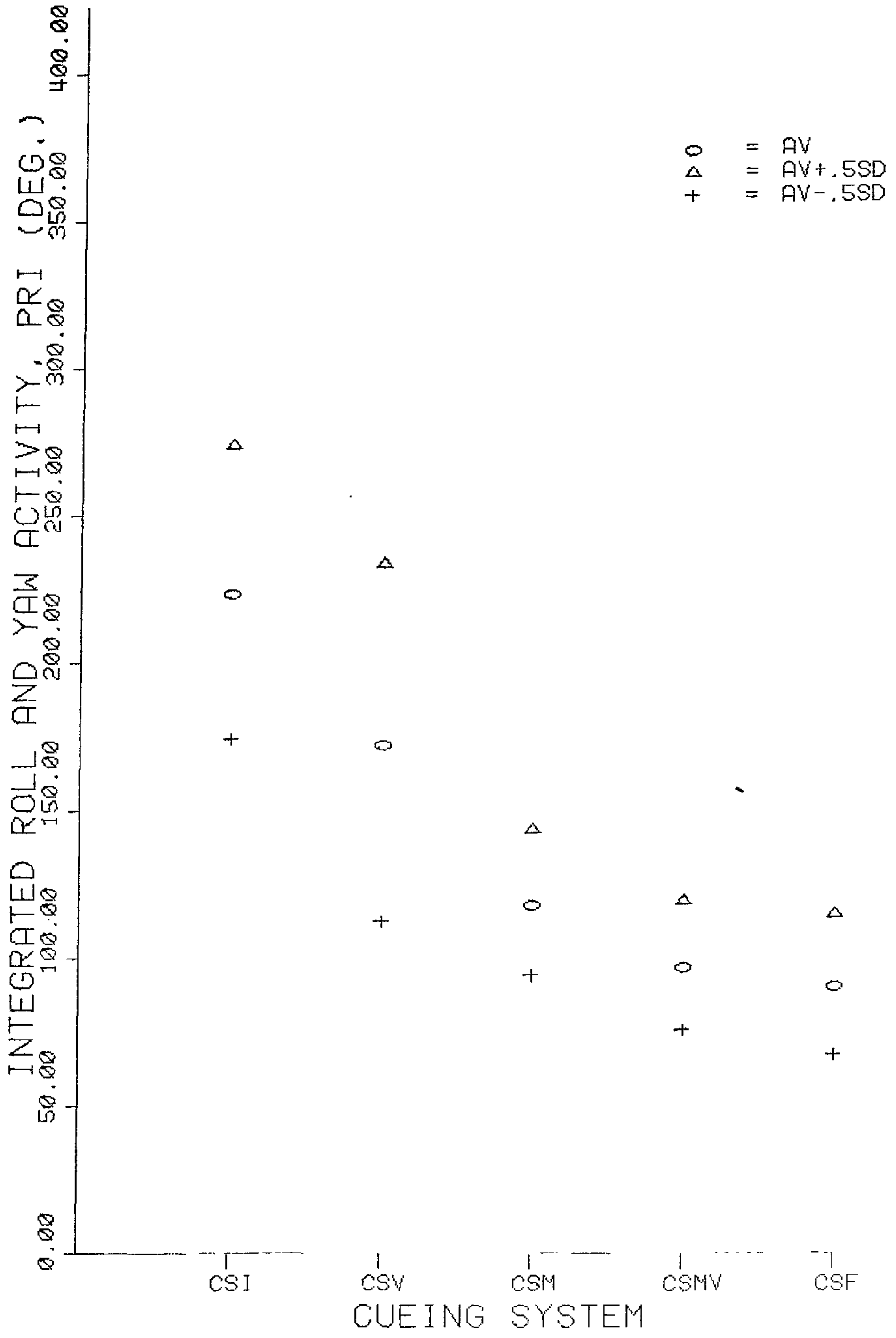

Figure 32.– Integrated roll and yaw activity average group performance during Phase II for outboard engine failures after lift-off.

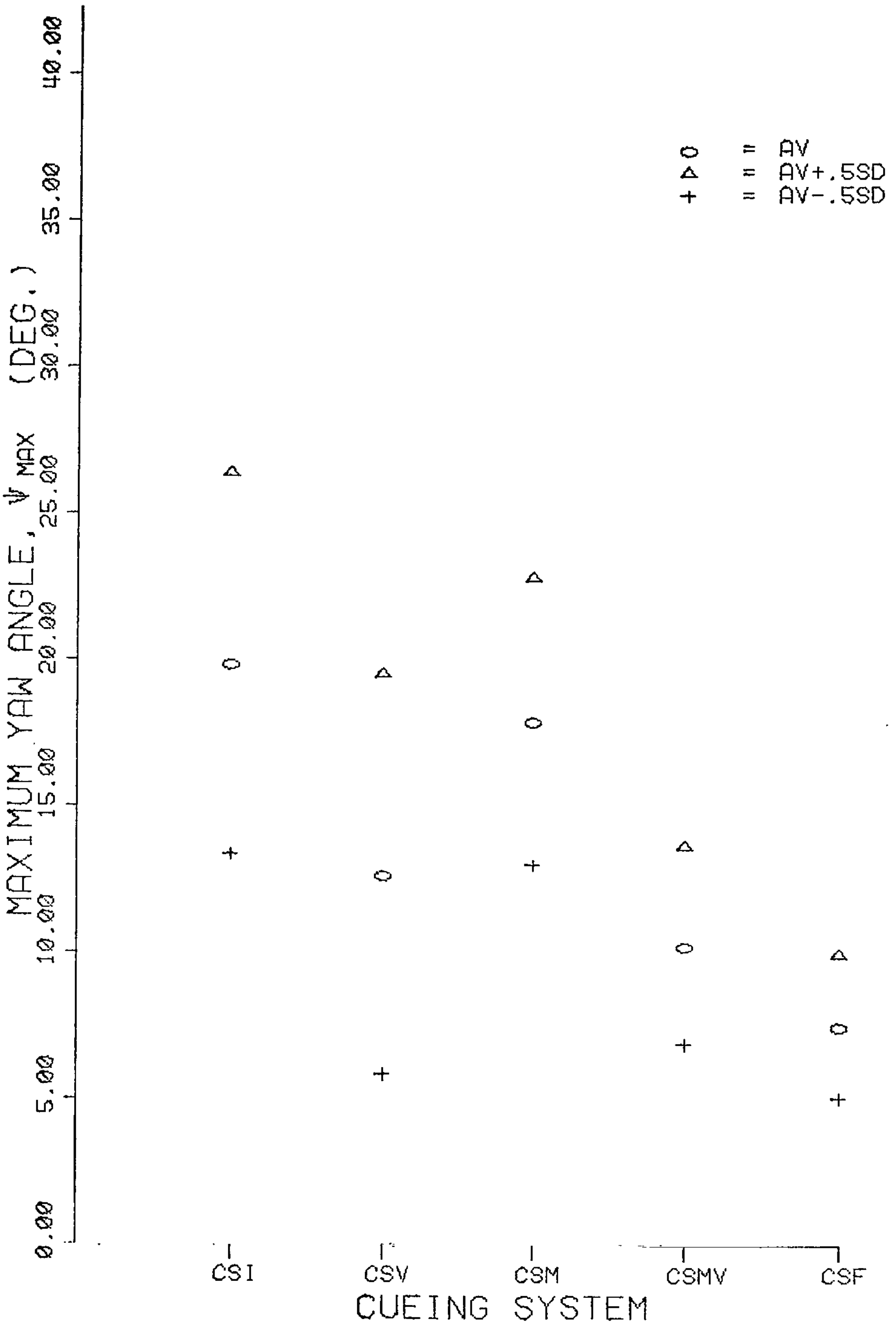

Figure 33.– Maximum yaw angle average group performance during Phase II for outboard engine failures after lift-off.

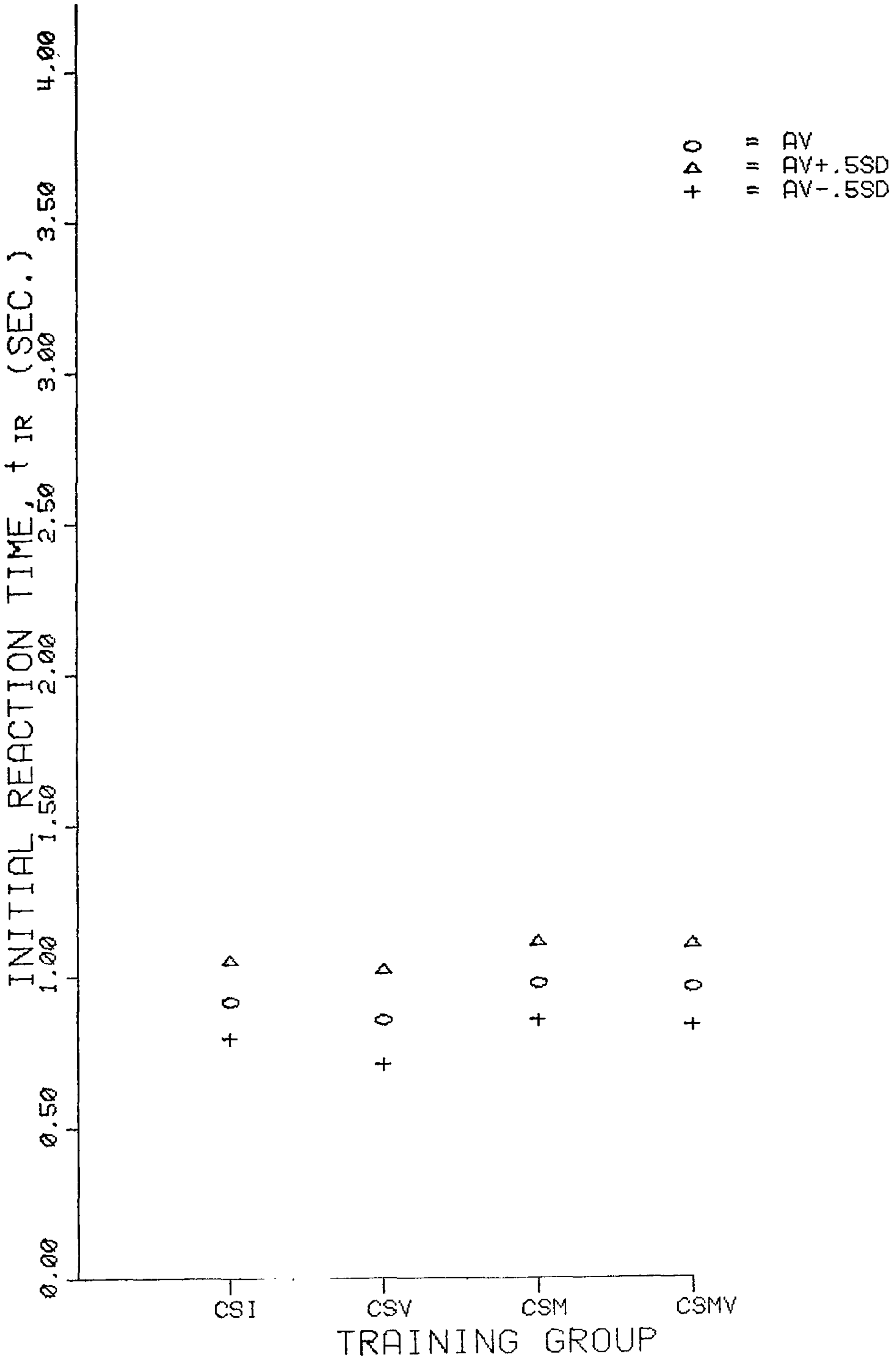

Figure 34.– Initial reaction time average group performance during Phase III for outboard engine failures prior to lift-off.

