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Effect of Lead-Aircraft Ground-Speed Quantization on Self-Spacing Performance Using a Cockpit Display of Traffic Information

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SUMMARY

A simulator investigation was conducted to determine the effect of the lead-aircraft ground-speed quantization level on self-spacing performance using a Cockpit Display of Traffic Information (CDTI). The study utilized the Terminal Configured Vehicle simulator at the Langley Research Center, which represents an advanced aircraft employing cathode-ray tubes for the primary flight and navigation displays and highly augmented flight control modes.

The pilot's task was to follow a lead aircraft which was performing an idle-thrust profile descent to an instrument landing system (ILS) approach and landing. The spacing requirement was specified in terms of both a minimum distance and a time interval by using a combined constant-distance—constant-time-predictor spacing cue. The four ground-speed quantization levels explored were 1, 5, 10, and 20 knots.

The results indicate that the ground-speed quantization level, lead-aircraft scenario, and pilot technique had a significant effect on self-spacing performance. Specifically, there was a tendency for the following aircraft (ownship) to be closer to the lead aircraft for large ground-speed quantization increments, particularly during the latter stages of the approach. In addition, the deceleration characteristics of the lead aircraft had a first-order effect on self-spacing performance, and variations in pilot technique were readily discernible.

INTRODUCTION

A Cockpit Display of Traffic Information (CDTI) has been proposed for numerous applications (see, e.g., ref. 1), ranging from its use as a device to simply monitor the surrounding traffic situation to a display which would permit tactical-type operations to be performed, such as merging and spacing. One of the most obvious applications of CDTI is the in-trail following operation in which the CDTI-equipped aircraft (referred to as ownship hereinafter) follows a lead aircraft making an approach to landing. The projected benefits in runway throughput are based on the assumption that CDTI self-spacing would result in a lower interarrival-time dispersion at the runway threshold than can presently be achieved with ground-controlled spacing techniques. This, in turn, would permit a reduction in the mean spacing required and, hence, an improvement in runway throughput. (See ref. 2.)

The first series of studies directed toward obtaining quantitative data on in-trail self-spacing performance known to the author was done at the Massachusetts Institute of Technology in the 1970-1975 time period. (See ref. 3.) Recently, the National Aeronautics and Space Administration (NASA) has begun a series of experiments to explore the effect of various parameters on self-spacing performance. (See, e.g., refs. 4 and 5.) The primary parameter chosen for the present experiment was the quantization level (resolution) of the ground speed of the target displayed to the pilot.

The experiment utilized the Terminal Configured Vehicle (TCV) fixed-base simulator at the Langley Research Center, which represents an advanced aircraft cockpit configuration similar to the fourth-generation jets presently entering the market. The simulator incorporates cathode-ray tube (CRT) primary flight and navigation

displays. The navigation display was modified to include traffic information for the purpose of this study. The pilot's task was to self-space on a lead aircraft which was performing an idle-thrust profile descent to an instrument landing system (ILS) approach and landing to runway 35R (right) at Stapleton International Airport, Denver, Colorado. The pilot's spacing requirement was specified in terms of both a minimum distance and a time interval based on a combined constant-distance—constant-time-predictor spacing cue. Two separate test series were conducted using different test matrices, and these will be referred to as the phase I and phase II test series in this report. The test program (both phases) required 100 approaches.

The primary performance measure used for the data analysis was the interarrival time (IAT) at specific points, called "gates," along the approach path. The IAT was simply the difference between the time when the lead aircraft passed the gate and when ownship passed the gate.

SYMBOLS AND ABBREVIATIONS

AGCS	Advanced Guidance and Control System
ALT ENG	altitude engage
ANOVA	analysis of variance
ATC	Air Traffic Control
ATCAC	Air Traffic Control Advisory Committee
ATT CWS	attitude control wheel steering
CAS ENG	calibrated airspeed engage
CD	constant distance
CDTI	Cockpit Display of Traffic Information
CRT	cathode-ray tube
CTP	constant time predictor
FPA SEL	flight-path angle select
GS	ground speed
IAT	interarrival time
ILS	instrument landing system
IXX	unaided inertial-navigation mode
MAG	magnetic
MSL	mean sea level
NASA	National Aeronautics and Space Administration

RAD	radius
s	Laplacian operator
SEL/CAS	calibrated-airspeed mode selected
STAR	standard terminal arrival route
TCV	Terminal Configured Vehicle
TKA SEL	track angle select
V_L	ground speed of lead aircraft, knots
V_O	ideal ground speed of ownship, knots
VEL CWS	velocity control wheel steering
X,Y	aircraft displacement in runway-reference coordinate frame, n.mi.
τ	time constant, sec

SIMULATION FACILITY

Cockpit

The tests were conducted using the Terminal Configured Vehicle (TCV) fixed-base simulator at the Langley Research Center. This facility is configured to support the NASA TCV Boeing 737 research aircraft described in reference 6. The simulator cockpit shown in figure 1 is a replica of the aft flight deck installed on the research aircraft. This cockpit is connected to a digital-computer complex programmed to provide a full range of control and display options similar to those available on the aircraft. The computer program is a six-degree-of-freedom simulation which includes nonlinear aerodynamic data, realistic engine dynamics, and a flight-control-system model incorporating nonlinear actuators, hysteresis, dead bands, and so forth. The tests were conducted under simulated calm wind conditions and in smooth air (i.e., no turbulence). Density-altitude effects were included in the simulation. The cockpit is equipped with panel-mounted controllers which take the place of the conventional wheel and column. The controllers are located so as to provide an unobstructed view of the CRT displays mounted on the pilot's and copilot's panels. Conventional rudder pedals are installed, but they are not used with the advanced control modes.

Controls for the landing gear, flaps, and speed brakes are provided along with status indicators for the landing gear and flaps. The speed-brake position is derived from the position of the speed-brake handle.

Control Modes

The tests were conducted by using velocity control wheel steering (VEL CWS) modes in both the horizontal and vertical planes. These modes provide track-angle and flight-path-angle hold in nonmaneuvering flight. The pilot can change his flight-path angle or track angle by pitch and roll inputs, respectively, through the panel-mounted controllers. Detailed descriptions of the velocity control wheel

steering modes are given in references 7 and 8 for the lateral and the longitudinal degrees of freedom, respectively.

The two speed-control options available to the pilot were manual throttles and the calibrated airspeed engage (CAS ENG) mode. The manual-throttle mode is a standard nonautomatic mode. The CAS ENG is an automatic mode which drives the throttles to capture and maintain a reference airspeed. The reference speed is selected by using a knob on the Advanced Guidance and Control System (AGCS) control-mode panel shown in figure 2.

Displays

The pilot's and copilot's instrument panels each contained three CRT's. The upper CRT on each side presented vertical situation and predictive information by using the improved format reported in reference 8. The middle CRT on each side, the CDTI, presented horizontal-situation and predictive information and a proximate aircraft (the lead aircraft) on a 7 1/2-in. (high) by 5 1/2-in. (wide) display. The lower CRT, a navigation-control and display unit, was not used during the present experiment. Airspeed, altitude, vertical speed, and engine status were displayed on conventional dial-type instruments.

CDTI DESCRIPTION

Symbology

The CDTI-display format used for this investigation is shown in figure 3. This format incorporates the essential features of the standard TCV navigation display, and it includes traffic information as well. It is a track-up display with both a digital readout and a moving-tape indication of the current magnetic track angle. A fixed-reference mark is provided for the moving tape.

The nominal flight path is displayed by a dashed line and star-shaped waypoint symbols. Tags can be selected by the pilot from a display control panel mounted on the center console forward of the throttles. These tags give the waypoint identification, the nominal crossing airspeed in knots, and the minimum crossing altitude in feet.

Six different map scales, 1, 2, 4, 8, 16, and 32 n.mi./in., can be selected by the pilot. The current map scale is indicated by an alphanumeric tag in the lower-left corner of the display. Other readouts include the flight control mode selected (SEL/CAS for the calibrated-airspeed engage mode), the ownship ground speed (GS) in knots, the navigation mode (IXX indicating an unaided inertial-navigation mode), and a readout showing the range (RAD for radius) of a tick mark displayed on a trend vector in front of ownship (3 n.mi. for these tests).

Ownship (the following aircraft) is represented by a chevron-shaped symbol fixed in the center of the screen laterally and 5 in. from the top of the screen vertically (which is two-thirds of the total display height). The reference point for the ownship symbol is the apex of the chevron. The chevron symbol was selected based on the results presented in reference 9.

A time-based predictor vector, composed of three segments, indicates the location where ownship is projected to be in 30-, 60-, and 90-sec segments. The gaps between segments are 6 sec in length, and the vector curves are shown in figure 4 as a function of the aircraft turning radius. Only the 30- and 60-sec segments are displayed on the 1-n.mi./in. map scale; all three segments are displayed on the remaining map scales.

A tick mark is displayed perpendicular to the time vector 3 miles ahead of the aircraft. When the aircraft is turning so that the trend vector is curved, the 3-mile tick is positioned to represent the path length (circular-arc distance) as opposed to a radial distance ahead of ownship.

The "traffic" (lead aircraft) is represented by a triangular-shaped symbol with the apex as the reference point. The angular orientation of the triangle reflects the current track angle of the aircraft. A tag, showing the lead-aircraft ground speed in knots, is displayed adjacent to the triangle. The tag maintains an upright orientation when the triangle rotates.

Operational Aspects

The trend vector of ownship, the track-angle displays, the map translation, and the map rotation were updated 16 times per second, which appears continuous from the pilot's viewpoint. The lead-aircraft position, the ground-speed tag, and the alphanumeric data of ownship (other than the track-angle readouts) were updated only once every 4 sec. As such, the lead aircraft moved in a leapfrog fashion, jumping forward at the 4-sec update and then remaining fixed relative to the map between updates. The display update was synchronized with the traffic-position-data update so as to minimize the transport lag between the time at which new traffic-position data were "received" and the time at which the data were displayed to the pilot. In a worst-case situation, this lag was equal to two real-time computer iterations, or 0.0625 sec. For all practical purposes, therefore, the CDTI accurately displayed the position of the lead aircraft once every 4 sec.

TEST DESCRIPTION

Ground-Speed Quantization

The primary variable in this experiment was the increment in which the lead-aircraft ground speed was displayed on the CDTI. The four levels explored were 1, 5, 10, and 20 knots. However, the actual uncertainty between the lead-aircraft true ground speed and that indicated by the tag is only one-half this value. The reason for this is as follows: if, for example, the quantization level were 20 knots, the traffic ground-speed tag would display values such as 220, 240, 260, and 280 knots. If the traffic actual ground speed were, for example, 249.9 knots, the tag would indicate 240 knots, approximately 10 knots low. If, on the other hand, the actual ground speed were 250 knots, the tag would indicate 260 knots, or 10 knots too high. At most, therefore, the indicated ground speed of the lead aircraft would be only 10 knots in error. It is important to note that the ground-speed quantization of ownship remained fixed at 1 knot during the entire experiment.

Test Subjects

Four NASA test pilots were used as subjects for this experiment. All four were familiar with the TCV configuration and its operating characteristics. In addition, three of the four pilots had participated in a previous CDTI study conducted in the TCV simulator. (See ref. 4.) All four test subjects had also participated in another CDTI study (ref. 5) using a conventional-cockpit aircraft simulator. Since all pilots were familiar with the CDTI concept and also the TCV simulator, familiarization runs as such were not conducted.

The tests assumed a two-man crew type of operation wherein the second crewman, the first officer, would handle radio communications, aircraft-systems monitoring, and so forth. It was also assumed that the first officer would monitor his CDTI for traffic and, hence, the captain could select a map scale predicated solely on the self-spacing task.

The same first officer was used for all test subjects and performed essentially the same duties. Besides the radio communications and system tasks, the first officer actuated the landing gear and flap controls on command of the captain.

Standard Terminal Arrival Route

The scenarios used in this experiment employed a hypothetical profile descent to runway 35R at Stapleton International Airport, Denver, Colorado. The profile descent was defined by the standard terminal arrival route (STAR) as shown in figure 5. The segment from the KEANN intersection to the FLOTS intersection was based on previously published, profile-descent procedures for Denver. The segments from FLOTS to GANDR (the outer marker) were based on vectoring practices by Denver approach controllers. The STAR terminated with an ILS approach to 35R.