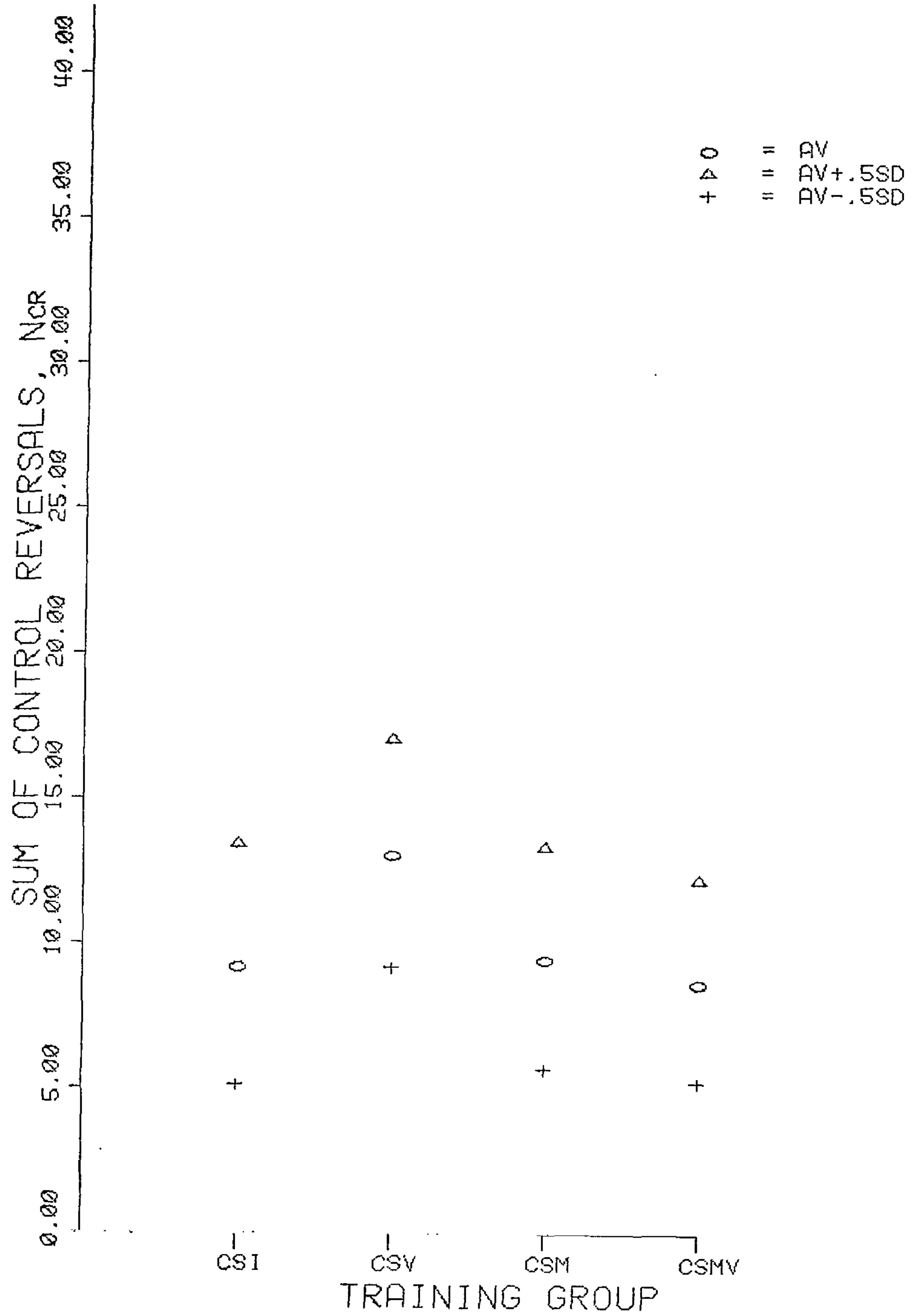

Figure 35.– Control reversal average group performance during Phase III for outboard engine failures prior to lift-off.

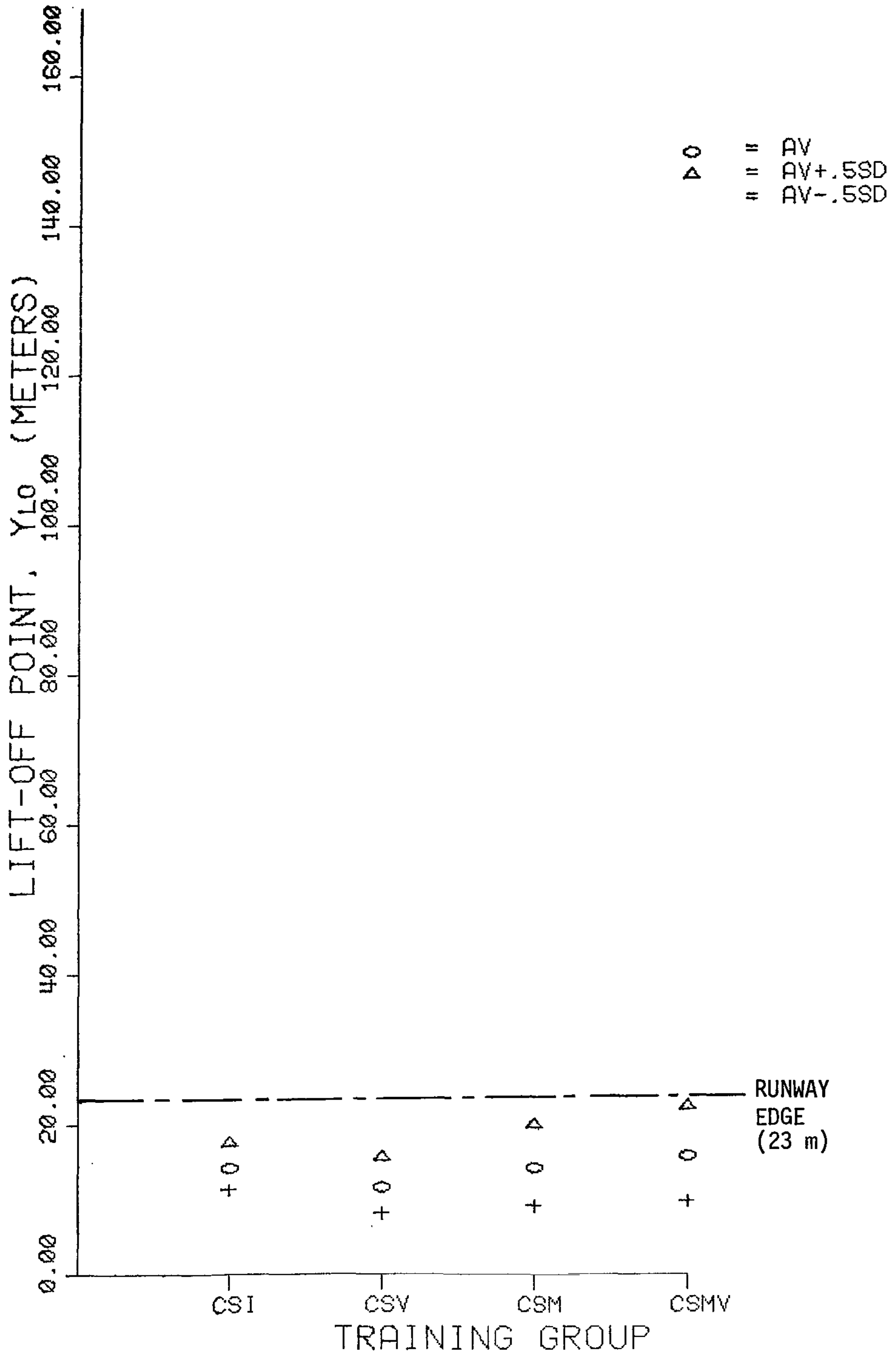

Figure 36.– Lift-off point average group performance during Phase III for outboard engine failures prior to lift-off.

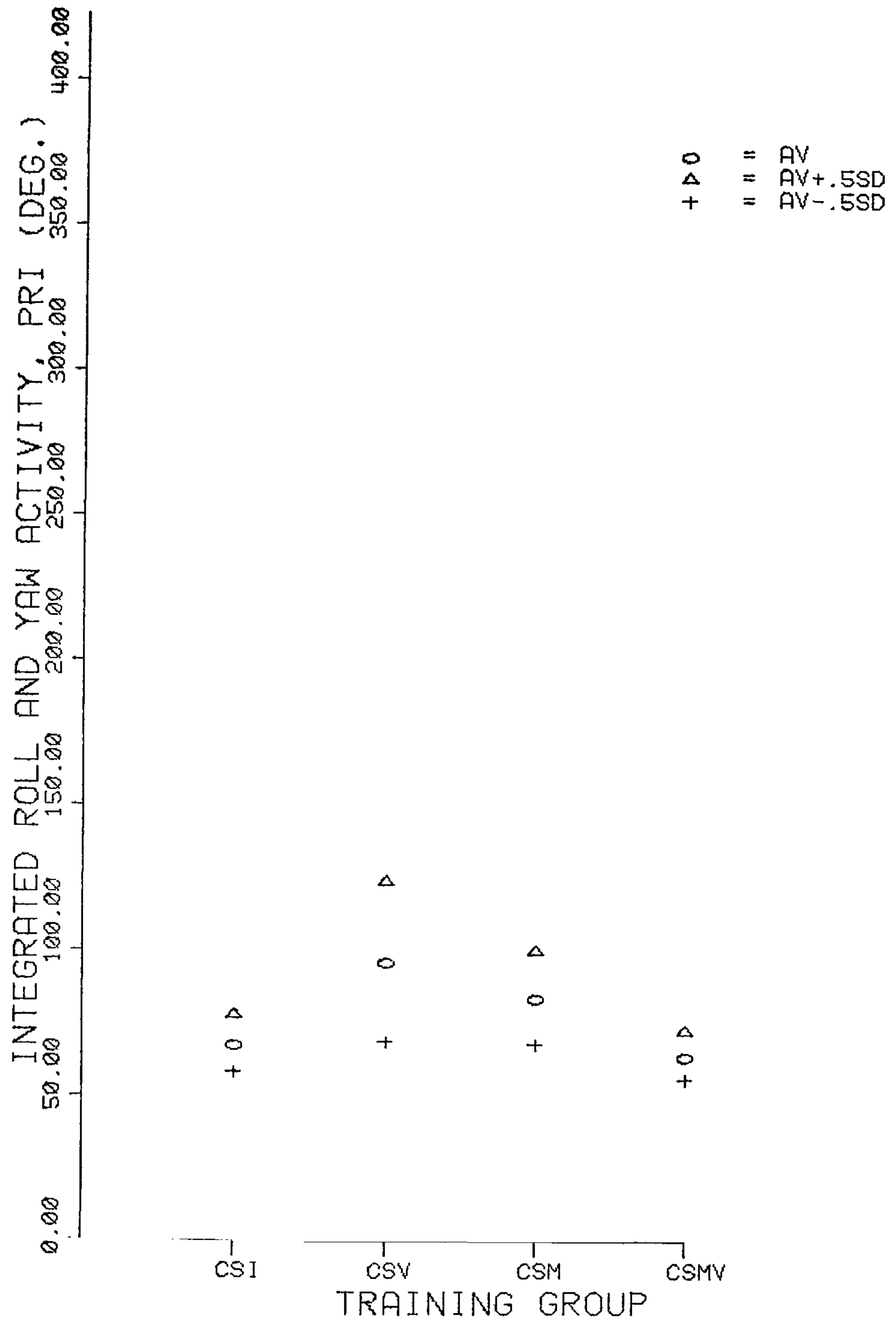

Figure 37.– Integrated roll and yaw activity average group performance during Phase III for outboard engine failures prior to lift-off.

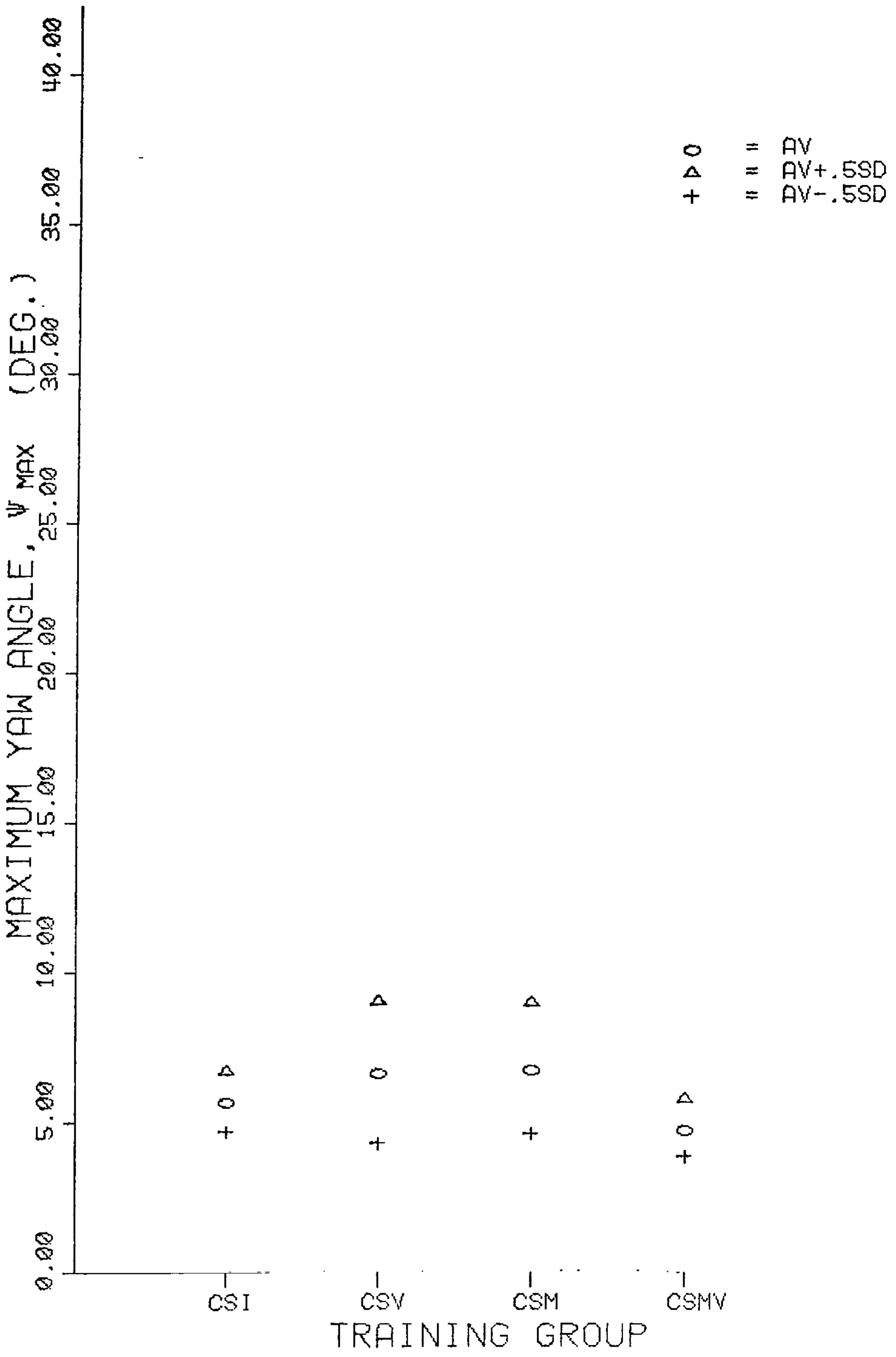

Figure 38.– Maximum yaw angle average group performance during Phase III for outboard engine failures prior to lift-off.

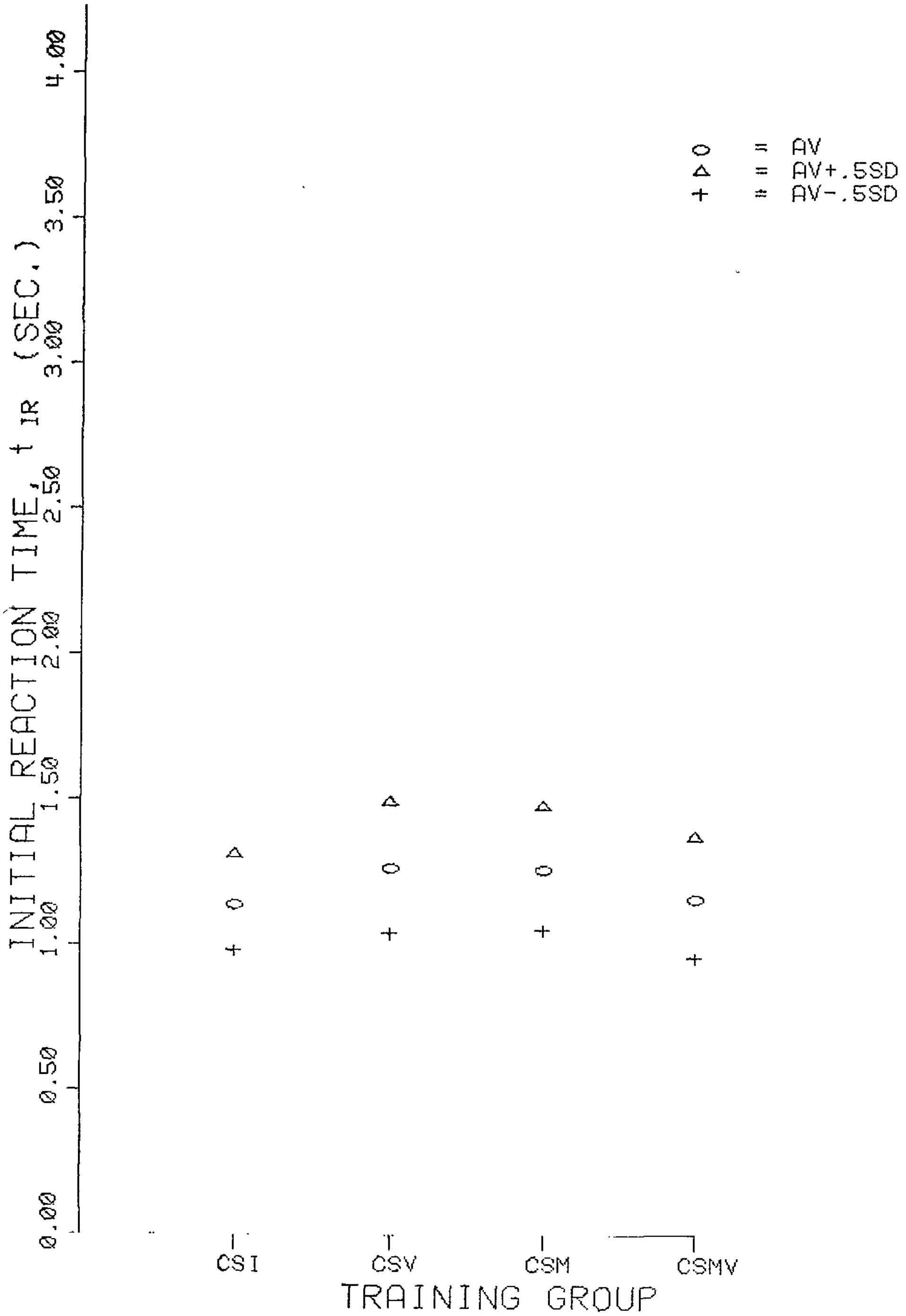

Figure 39.– Initial reaction time average group performance during Phase III for outboard engine failures after lift-off.