The speeds shown adjacent to the waypoints are indicated airspeeds in knots. They represent the desired nominal speeds at the waypoints. The altitudes, on the other hand, represent the minimum allowable crossing altitude, in feet, at the waypoint.

Lead-Aircraft Scenarios

In order to generate traffic data (and become familiar with the STAR), each test subject flew a minimum of two profile-descent approaches without a lead aircraft. One of these approaches started at the FLOTS intersection, whereas the other started on a downwind leg 10 n.mi. from the LOOOT waypoint. The approaches were recorded at a sample rate of one every 4 sec and were used as lead aircraft during the subsequent testing. All in all, there were eight different scenarios created, four pilots' flying approaches from each of two initial conditions.

All eight approach tracks were similar, but far from identical, as shown in figure 6. This figure is a composite plot showing all the tracks in the horizontal plane. The primary difference between scenarios stemmed from the variation in the speed profiles flown by the pilots as shown in figure 7 for the phase I test series. Figure 7(a) is a composite plot of all eight scenarios showing the lead-aircraft ground speed as a function of time to go to the runway threshold (time to threshold), whereas figure 7(b) is a plot of the lead-aircraft ground speed as a function of distance to go to the runway threshold (distance to threshold). As indicated by the

figures, there is quite a variation in when (or where) a specific ground speed occurs during the approach. In general, each pilot flew essentially the same type of profile (i.e., fast or slow) during his two approaches. The spread in the ground-speed profiles was due primarily to variations in pilot technique as opposed to repeatability by a given pilot.

Task

The pilot's primary task in this experiment was to maintain separation from a lead aircraft executing a profile descent to runway 35R at Denver. In the first series of tests (i.e., phase I of the investigation), two subtasks were employed. The first involved rendezvousing with a lead aircraft from an in-trail position. The initial condition of the traffic was at the FLOTS intersection as shown in figure 8. Ownship was 7 n.mi. from FLOTS, on course at 17 200-ft altitude, and trimmed for an idle-thrust descent in the clean configuration. The second subtask involved merging in behind an aircraft that was approaching the LOOOT waypoint from the north as shown in figure 9. The initial condition of the traffic was 10 n.mi. from LOOOT at a 16 000-ft altitude and 250-knot indicated airspeed. The initial conditions of ownship were the same as in the in-trail subtask.

The pilot was instructed to establish a 60-sec interval behind the lead aircraft by the time that ownship crossed the DW35R waypoint. This applied to both the merge and in-trail subtasks. The pilot was also instructed to maintain this interval, but keep at least a 3-n.mi. separation from the lead aircraft. The 3-n.mi. requirement took precedence over the 60-sec requirement and, hence, the pilot had to make a transition from time spacing to distance spacing during the approach. This transition typically occurred in the vicinity of the base-to-final turn where ownship was decelerating through a 180-knot ground speed.

Additional instructions given to the pilot dealt with speed and path restrictions during the approach. The complete set of pilot instructions are given in table I.

The second test series (phase II of the investigation) was directed toward separating the lead-aircraft deceleration-profile effect from the ground-speed quantization-level effect. The task used in phase II of this investigation, therefore, did not include the rendezvous or merging subtasks. In phase II, the initial position of the lead aircraft was at DW35R, and ownship was approximately 66 sec (about 5.5 n.mi.) behind it. The initial conditions were selected to yield interarrival times at DW35R similar to those achieved during the phase I tests.

Test Matrix

Phase I.- The first series of tests (phase I) used an experimental design based on three factors: ground-speed quantization, pilots, and subtask. These factors included four ground-speed quantization levels (1, 5, 10, and 20 knots), four test subjects, and two subtasks (merge and in-trail). In addition, the entire test sequence was replicated. This arrangement required a total of 64 test runs (4 resolutions × 4 pilots × 2 tasks × 2 replications). Each test subject was given two simulation sessions. During the first session, the pilot flew a sequence of four merge and four in-trail subtasks. The ground-speed quantization level was varied for each run in a preselected pattern as shown in table II. The second simulation session was similar to the first, except that the ground-speed quantization pattern was

altered. The pairing of ground-speed quantization levels and lead-aircraft scenarios in the test matrix assumed that variations between scenarios would not have a significant effect on the results. Preliminary analysis of the phase I data indicated that this was a highly questionable assumption; the individual scenarios did, in fact, appear to have a significant effect on the results.

Phase II.- The second series of tests (phase II) was structured to gain additional data on the scenario effect indicated by the phase I data. The test matrix employed a full factorial design using ground-speed quantization level, pilots, and lead-aircraft scenarios as factors. The factor levels included three ground-speed quantization levels (5, 10, and 20 knots), four test subjects, and three scenarios. The test sequence was not replicated; therefore, only 36 approaches were required. The approaches were made in nine run blocks (approaches), one for each pilot, and were accomplished during a single simulation session with each test subject using the test matrix shown in table III.

DATA ANALYSIS

Interarrival-Time Computation

The primary self-spacing performance measure used in this investigation was the interarrival time (IAT) between the lead aircraft and ownship at preselected points ("gates") along the approach path. As shown in figure 10, six gates were employed: one at the runway threshold, one at the outer marker, one on the base leg, and three on the downwind leg. The time at which an aircraft crossed a gate was determined by interpolating the recorded data, assuming that the aircraft acceleration was constant over the 4-sec data-sample period. The interarrival time was computed by taking the difference between the time the target crossed a gate and the time that ownship crossed the same gate. An "ideal" interarrival time was also computed by assuming that ownship flew the specific speed profile required to satisfy the spacing criteria.

Statistical Treatment

A three-factor analysis of variance (ANOVA) was carried out on the IAT for each gate. As noted in a previous section, the three factors for phase I were the ground-speed quantization level, the pilot, and the subtask (merge and in-trail). In phase II, the third factor was the lead-aircraft scenarios instead of the merge and in-trail subtasks. In addition to computing the F values for each gate, the grand mean, standard deviation, and effect means of the IAT were also determined.

SPACING CRITERIA

Before discussing the results of the IAT analyses, it is necessary to understand the ramifications of the spacing criteria for constant time predictor/constant distance used in this investigation. By considering the constant time predictor (CTP) criterion first, it can be shown (see ref. 10) that the ideal ground speed of ownship V_O is a function of the lead-aircraft ground speed V_L as given by

$$V_O(s) = \frac{1}{\tau s + 1} V_L(s)$$

where the time constant τ is the prediction interval used. In this study, τ equaled 60 sec, which meant that ownship would arrive at a given point 60 sec after the lead aircraft arrived, providing ownship maintained its current ground speed. In a typical approach, however, the ground speed of the lead aircraft is continually decreasing (even if it is holding constant the indicated airspeed while descending), which forces ownship to decelerate also. Since the 60-sec prediction was based on the ground speed of ownship staying constant, and ownship has slowed down, the IAT will be greater than 60 sec, even for the ideal case (i.e., perfect spacing). Furthermore, there will be a different ideal IAT associated with each lead aircraft at each gate since the speed profile of ownship is a function of the lead-aircraft speed profile.

Although, the CTP criterion generally results in the lead aircraft and ownship having different ground speeds at any instant time, the constant distance (CD) criterion requires that the ground speed of ownship match the lead-aircraft ground speed at all times. That is,

$$V_O(s) = V_L(s)$$

Here again, however, there will be a specific ideal IAT associated with each lead aircraft at each gate.

The transition point between the CTP criterion and the CD criterion is governed solely by the specific time and distance employed. In the present study, the 60-sec (but not less than 3-n.mi.) criterion meant that the transition occurred when the ground speed of ownship reached 180 knots. However, from a practical standpoint, the criteria cannot be satisfied near the transition point because it requires an instantaneous decrease in the ground speed of ownship at that point, since the lead aircraft was invariably slower than ownship. For the scenarios in this study, a change from 14 to 48 knots in the ground speed of ownship at the transition point would be required to keep the criteria satisfied. This phenomenon is illustrated in figure 11, which shows the transition occurring at about 130 sec, where the ideal ground speed of ownship decreases instantaneously by almost 40 knots. The technique developed by the pilots to overcome the spacing-criteria deficiency is covered in the "Results and Discussion" section.

The ideal ground speed of ownship (such as that shown in fig. 11) was obtained by filtering the lead-aircraft ground speed with a 60-sec first-order filter to create the ideal ground speed for the CTP portion of the approach. When this ground speed dropped to 180 knots, the ideal ground speed became equal to the lead-aircraft ground speed. This procedure was applied to each lead aircraft to yield an ideal ground-speed profile for ownship for each scenario. These ideal profiles were utilized to compute the ideal interarrival times referred to in subsequent sections of this report.

RESULTS AND DISCUSSION

Phase I - Tracking Performance

Prior to conducting the analysis of variance on the IAT, the pilot's tracking performance was examined to determine if the path deviations that occurred relative to the lead-aircraft path had any influence on the IAT. (It may be recalled that the pilots were instructed that path deviations were to be used only to prevent violating the minimum spacing criterion.) The analysis utilized approach plots such as the

ones shown in figure 12, a typical in-trail case, and in figure 13, a typical merge case. These figures show the approach tracks of both the lead aircraft and ownship in the horizontal plane. The stars in figure 14 indicate the position of ownship at 2-min intervals, starting at time zero, and the circles represent the position of the lead aircraft at the corresponding times. To avoid clutter, the nominal path has not been shown.

The first step in the analysis was to determine from visual inspection if any obvious path deviations (lateral deviations of 2000 ft or more) had occurred during the base turn and the turn to the final approach leg. Small deviations were not considered significant, since accurate path control was neither necessary nor required during this experiment. Once an obvious path deviation was found, the next step was to check the spacing (IAT) before and after the turn to see what effect the path alteration had on the spacing. Three possibilities could exist: (1) there was no appreciable effect on the spacing, (2) the path alteration helped spacing, and (3) the path alteration hindered spacing.

The results of the analysis are given in the following table:

Effect on spacing	Base turn	Final turn
None	10	7
Helped	8	5
Hindered	4	3
Total	22	15

As seen from the table, there were only 37 obvious path deviations out of 128 turns. Of the 37, only about one-third were found to have helped spacing. The remainder either had no effect on spacing or actually hindered it. It appears, therefore, that the path deviations did not have any appreciable effect on the spacing performance. In addition, there is no indication that the pilots were using path deviations for spacing, even subconsciously.

In addition to conducting the spacing analysis described previously, particular attention was given to the base turn to see if there was any tendency for the pilots to initiate the turn prematurely. Early in the experiment, the pilots commented that between the time the lead aircraft turned onto the base leg and the time that ownship turned onto the base leg, they had no spacing reference. This situation is illustrated in figure 14. All pilots indicated that they had to resist temptation to superimpose the trend vector on the lead aircraft, which would have resulted in turning too soon. An examination of the data indicated that there was no tendency toward early initiation of base turns.

Factors Affecting Phase I Interarrival Times

General.- The results of the analysis of variance (ANOVA) of the IAT from the phase I tests are shown in table IV. As indicated in this table, there is enough evidence at the 0.95 level of significance to believe that all three factors consid-

ered (ground-speed quantization, pilots, and subtask) affect the IAT at two or more gates. In addition, a significant interaction between the subtask and the ground-speed quantization was also indicated, which was completely unexpected and was the initial quantitative clue that the variation between scenarios may have been having a pronounced effect on the results. As described in the following sections, examination of the various effect means provided enough additional evidence of a pairing effect between ground-speed quantization and scenarios that a second test series (phase II) was conducted to separate them.

Effect of ground-speed quantization.- Table IV indicates that ground-speed quantization has a significant effect on the IAT at both gates 1 and 2. Figure 15 is a plot of the effect means for each quantization level at each gate. The ideal values of IAT have been included in figure 15 for comparison purposes.

As seen from figure 15, there was a general tendency for the separation to be greater (i.e., the measured IAT was greater than the ideal IAT) than that specified by the criterion. The data also indicate that the separation was generally greater at finer ground-speed quantization levels, and it became even more so as the approach progressed. A clear understanding of what was taking place was difficult to obtain because the ideal values of IAT were considerably different for the fine (1 and 5 knots) and coarse (10 and 20 knots) quantization levels.