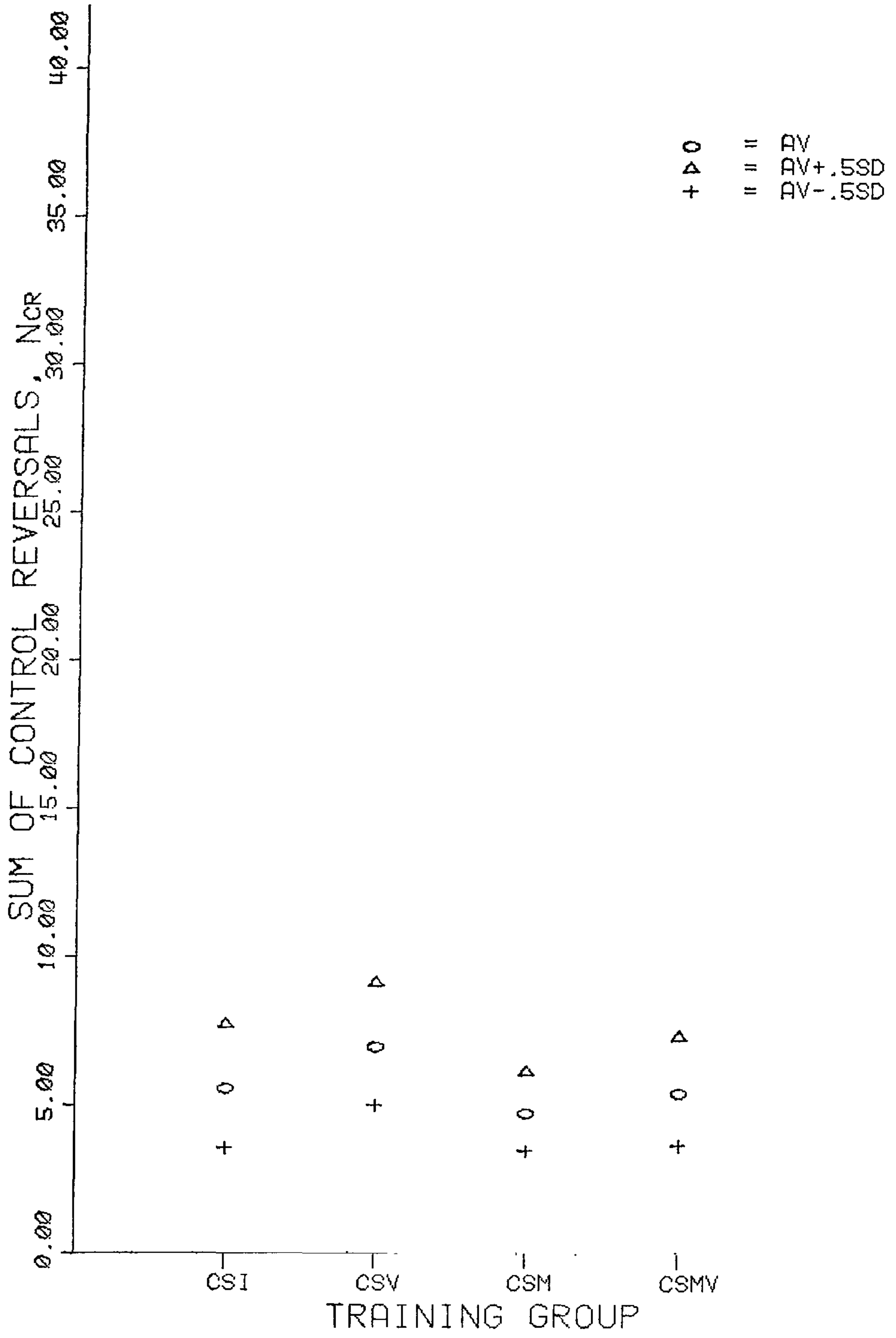

Figure 40.– Control reversal average group performance during Phase III for outboard engine failures after lift-off.

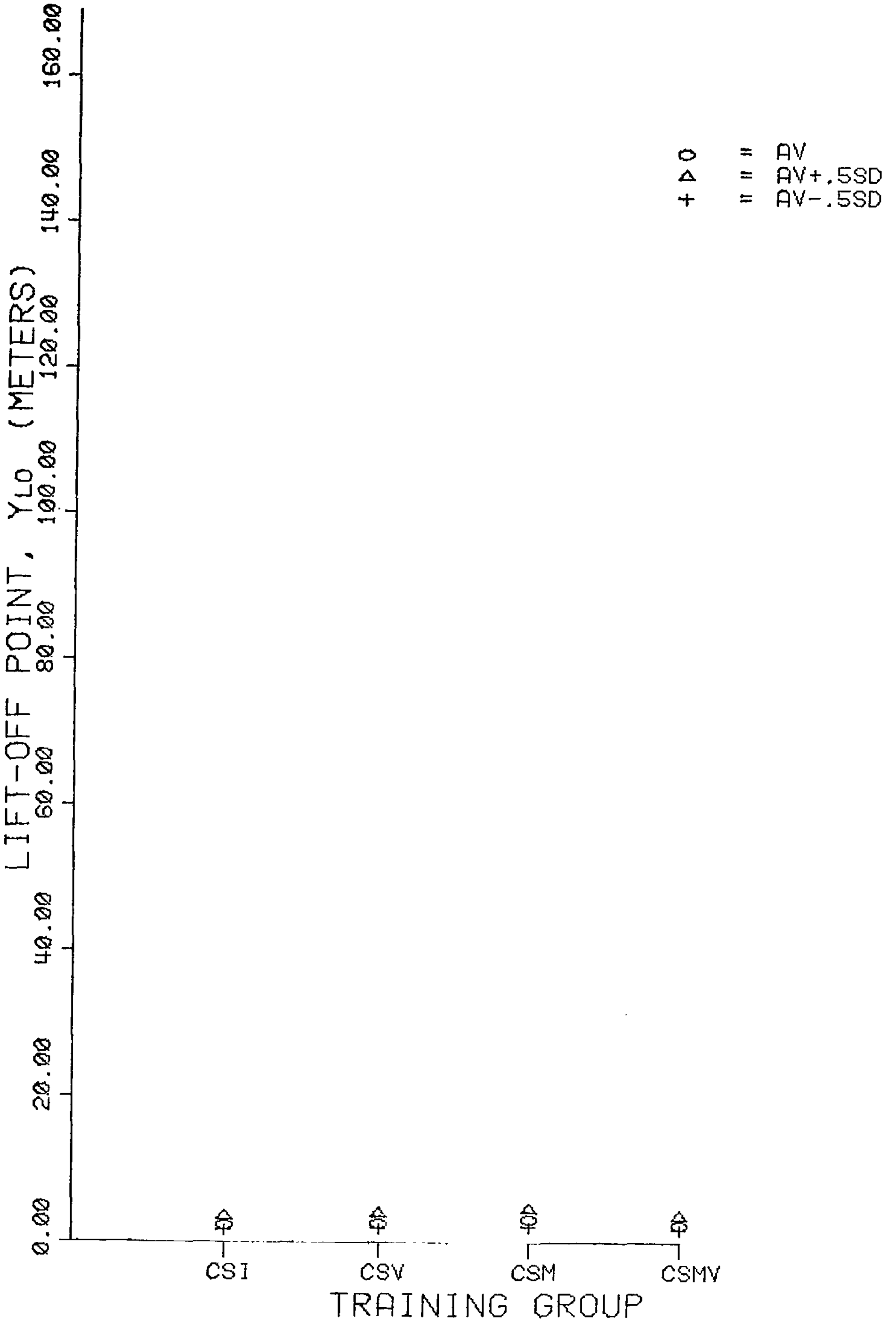

Figure 41.— Lift-off point average group performance during Phase III for outboard engine failures after lift-off.

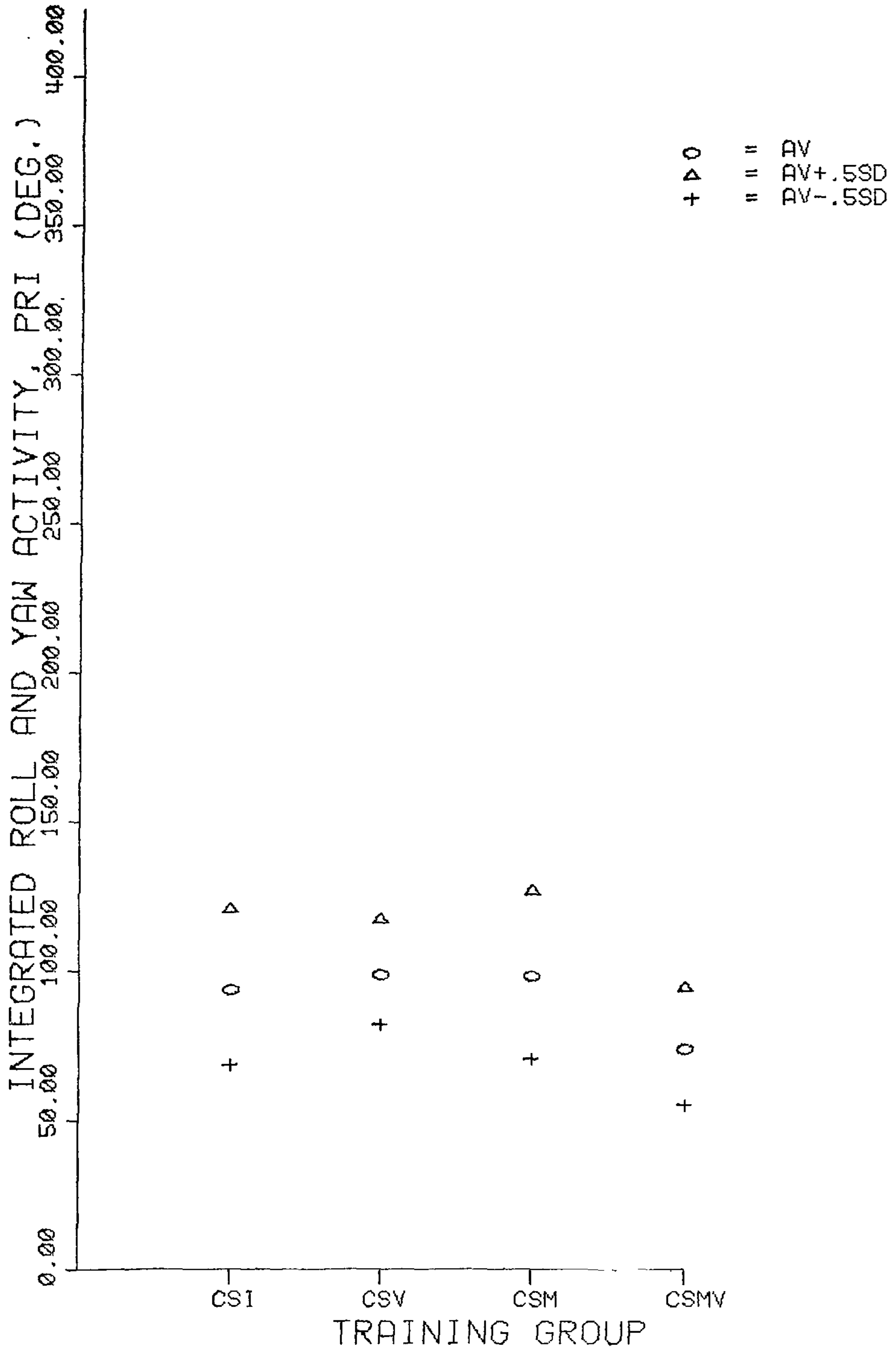

Figure 42.– Integrated roll and yaw activity average group performance during Phase III for outboard engine failures after lift-off.

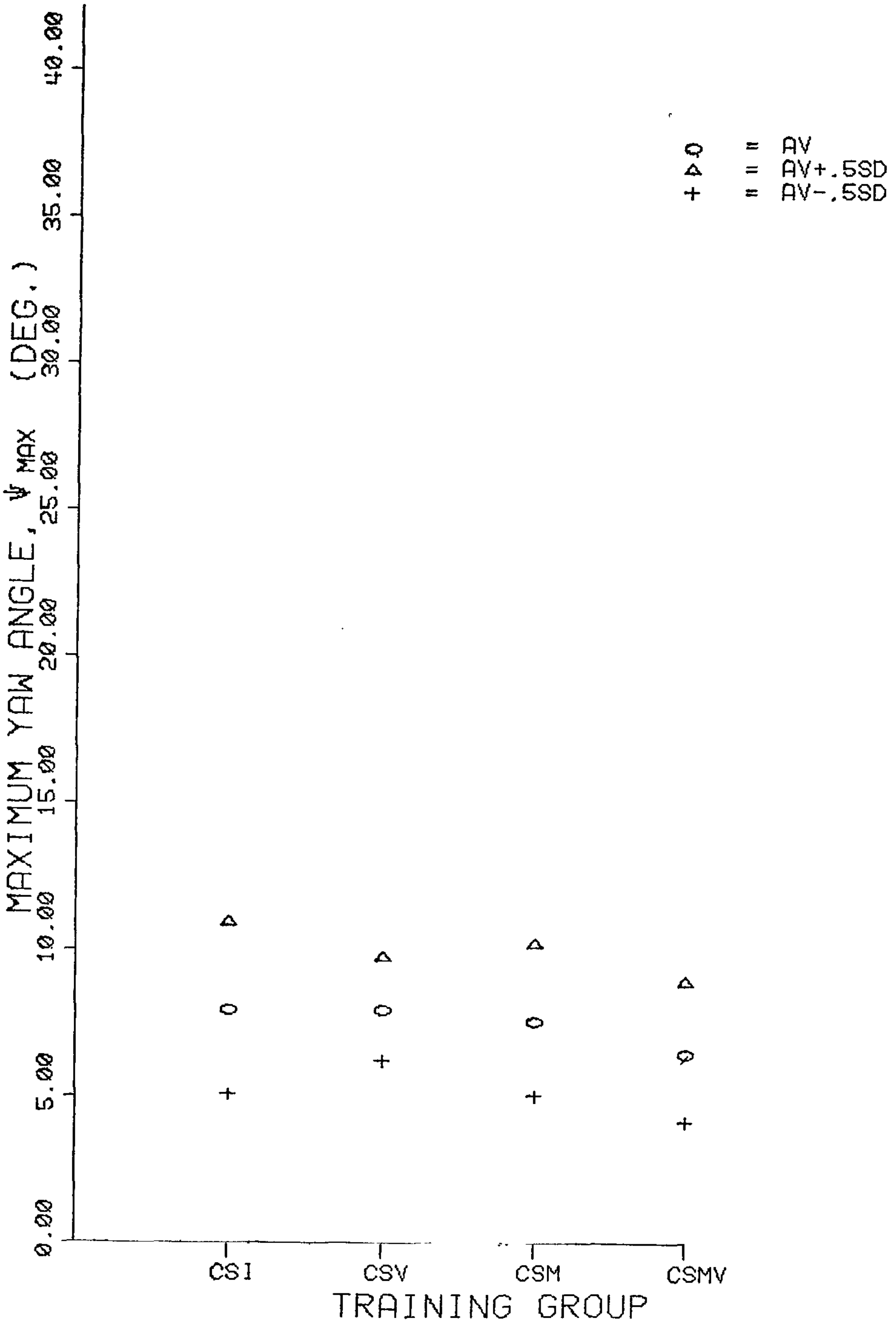

Figure 43.– Maximum yaw angle average group performance during Phase III for outboard engine failures after lift-off.

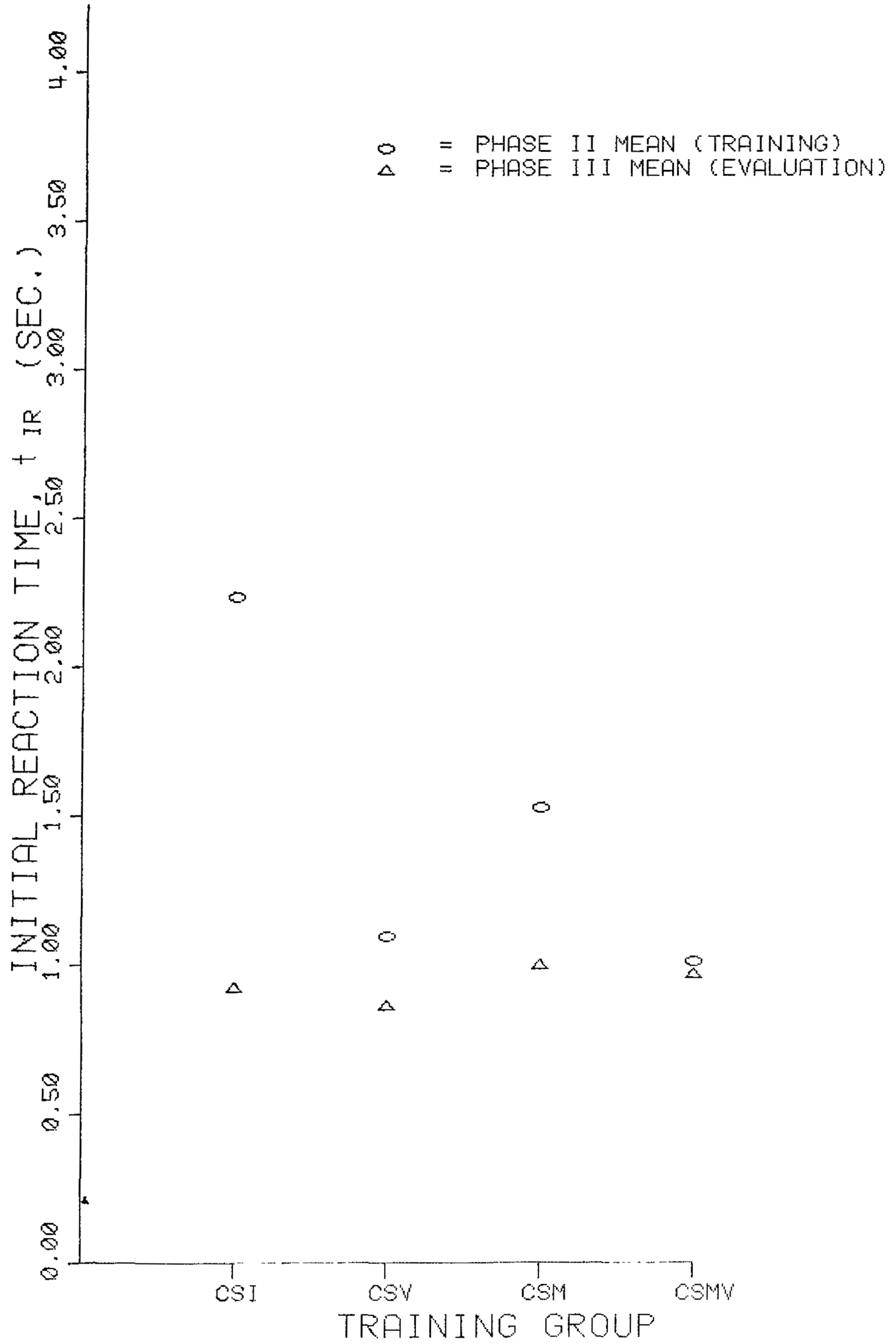

Figure 44.– Comparison of Phase II and Phase III mean initial reaction time for outboard engine failures prior to lift-off.

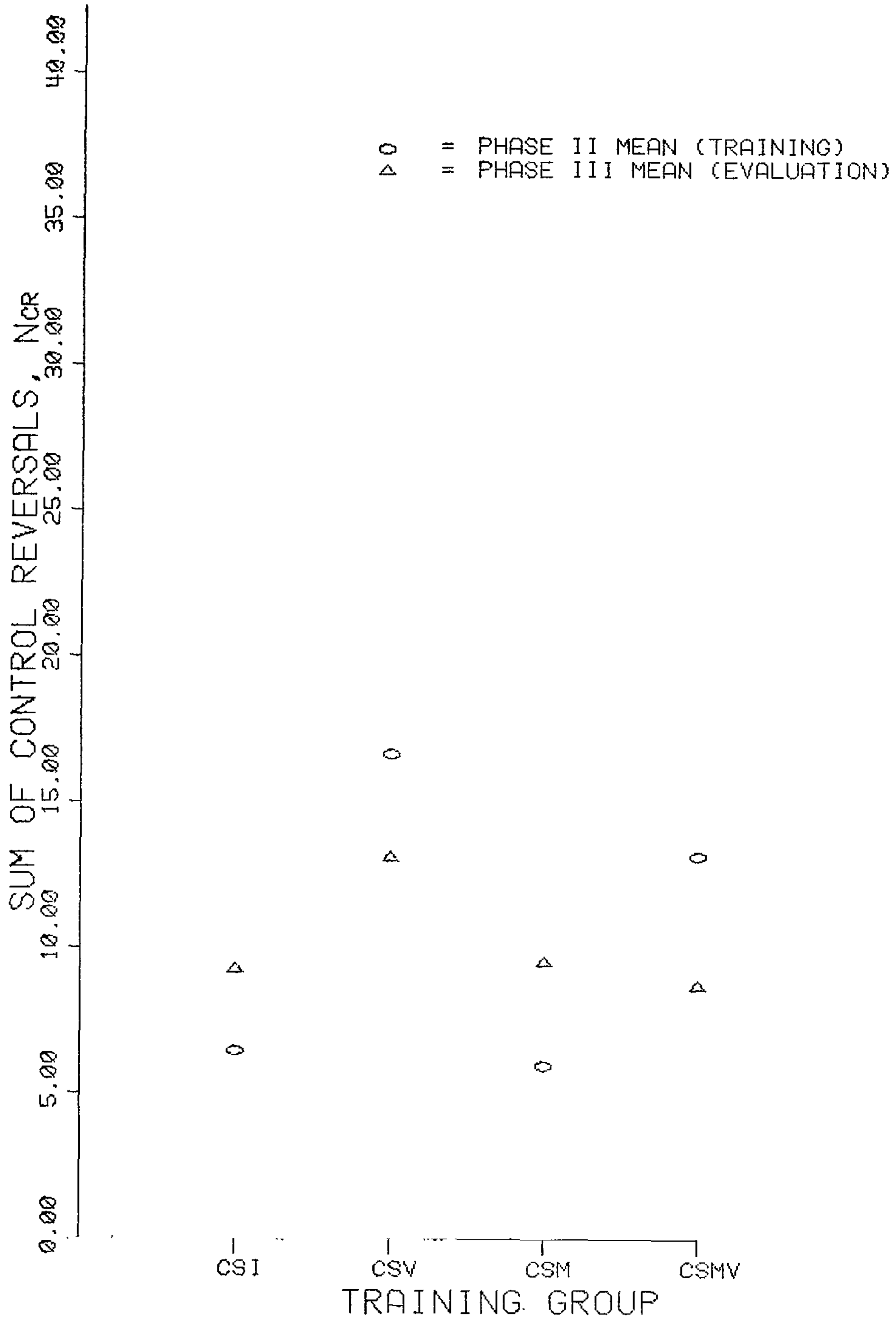

Figure 45.– Comparison of Phase II and Phase III mean control reversals for outboard engine failures prior to lift-off.