An assessment of the scenario characteristics revealed, with one exception, that the lead aircraft paired with the 10- and 20-knot quantization levels decelerated to final approach speed sooner than the four lead aircraft paired with the 1- and 5-knot quantization levels. This characteristic of the scenarios accounts for the tendency of the ideal IAT to be less for fine quantization levels than for coarse ones. In order to determine what effect this pairing had on the experimental IAT, a second set of approaches were flown by using a full factorial ANOVA design. The results of these tests are reported subsequently under phase II of this study.

Pilot effect.- The pilot effect on the IAT was found to be significant at gates 3 and 6. Figure 16 is a plot of the mean IAT achieved by each pilot at each gate. The ideal mean IAT values are also shown, and in this case they are the same for each pilot since they are averaged across quantization levels and subtasks.

It is readily apparent that pilot 4 simply takes more time in initially closing up spacing than the other pilots. Although all the pilots tended to maintain greater separation on downwind (gates 4, 5, and 6) than specified by the criterion, the separation for pilot 4 was even larger still.

Although pilot 4 produced the significant effect at gate 6, pilot 3 was found to be causing the significant effect at gate 3 (base leg). Ironically, the mean IAT of pilot 3 is closer to the ideal mean at gate 3 than that of any of the other pilots. Trying to satisfy the criterion at gate 3, however, appears to carry over to gate 2 (final approach), where the mean IAT for pilot 3 is seen to be less than the ideal mean IAT.

As a general rule, the pilots tended to maintain a larger separation on the lead aircraft than that specified by the spacing criteria. In addition, they tended to "hang back" in the transition region (between the CTP and CD criteria) so as not to end up too close on final approach. If a pilot were caught inside the 3-n.mi. limit on final approach, it was virtually impossible to increase the separation from the lead aircraft. Despite all their caution, however, it is interesting to note that

none of the pilots achieved a mean IAT greater than the ideal at the runway threshold (gate 1).

Subtask effect.- Rendezvous and merging subtasks were included in the phase I test series to explore the effect of two distinct initial conditions on the IAT. The expectation was that the transients associated with the two subtasks would subside somewhere past the merge-rendezvous point (gate 6), after which both subtasks would be identical. It was anticipated, therefore, that if any significant effects occurred, they would occur at the beginning of the approach (gate 6) and eventually disappear. Based on the ANOVA, however, the subtask effect was found to be significant (at the 95-percent level) not only at gates 6 and 5 but also at gates 3 and 2. This turned out to be caused by two independent factors as explained subsequently.

Figure 17 shows the experimental and ideal subtask effect means at each gate. The large difference in the experimental mean IAT between the in-trail subtask and the merge subtask at gate 6 was attributed to the initial conditions employed in the simulation. On the average, ownship was effectively about 9 sec closer to the lead aircraft in the merge case than in the in-trail case at the start of the run. As indicated by figure 17, when ownship reached gate 6, this discrepancy had been reduced to about 6 sec.

The difference between the in-trail and merge ideal mean IAT (most obvious for gates 2 and 3) is a direct result of the difference in lead-aircraft scenarios. Since the experimental IAT follows the same trend as the ideal IAT for gates 5 through 2, the subtask effect shown by the ANOVA is more than likely due to the particular pairing of subtask and lead aircraft used in the phase I tests. (This hypothesis was verified by the phase II tests.) It should be noted that the difference in the experimental IAT at gate 1 was not statistically significant and was attributed to a carry-over effect from gate 2.

Self-Spacing Performance for Phase I Test Series

The self-spacing performance achieved during the initial test series is indicated in figure 18. This figure presents the mean and standard deviation of both the ideal and experimental IAT at each gate for all the approaches of phase I. The ideal IAT at the runway threshold (gate 1) assumes that ownship flies the approach at 122-knots indicated airspeed and is exactly 3 n.mi. behind each lead aircraft when it crosses the threshold; hence, the standard deviation equals zero. At all other gates, the standard deviation of the ideal IAT provides a direct indication of the variation in lead-aircraft profiles. In addition, the square root of the difference between the squares of the experimental and ideal standard deviations is equal to the standard deviation of the IAT error. Implicit in this relationship is the fact that perfect following would yield an experimental IAT standard deviation equal to the ideal IAT standard deviation.

Figure 18 indicates that, overall, the pilots kept a greater separation on the downwind leg (gates 4 to 6) than specified. This also applies to the base leg (gate 3) where, as noted in a previous section, the pilots intentionally increased their spacing interval to prevent getting "trapped" inside 3 n.mi. at the spacing-criteria transition point. Nonetheless, the IAT at gate 1 indicates that the mean separation was less than 3 n.mi. when the lead aircraft crossed the threshold. An examination of the separation data at gate 1 yielded a computed mean and standard deviation for the 64 approaches of 2.95 n.mi. and 0.31 n.mi., respectively. It is interesting to note that, even though explicit instructions were given to maintain a

minimum separation of 3 n.mi., the pilots let their separation get within 3 n.mi. on 38 of the 64 approaches flown. One possible explanation for this anomaly is that the 60-sec time constant tended to lead the pilots into a smaller separation. In retrospect, the CTP and CD criteria should have been matched so that a nominal approach would not require a switchover to the CD criterion. In the present tests, a time constant of about 83 sec should have been employed to keep the separation interval at 3 n.mi. or more.

Factors Affecting Phase II Interarrival Times

General.- The phase II test matrix (table III) was a full factorial design using three ground-speed quantization levels (5, 10, and 20 knots), the same four test subjects as phase I, and three of the eight lead-aircraft scenarios from phase I. The lead-aircraft scenarios selected for phase II are shown in figure 19 and represent the spectrum of scenarios employed in the phase I tests. Figures 19(a) and 19(b) are plots of the lead-aircraft ground speed as a function of time to go to the runway threshold (time to threshold) and distance to go to the runway threshold (distance to threshold), respectively. It can be seen for case 1 that the pilot of the lead aircraft flies a much faster approach, in general, and does not reach his final approach speed until he is fairly close in. On the other end of the spectrum, the pilot in case 3 decelerated rapidly and reached final approach speed almost 2 min earlier than in case 1. In terms of distance, the lead aircraft in case 1 crosses the outer marker at about 170 knots, whereas the aircraft in case 3 reaches the final approach speed of 135 knots (about 122 knots indicated airspeed) more than 2 miles outside the outer marker. The third case falls between the two previous extremes described and represents, roughly, four of the eight scenarios used in the phase I tests. It is characterized by a more continuous gradual deceleration, wherein the final approach speed is reached just as the aircraft crosses the outer marker.

The results of the analysis of variance of the IAT obtained during the phase II data runs are shown in table V. As indicated by this table, all three factors (ground-speed quantization level, pilots, and scenarios) appear to have a statistically significant effect (at the 0.95 level) on the IAT at two or more gates. This is essentially the same result that was obtained in phase I, except that the significant effects do not necessarily occur at the same gates. The ANOVA also suggests that there are interactions between the quantization level and the scenarios, and also between the pilots and the scenarios. As done previously with the phase I data, the significant effects were analyzed with the aid of plots of the effect means.

Effect of ground-speed quantization.- Figure 20 is a plot of the mean IAT for each quantization level at each gate. Also included in the plot are the effect means from the phase I data at the 5-, 10-, and 20-knot quantization levels and the ideal mean IAT for the phase II tests. It is apparent that the phase II results exhibit the same trends as the previous data. It is also apparent that the pilots maintained greater separation from the lead aircraft during the phase II tests than they did during the phase I tests. This probably results from their phase I experience where they were frequently caught inside the minimum-separation criterion of 3 n.mi. It can be seen that, on the average, they adhered to the minimum-spacing criterion of 3 n.mi. during the phase II tests.

An examination of the quantization-level—scenario interaction (the AC interaction as shown in table V) revealed that the phase II quantization-level results were dominated by scenario case 1 as illustrated in figure 21. In other words, if case 1

were not included in the test matrix, neither the quantization-level effect nor the AC interaction would have been significant.

The interaction analysis indicated that the mean IAT associated with the 5-knot quantization level and scenario case 1 was much larger at gates 1 and 2 than the mean IAT associated with all other combinations of quantization levels and scenarios. It appears that, in general, although the pilot can detect when the lead aircraft starts decelerating sooner with fine quantization levels than with coarse ones, the pilot has no way of knowing at this point in time whether the lead aircraft will be flying a fast or slow approach. Consequently, the pilot initiates a nominal deceleration and delays adjusting his profile until he has a clearer understanding of what the lead aircraft is doing. Basically, therefore, the IAT tends to reflect the lead-aircraft profile more than the followers' activities during the early stages of the deceleration. This effect is most conspicuous for the 5-knot quantization level and scenario case 1 where the pilot of ownship detects the lead-aircraft deceleration sooner than with the coarse quantization levels but does not realize that the lead aircraft will be flying a fast approach. The pilot initiates his own deceleration and the lead aircraft simply moves away from ownship, which results in increased spacing and greater IAT. By the time the pilot in ownship recognizes that this lead aircraft is flying a very fast approach, there is little he can do to effect the IAT without making a major alteration to his own profile. Since the pilots elected not to make such a change (that is, not to catch up with the lead aircraft on final approach), the IAT associated with the combination of the 5-knot quantization level and scenario case 1 became progressively larger at each successive gate down the approach and, finally, the interaction became significant at gate 1.

In retrospect, this same hypothesis holds for the results of the phase I tests. Both of the lead aircraft which were paired with the 5-knot quantization level (it may be recalled that phase I was not a full factorial experiment design) flew fast final approaches. In fact, one of the lead aircraft was the scenario case 1 for phase II.

The overall conclusion of this analysis is that the ground-speed quantization level had a significant effect on IAT when the lead aircraft flew a much faster final approach than was typically flown. When the lead-aircraft speed profile was nominal, ground-speed quantization had no significant effect.

Pilot effect.- The mean IAT from phase II for each pilot at each gate is shown in figure 22. Also shown in this figure are the mean IAT for each pilot from the phase I approaches and the ideal mean IAT for the phase II scenarios.

The similarity between the two sets of data is immediately obvious. This is considered to be quite "significant," since the two simulation periods were approximately 4 months apart. The similarity in the two sets of data implies that the pilots have adopted a particular self-spacing technique with which they can achieve repeatable results. As in the phase I tests, pilot 3 tends to be much closer to the lead aircraft when crossing gate 3 than the other pilots.

The same carry-over effect from gate 3 exists at gate 2 as it did during phase I. The mean IAT for pilot 3 is very close to the ideal mean IAT at the runway threshold (gate 1), whereas the other pilots average 3 to 5 sec late (although the differences are not statistically significant).

An examination of the pilot-scenario interaction (the BC interaction) revealed that, as in the AC interaction, scenario case 1 dominated the results. The effect

means showed a large variation in the IAT between the pilots for scenario case 1 compared with cases 2 and 3. The two test subjects with the least experience in the simulator had much larger spacing errors at gate 2 than those of the other two subjects when following the lead aircraft used in scenario case 1. For the other two scenarios, the spread in IAT between pilots was much smaller and there was no apparent trend with regard to test subject.

Scenario effect.- It may be recalled that the original test series (phase I) was based on the assumption that variations between scenarios (i.e., lead-aircraft characteristics) would not have a significant effect on the results. The results of the phase I tests, however, indicated that this assumption was probably false. The phase II tests were, therefore, conducted to check the assumption and, if false, to determine what effect the individual scenarios were having on the IAT.

Figure 23 presents the mean IAT obtained with each scenario at each gate during the phase II tests. Also shown is the ideal IAT associated with each scenario. As seen from figure 23, the ideal IAT for case 1 is considerably less than the other two cases at both gates 3 and 2. This is a direct result of the deceleration profile associated with scenario case 1. All test subjects recognized that this aircraft was flying a fast approach, but they elected not to catch up with it on final approach. The effect on the experimental mean IAT due to the scenarios is significant at gate 3 where the pilots are initially maintaining position on the lead aircraft, and scenario case 1 is dominating the result. However, the IAT is not significantly different at the outer marker (gate 2) where the pilots have ceased to chase the lead aircraft and are, instead, setting up their own approaches. The IAT is significantly different at the threshold (gate 1) because of the lead aircraft in case 1 which flies a fast final approach (8 to 10 sec faster than the other two cases) and simply moves away from ownship and creates a significantly larger IAT.

Figure 23 provides another view of the pilot's tendency to employ excess separation. It is interesting to note that the IAT error at gate 4 is on the order of 6 sec, which is the same value as that used for the initial condition on each run. Typically, ownship crossed gate 4 at 2 1/4 min into the run during phase II, which provided ample time for the pilot to close up on the lead aircraft. An examination of the data, however, indicates that the pilots generally took action to slow down faster. On 32 of the 36 approaches flown, the pilots added drag in some form prior to crossing gate 4; two pilots used the speed brakes, and the remaining two pilots used the speed brakes and/or the landing gear.

Overall Spacing Performance

The overall spacing performance achieved during these tests is shown in figure 24. This figure presents the grand mean and standard deviation for all 100 runs of the experiment at the outer marker (gate 2) and the runway threshold (gate 1). As indicated, the performance at the runway threshold is slightly more consistent than at the outer marker. The mean interarrival time at the runway threshold for all 100 approaches flown during the experiment was 82.2 sec. The ideal mean interarrival time was 82.4 sec.

These results must be qualified, of course, primarily by the fact that they were obtained in a part-task simulator (in a calm-air environment) and involved only lead aircraft of the same type as ownship. By keeping these qualifications in mind, the following comparisons can be made. The standard deviation at the runway threshold of 8.1 sec achieved during these tests is about 50 percent better than the standard

deviation of 18 sec used to represent the current ATC manual control system in reference 2. The standard deviation of 8.1 sec is also somewhat better than the automated metering and spacing standard deviation of 11.1 sec reported in reference 3. It does not, however, meet the ATCAC goal of 5 sec suggested in reference 11 or the standard deviation achieved with four-dimensional concepts using continuous closed-loop speed control, which has been reported to be about 2 sec. (See refs. 3 and 12.)

Pilot Comments

Pilot comments were obtained following each simulation session relative to the effect of ground-speed quantization on their ability to self-space. Although the comments were obtained independently, all pilots stated essentially the same opinion. They all indicated that the 20-knot quantization level was a little too coarse, and it required guessing on their part to determine what the lead aircraft was doing. On the other hand, the 10-knot quantization level appeared to be satisfactory to all pilots.

All pilots indicated that the 1- and 5-knot quantization levels were better than those required to perform the task. One pilot stated that the 1-knot quantization level improved his confidence in evaluating the lead-aircraft deceleration maneuvers. This idea was echoed by another pilot, who stated that his performance probably did not change in going from 1- to 20-knot quantization, but his awareness of what was going on did change. He felt he could perform a more aggressive capture (in-trial rendezvous) by knowing the lead-aircraft speed to within 1 knot. Additional pilot comments indicated that 30 knots was about the maximum, comfortable overtake speed; anything higher than that was hard to arrest.

From the pilot's standpoint, it appears that the 10-knot quantization level is satisfactory. The reason finer levels were probably not required stems from the fact that the pilots do not, and cannot, match the lead-aircraft ground speed knot for knot and still satisfy the constant time predictor (CTP) criterion. By referring back to figure 11, it can be seen that during the CTP spacing phase, the ownship ground speed must be between 5 and 40 knots higher than that of the lead aircraft at any instant to satisfy the spacing criteria. As such, the pilots use the lead-aircraft ground speed primarily to detect the lead-aircraft deceleration, and they use the CTP vector as the primary spacing cue.

CONCLUSIONS

A simulation was conducted to determine the effect of the lead-aircraft ground-speed quantization level on self-spacing performance using a Cockpit Display of Traffic Information (CDTI). Based on the results obtained during these tests, the following conclusions are drawn:

1. Ground-speed quantization level had a significant effect on interarrival time only when the lead aircraft flew a fast final approach.

2. There was a tendency for ownship to be closer to the lead aircraft at coarse quantization levels, particularly during the latter stages of the approach.

3. The pilots commented that a 10-knot ground-speed quantization level was satisfactory, but 20 knots was too coarse. However, the spacing performance was not significantly different with either level.

4. The deceleration profile of the lead aircraft had a first-order effect on the spacing performance.

5. The mean interarrival time at the runway threshold for all 100 approaches flown during the experiment was 82.2 sec. The ideal mean interarrival time was 82.4 sec.

6. The standard deviation of the interarrival time at the runway threshold was 8.1 sec.

7. The constant time predictor (CTP) spacing technique had an inherent time error when following a decelerating lead aircraft since ownship must also decelerate to maintain spacing.

8. Differences in pilot techniques were readily discernible in the spacing-performance data.

9. Path alterations which occurred during the approaches had no apparent effect on the results.

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National Aeronautics and Space Administration
Hampton, VA 23665
August 22, 1983

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TABLE I.- PILOT INSTRUCTIONS

1. Establish 1 min (60 sec), in-trial, spacing before crossing DW35R.

2. Maintain 1 min, but not less than 3 n.mi. spacing, from DW35R to touchdown.

3. Adhere to the 250-knot speed limit below 10 000-ft MSL.

4. Path deviations should be used only to prevent violation of the 1-min (3-n.mi.) spacing criterion.

5. VEL CWS should be used in pitch and roll. Throttle control is optional (CAS ENG or MANUAL). Gear, flaps, and speed brakes may be used at your discretion.

6. The spacing task takes precedence over the profile descent airspeeds.

7. The star altitudes are given in terms of "cross at or above" the given waypoint altitude.

TABLE II.- PHASE I TEST MATRIX

Run	Ground-speed quantization level, knots				Subtask
	1	5	10	20	
Session 1					
1	X				In-trail
2			X		In-trail
3		X			In-trail
4				X	In-trail
5		X			Merge
6				X	Merge
7	X				Merge
8			X		Merge
Session 2					
9		X			In-trail
10				X	In-trail
11	X				In-trail
12			X		In-trail
13	X				Merge
14			X		Merge
15		X			Merge
16				X	Merge

TABLE III.- PHASE II TEST MATRIX

Run	Ground-speed quantization level, knots			Scenario case
	5	10	20	
1		X		3
2	X			1
3			X	3
4			X	2
5	X			3
6		X		2
7			X	1
8	X			2
9		X		1

TABLE IV.- FACTORS AFFECTING INTERARRIVAL TIME IN PHASE I TEST SERIES

Factor	Gate[a]					
	1	2	3	4	5	6
A (quantization level)	■	■				
B (pilot)			■			■
C (subtask)		■	■		■	■
AB						
AC	■	■	■			
BC						
ABC						

[a]The symbol ■ indicates 0.95 level of significance.

TABLE V.- FACTORS AFFECTING INTERARRIVAL TIME IN PHASE II TEST SERIES

Factor	Gate[a]			
	1	2	3	4
A (quantization level)	■		■	
B (pilot)		■	■	■
C (scenario)	■		■	
AB				
AC	■			
BC		■		

[a]The symbol ■ indicates 0.95 level of significance.

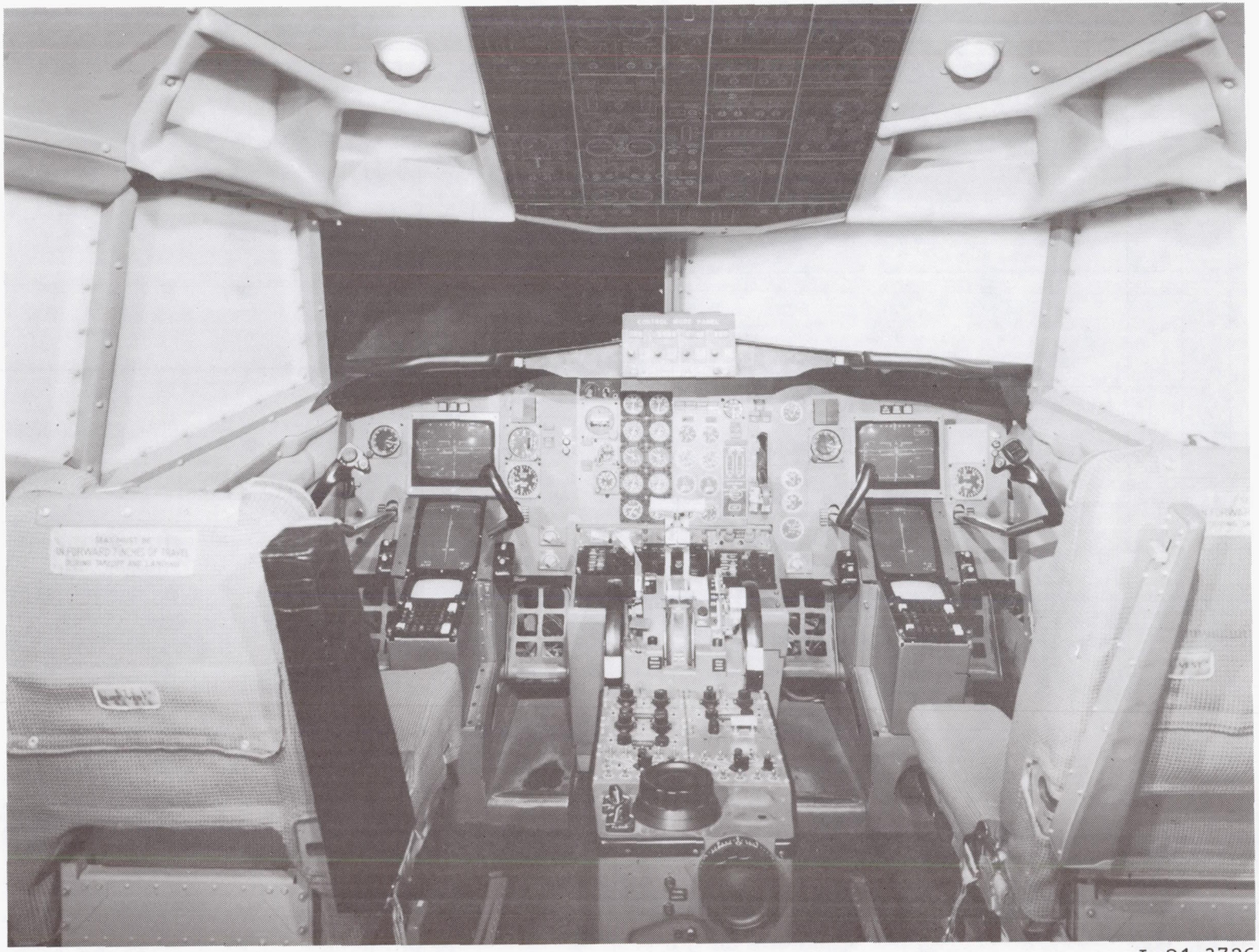

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Figure 1.- TCV simulator cockpit.