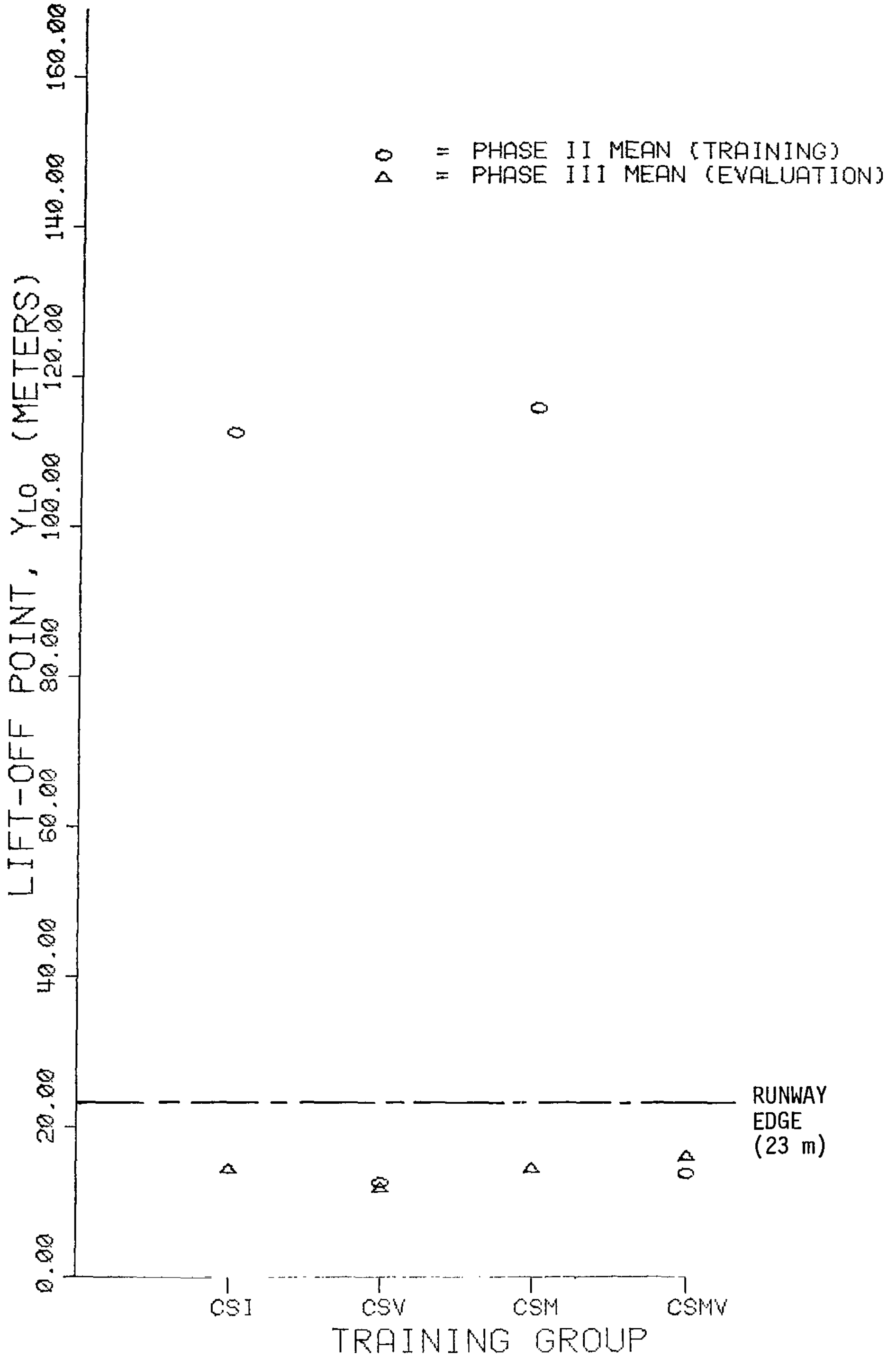

Figure 46.– Comparison of Phase II and Phase III mean lift-off point for outboard engine failures prior to lift-off.

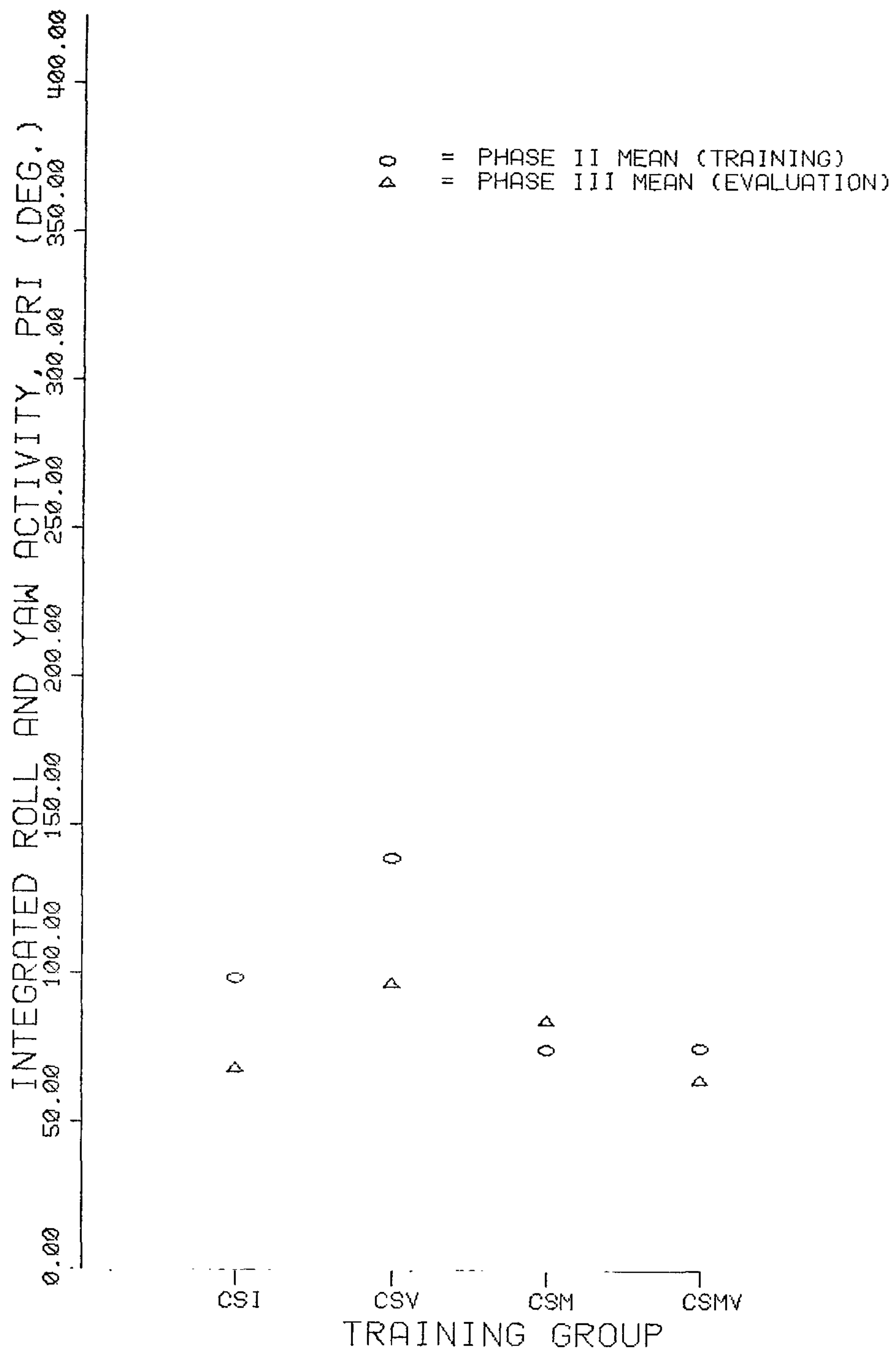

Figure 47.– Comparison of Phase II and Phase III mean integrated roll and yaw activity for outboard engine failures prior to lift-off.

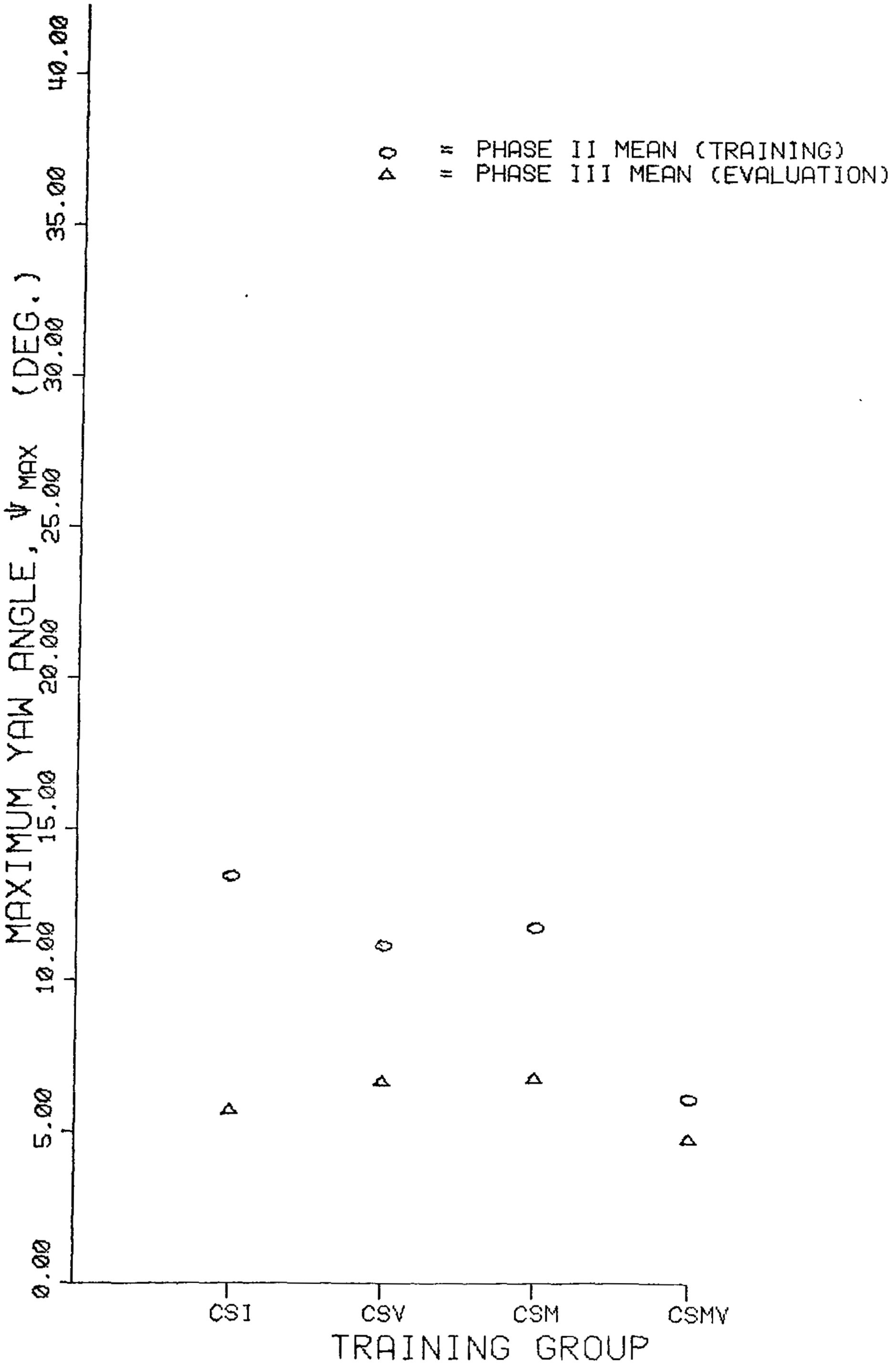

Figure 48.– Comparison of Phase II and Phase III mean maximum yaw angle for outboard engine failures prior to lift-off.