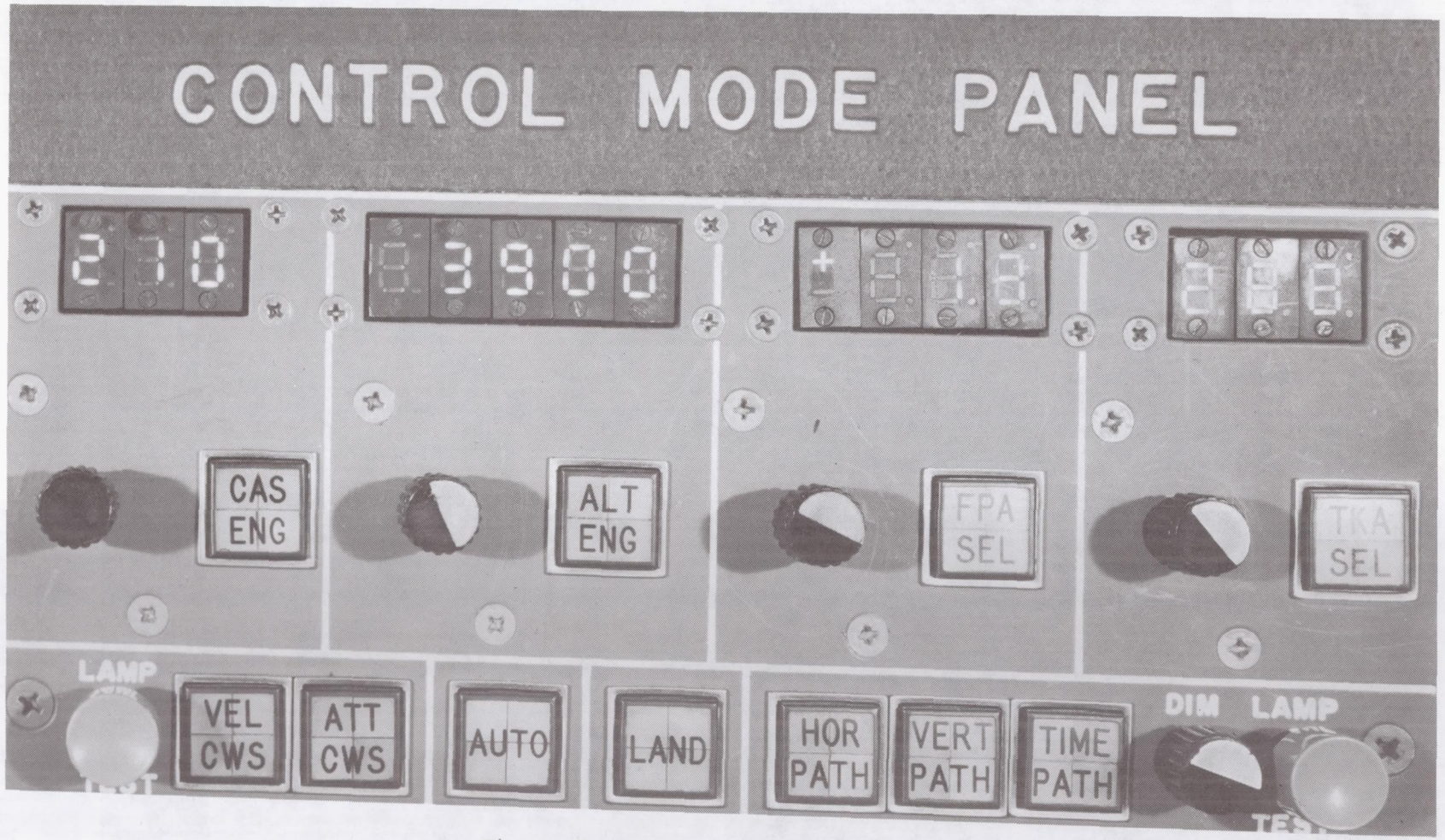

Figure 2.- AGCS control-mode panel.

L-76-4229

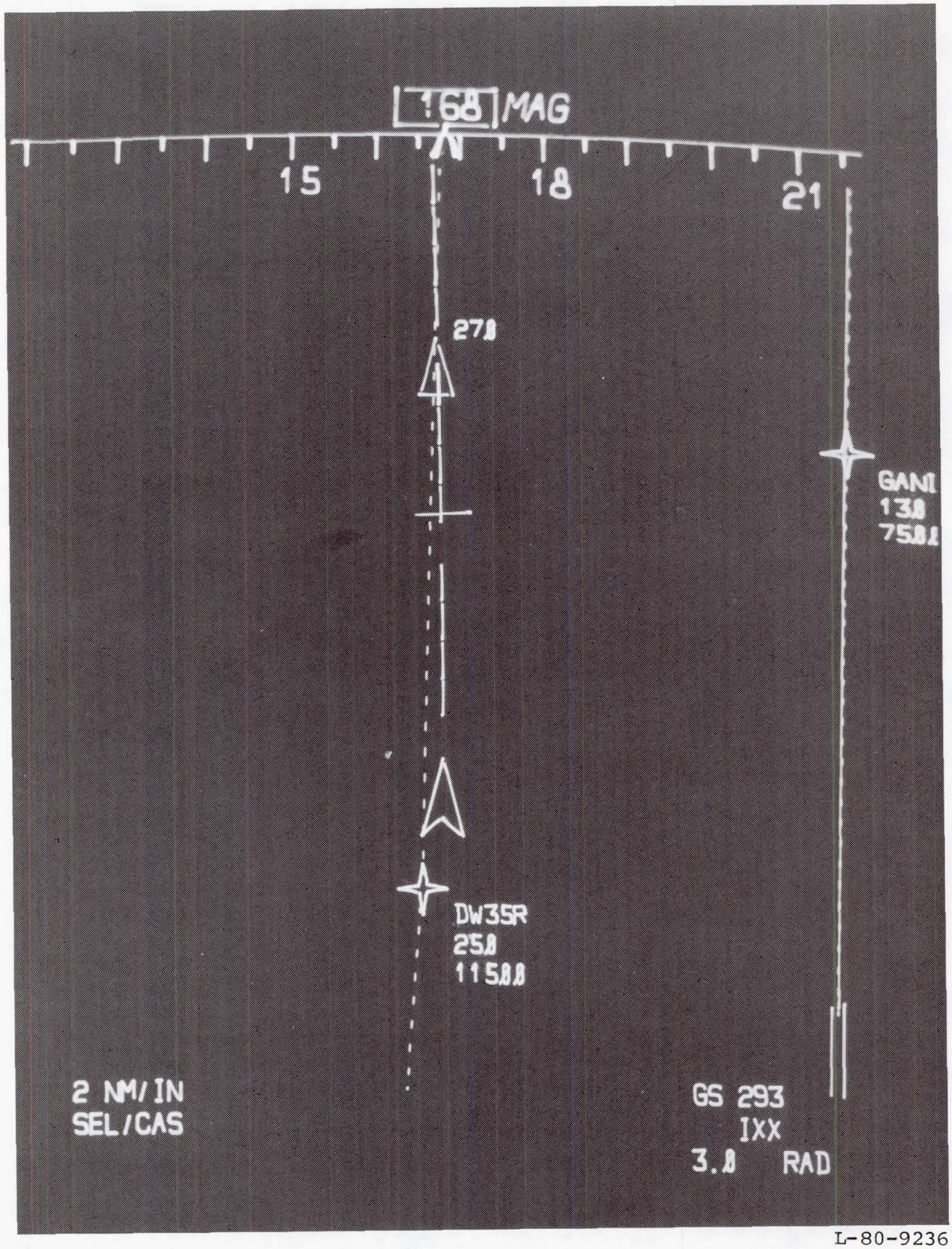

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Figure 3.- CDTI with waypoint tags selected.

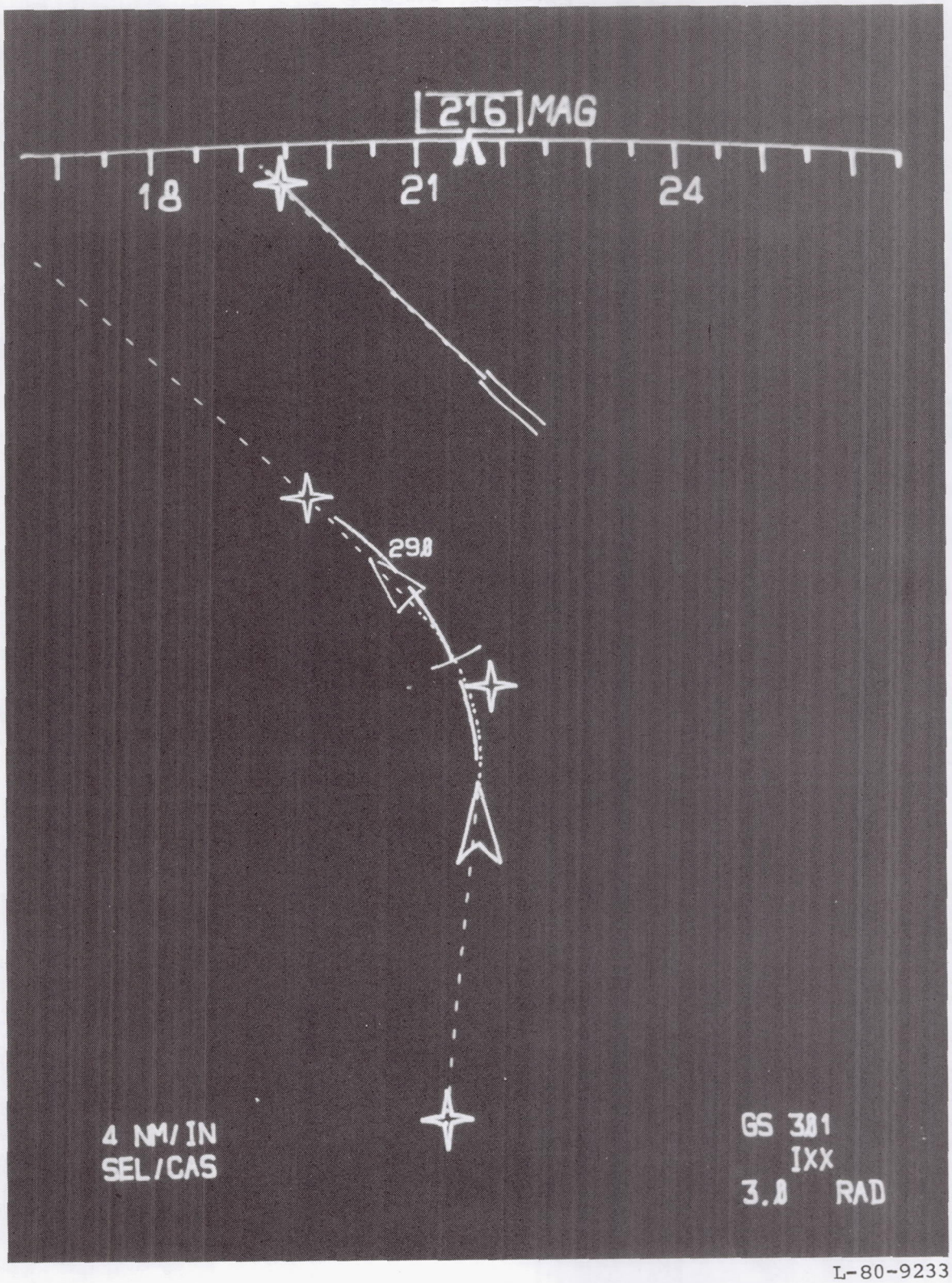

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Figure 4.- CDTI display format during a turn.

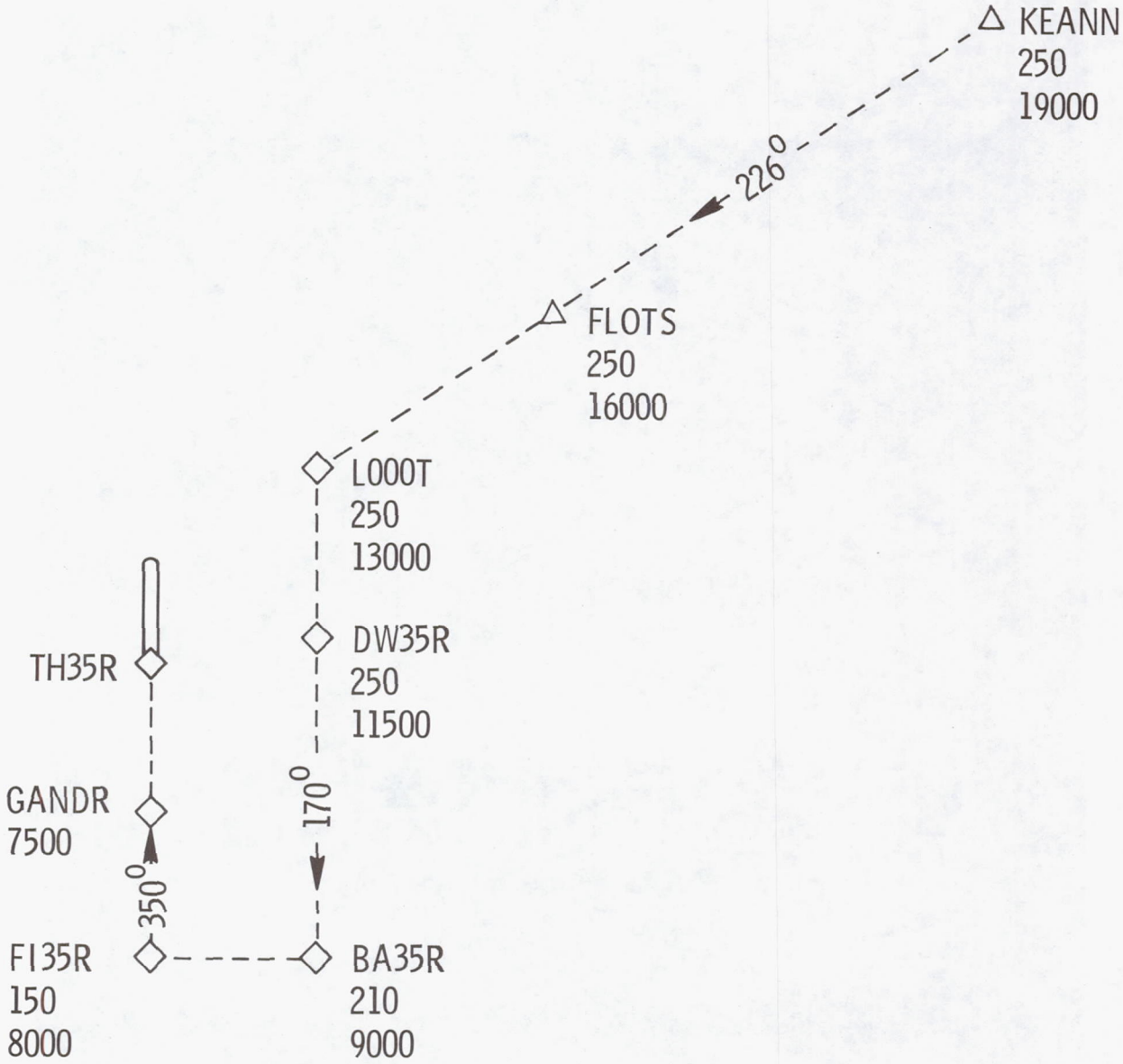


Figure 5.- STAR geometry.

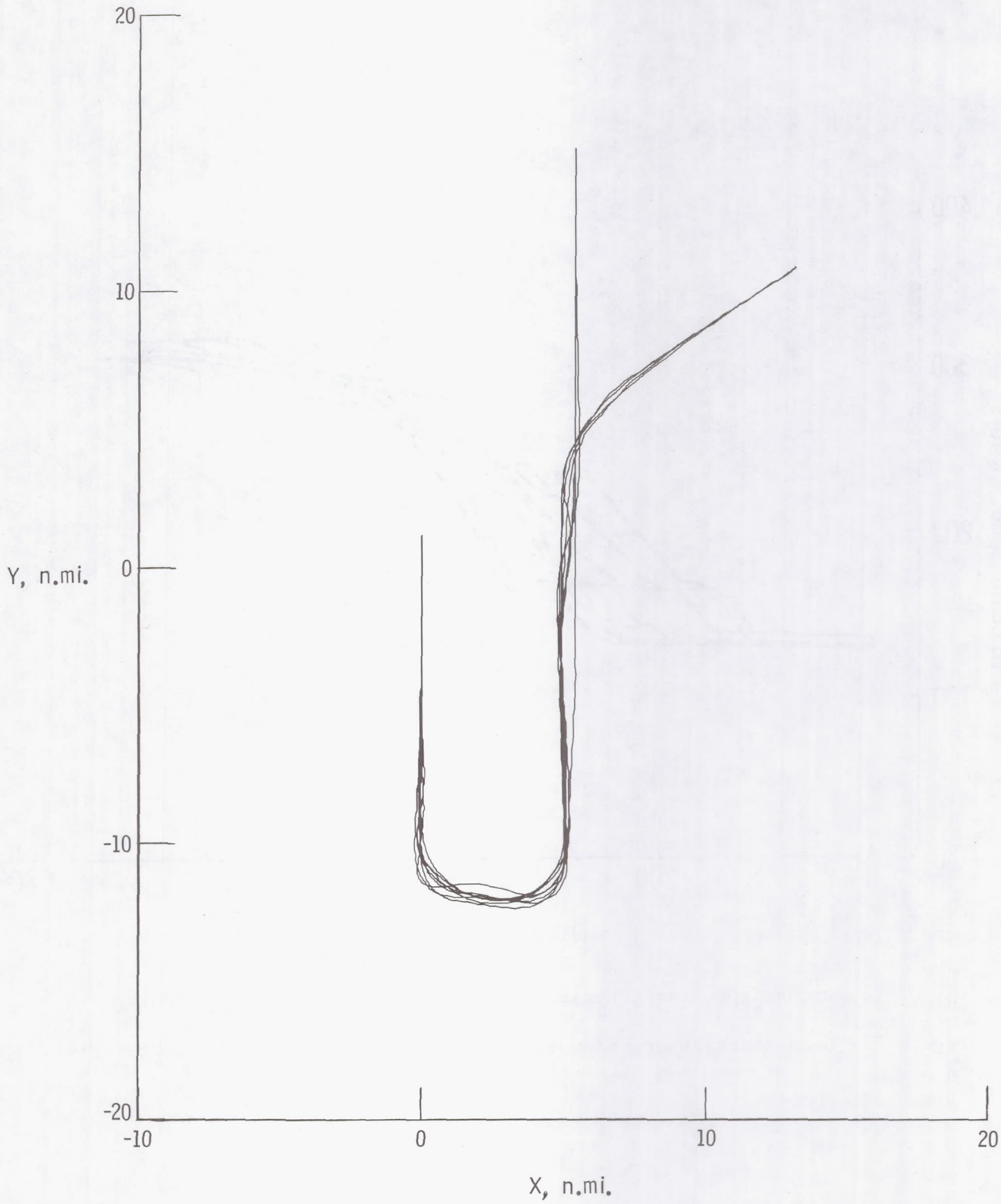
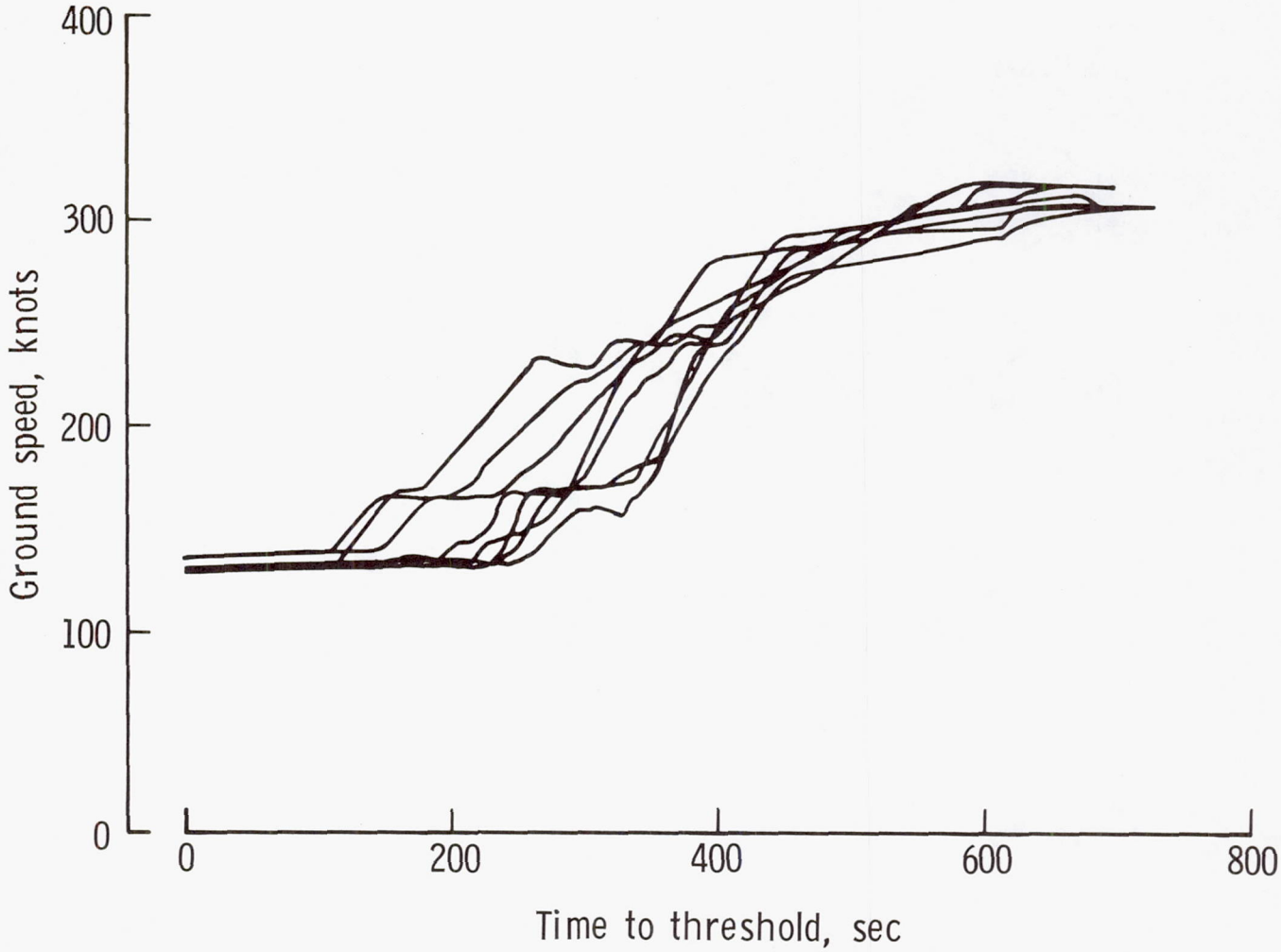
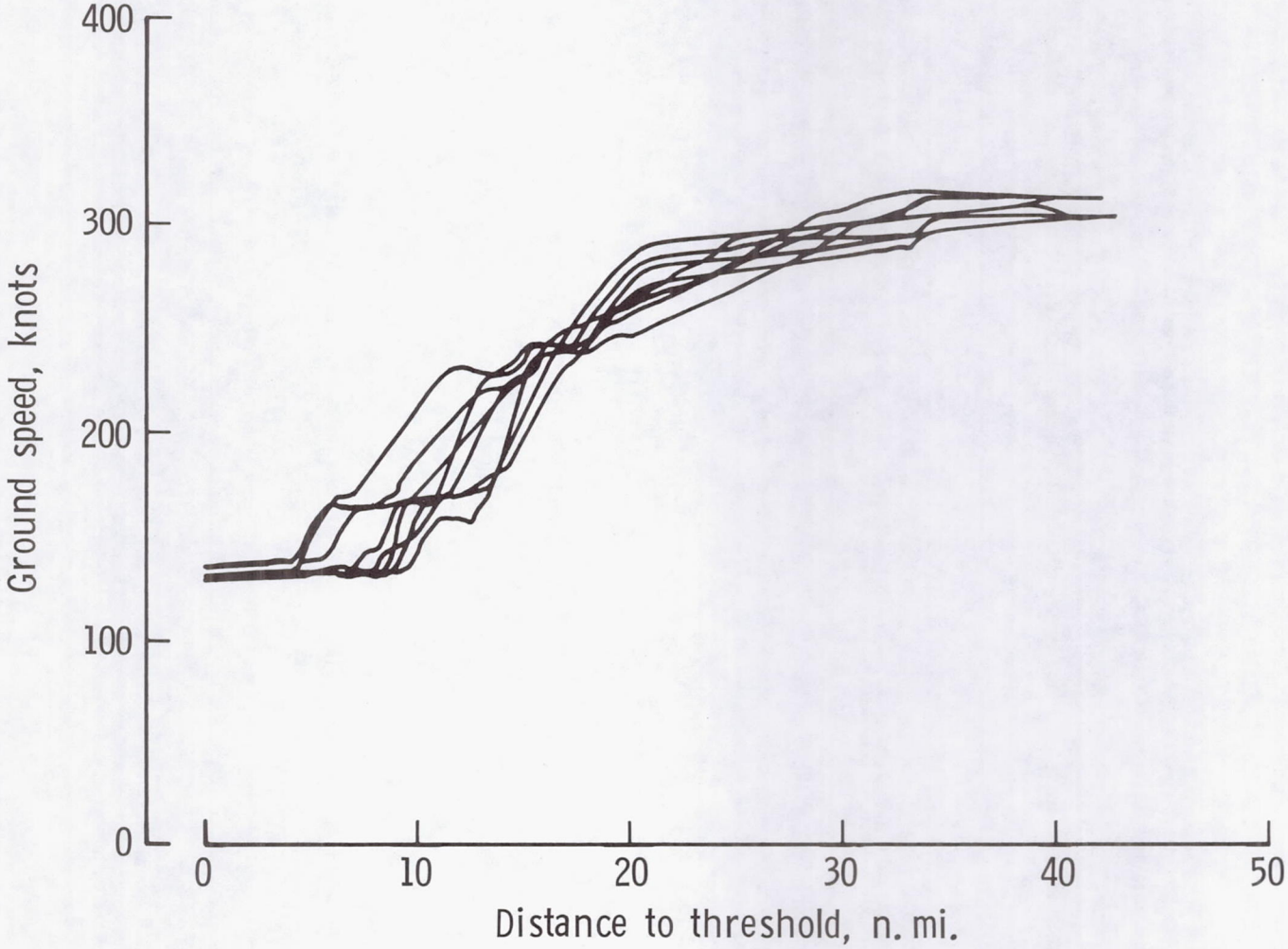


Figure 6.- Horizontal-approach tracks for all lead aircraft.