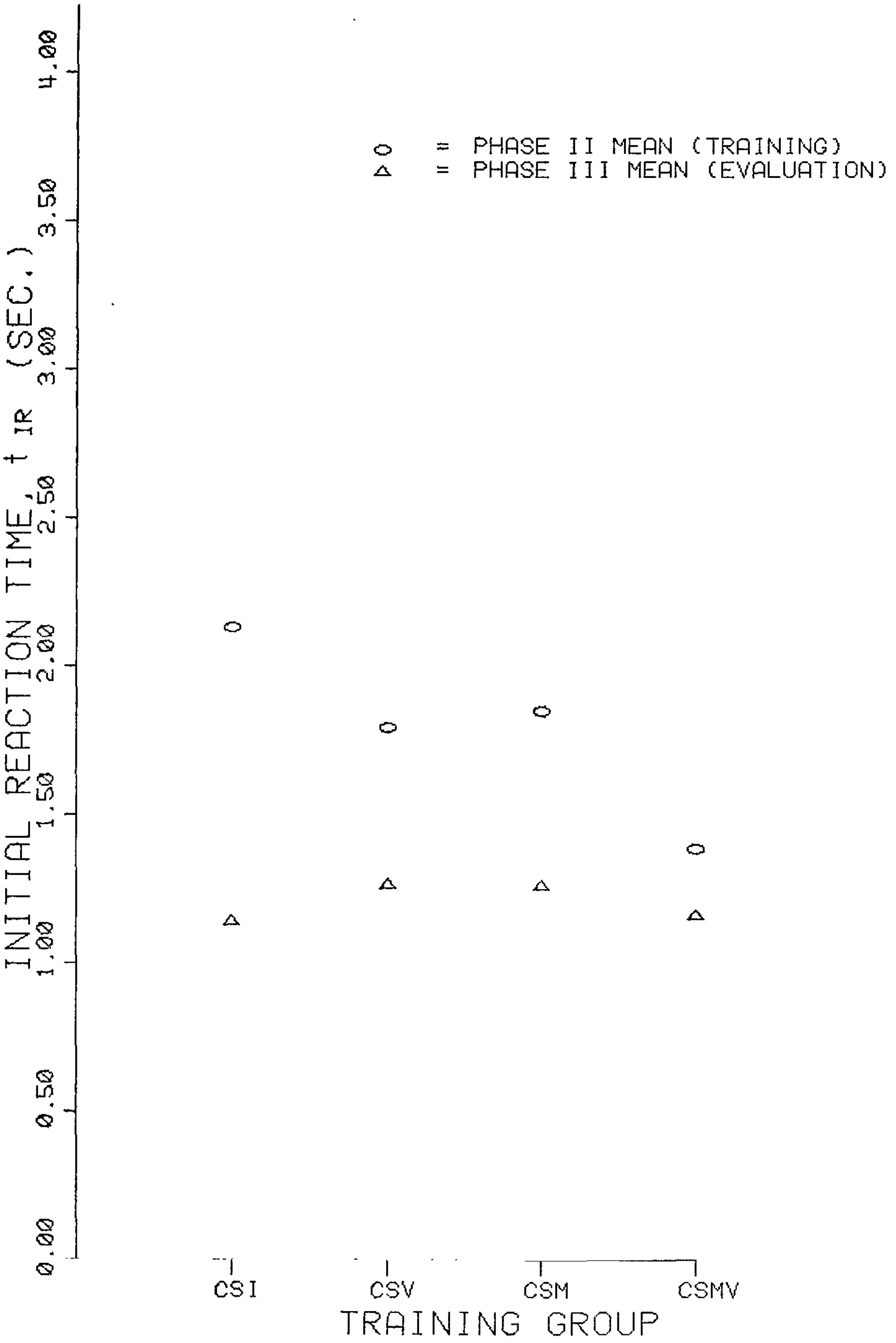

Figure 49.– Comparison of Phase II and Phase III mean initial reaction time for outboard engine failures after lift-off.

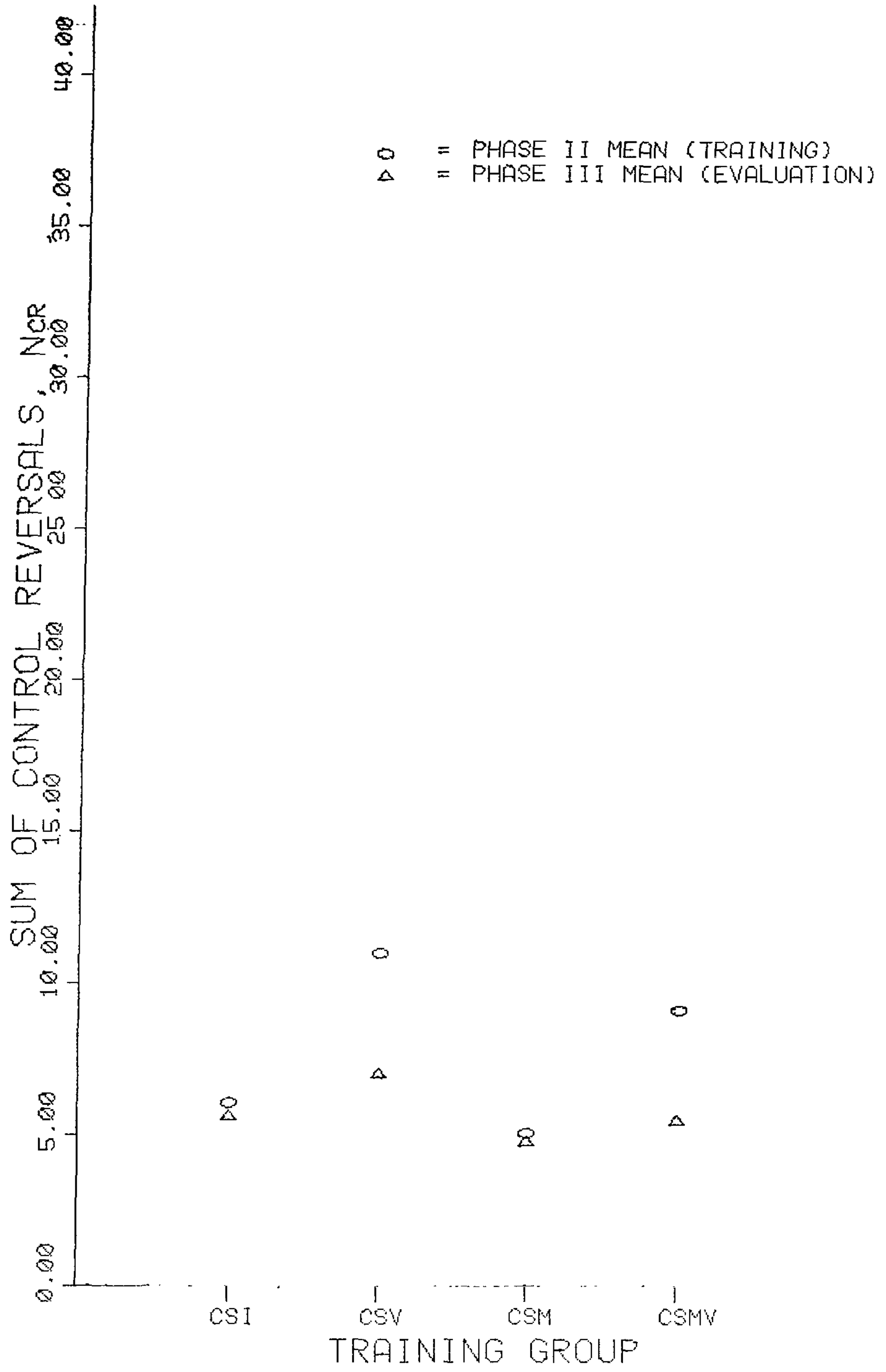

Figure 50.– Comparison of Phase II and Phase III mean control reversals for outboard engine failures after lift-off.

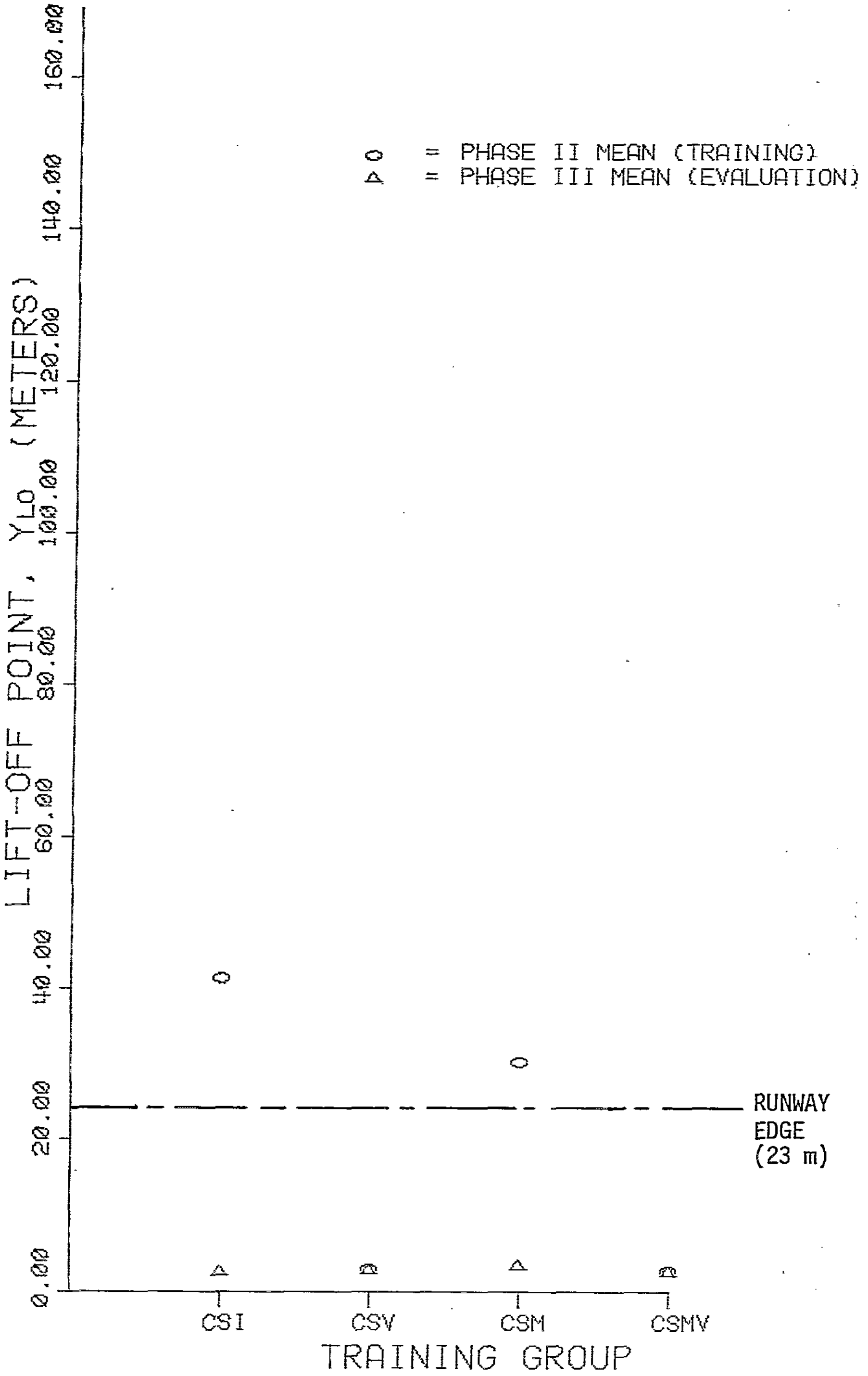

Figure 51.– Comparison of Phase II and Phase III mean lift-off point for outboard engine failures after lift-off.

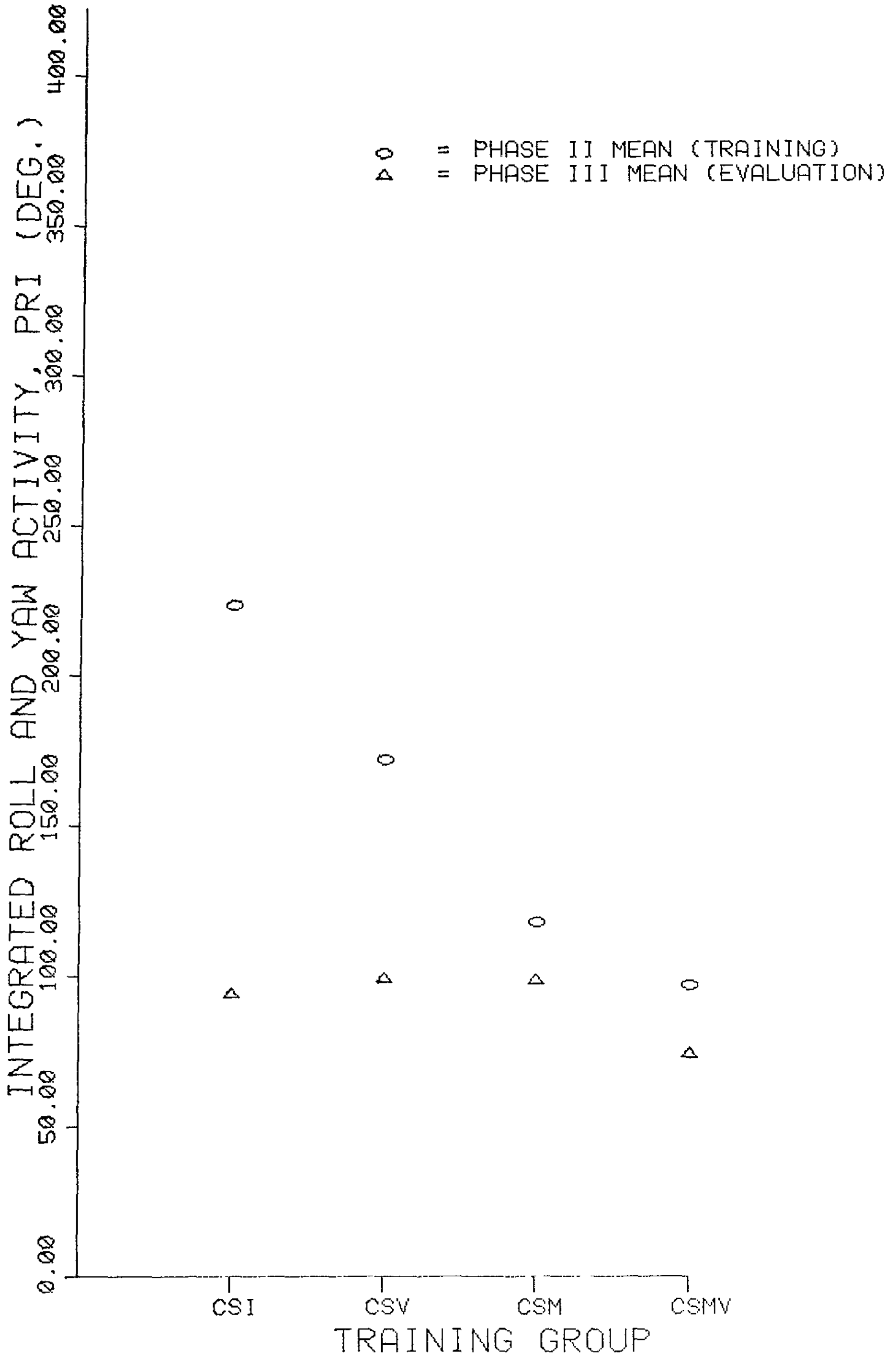

Figure 52.– Comparison of Phase II and Phase III mean integrated roll and yaw activity for outboard engine failures after lift-off.

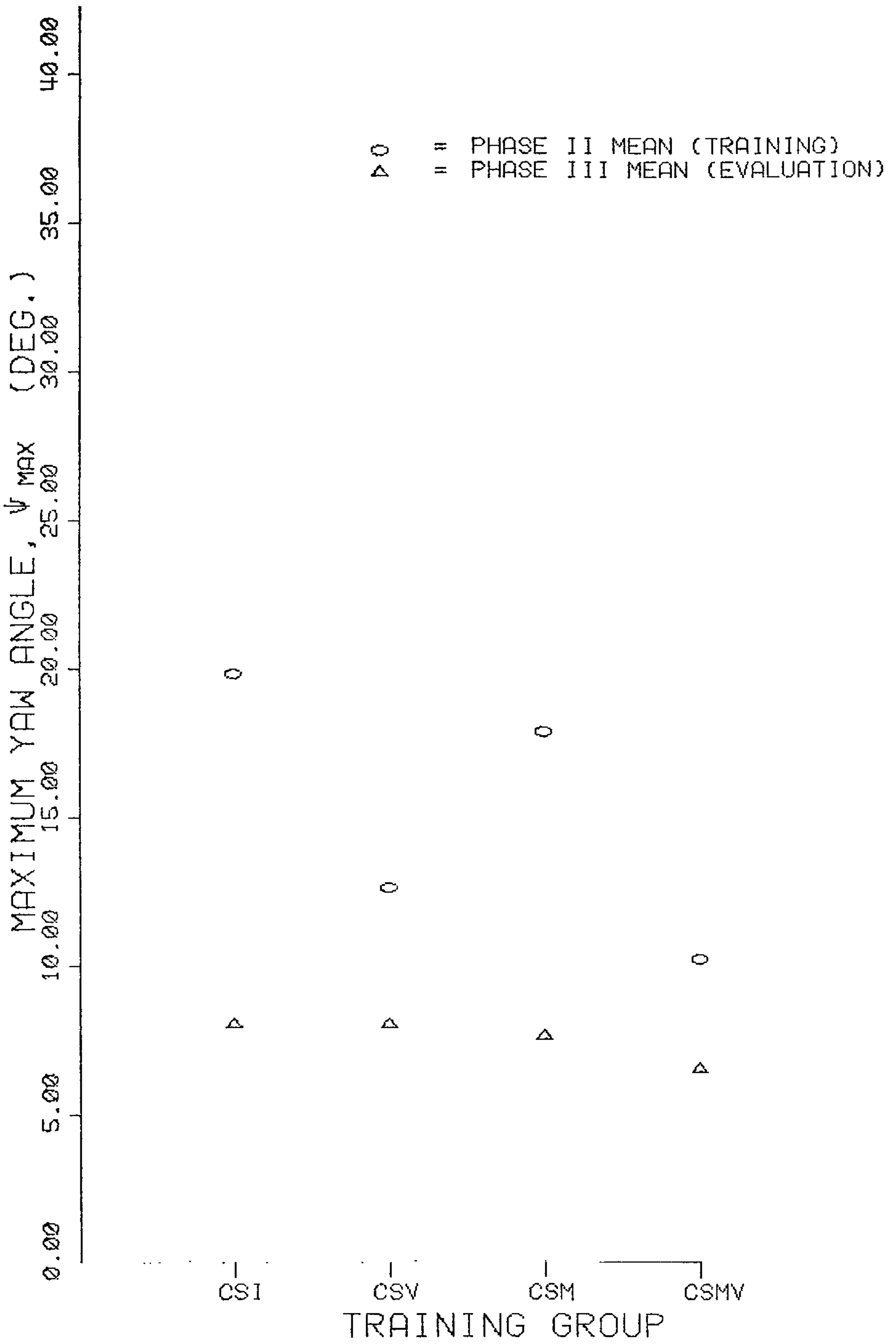

Figure 53.– Comparison of Phase II and Phase III mean maximum yaw angle for outboard engine failures after lift-off.

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15. Supplementary Notes

16. Abstract

Data are presented that show the effects of visual and motion cueing on pilot performance during takeoffs with engine failures. Four groups of USAF pilots flew a simulated KC-135 using four different cueing systems. The most basic of these systems was of the instrument-only type. Visual scene simulation and/or motion simulation was added to produce the other systems. Learning curves, mean performance, and subjective data are examined. These data show that the addition of visual cueing results in significant improvement in pilot performance, but the combined use of visual and motion cueing results in far better performance.

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