(a) Ground speed as function of time to go to runway threshold.

Figure 7.- Lead-aircraft ground-speed characteristics in phase I test series.



(b) Ground speed as function of distance to go to runway threshold.

Figure 7.- Concluded.

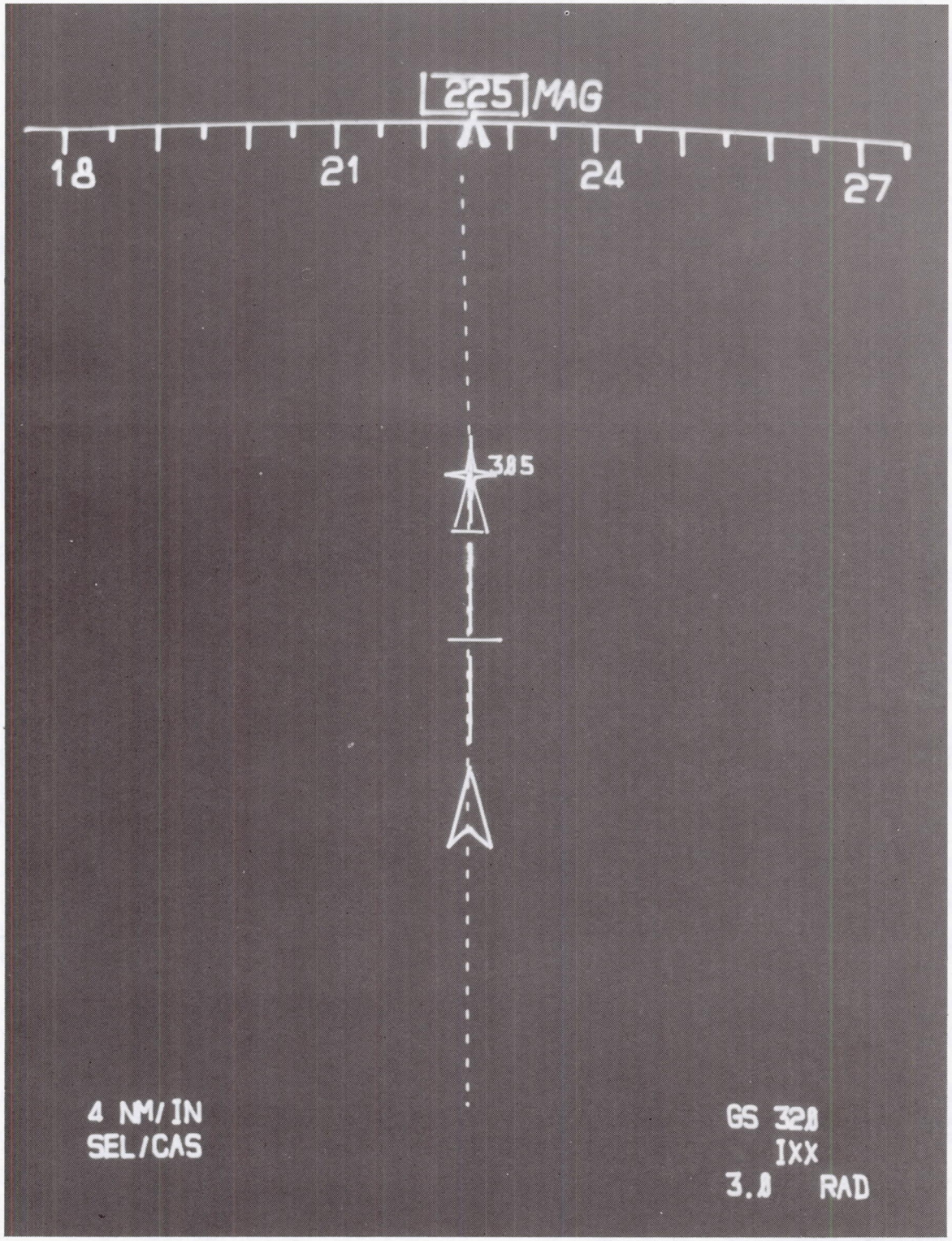


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Figure 8.- Initial condition of traffic and ownship for in-trail rendezvous subtask.

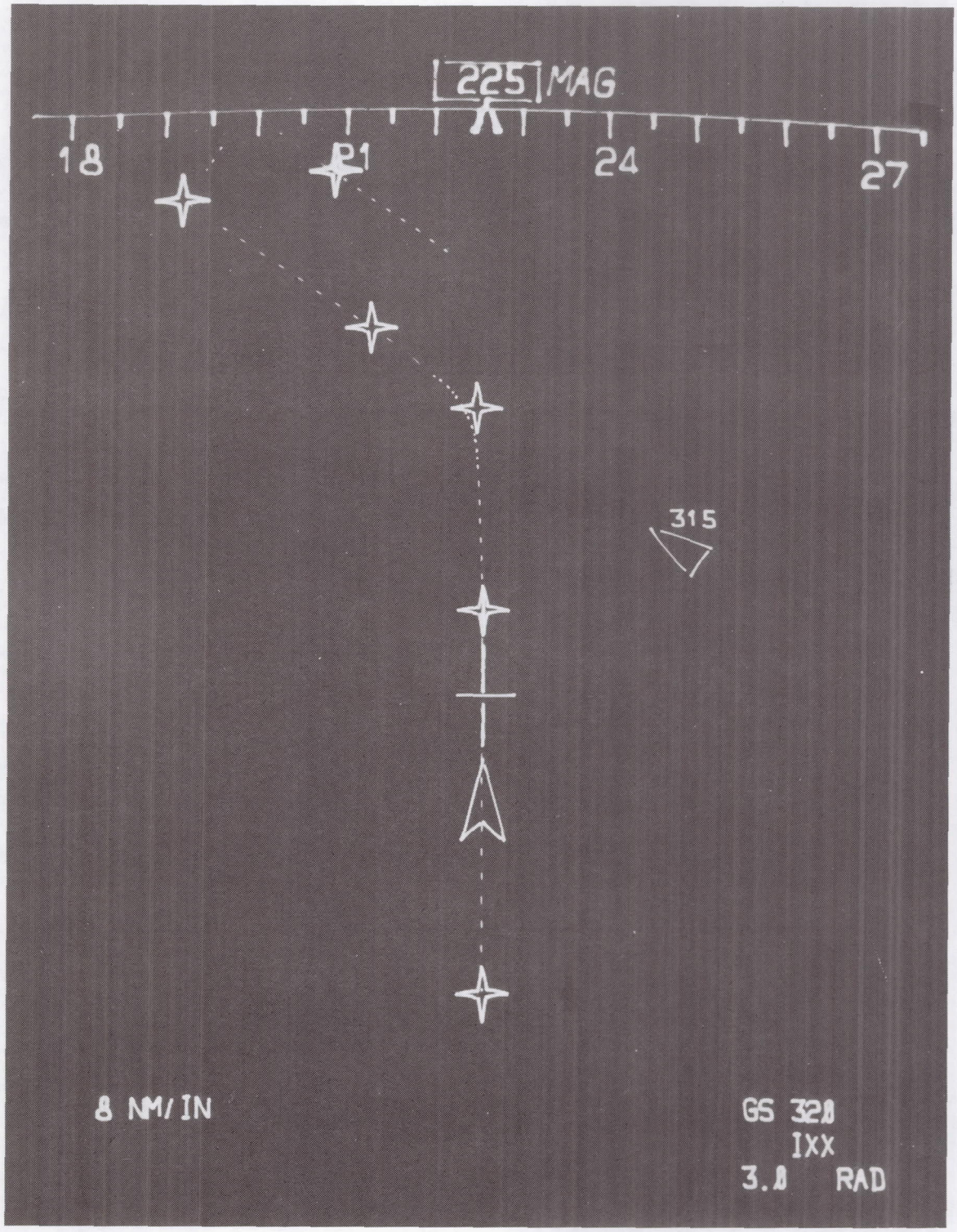

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Figure 9.- Initial condition of traffic and ownship for merge subtask.

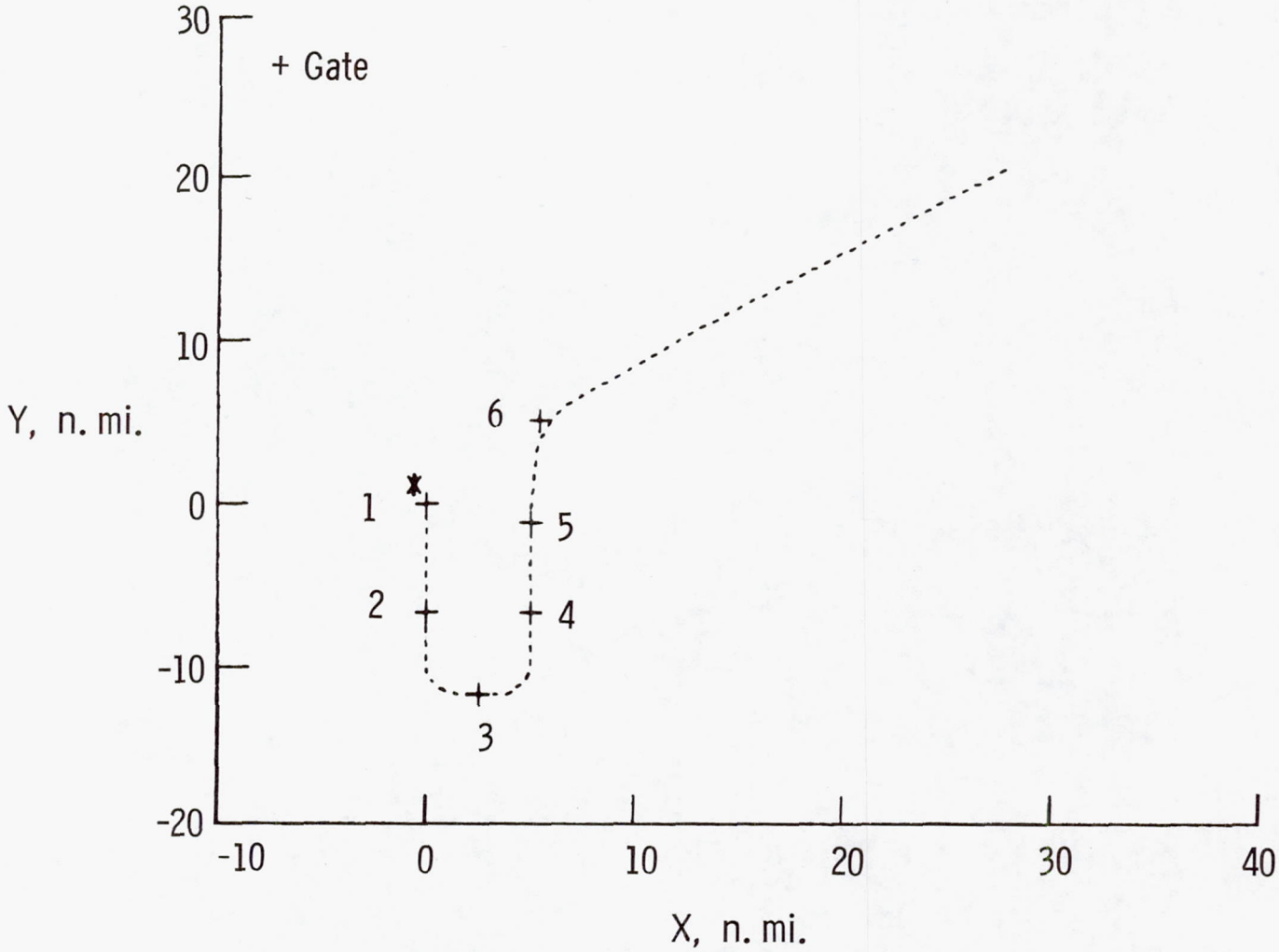

Figure 10.- Analysis gates.

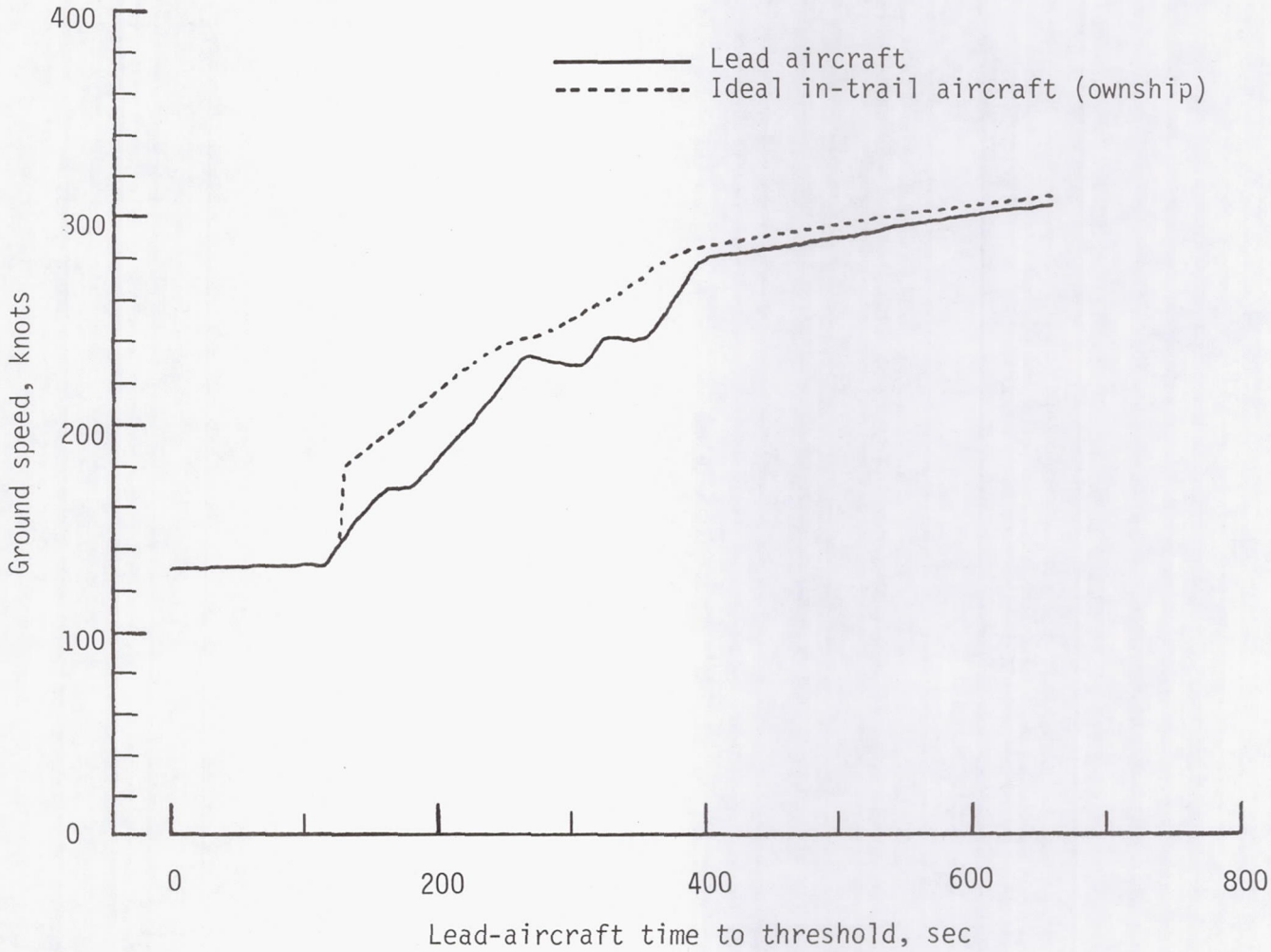

Figure 11.- Ground speed required for perfect spacing as function of lead-aircraft time to go to runway threshold.

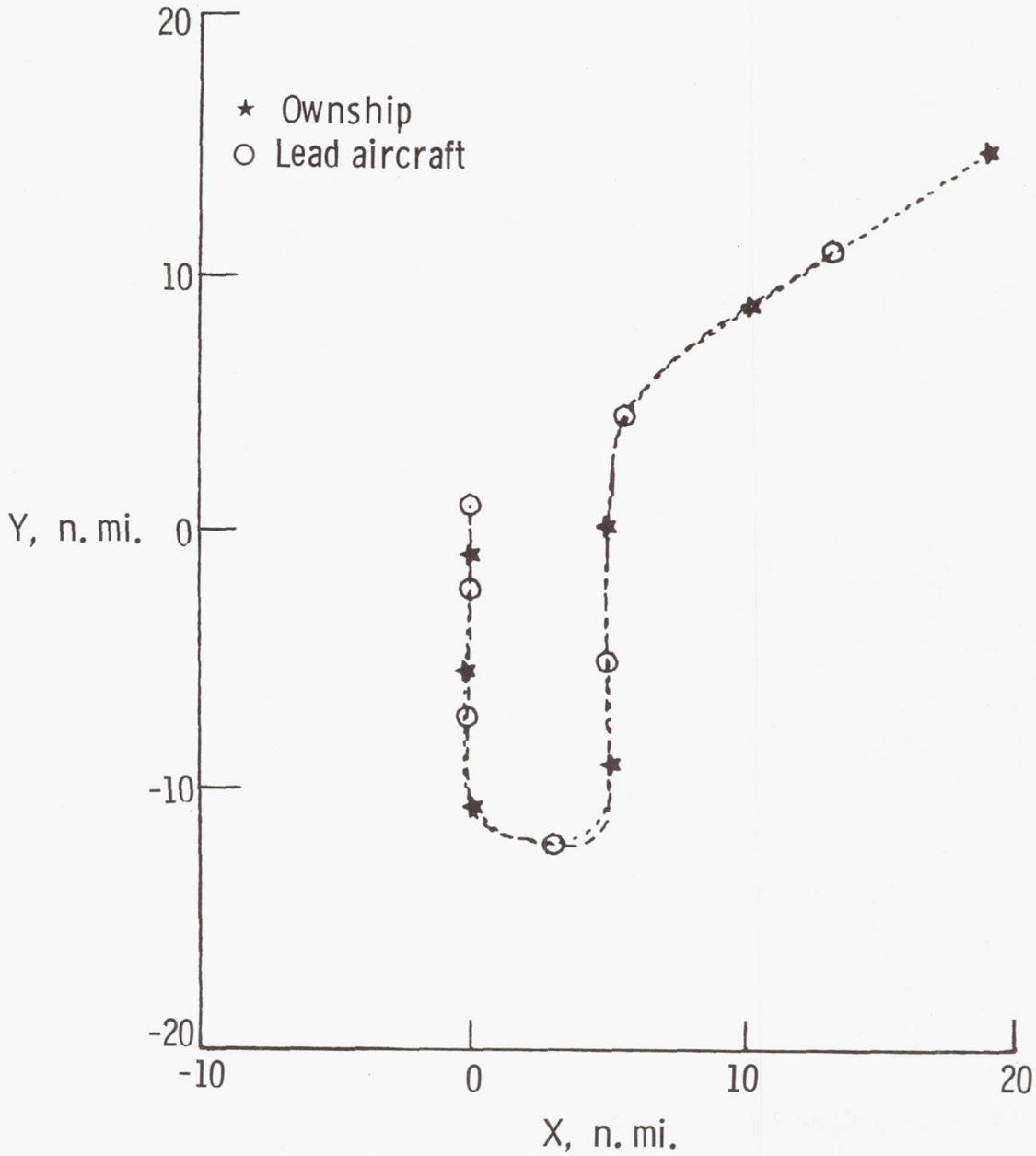

Figure 12.- Typical track plot of lead aircraft and ownship for in-trail initial condition.

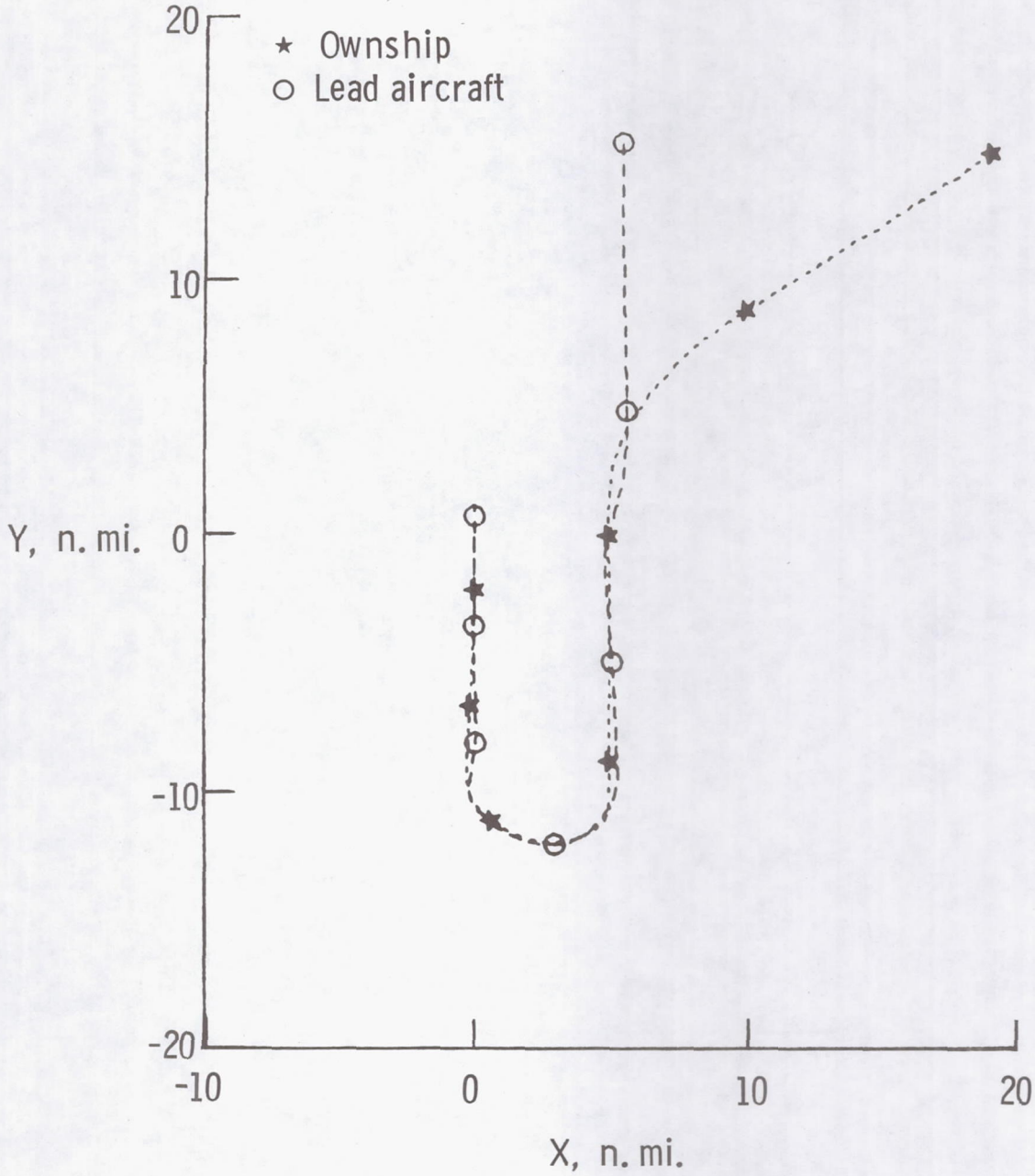

Figure 13.- Typical track plot of lead aircraft and ownship for merge initial condition.

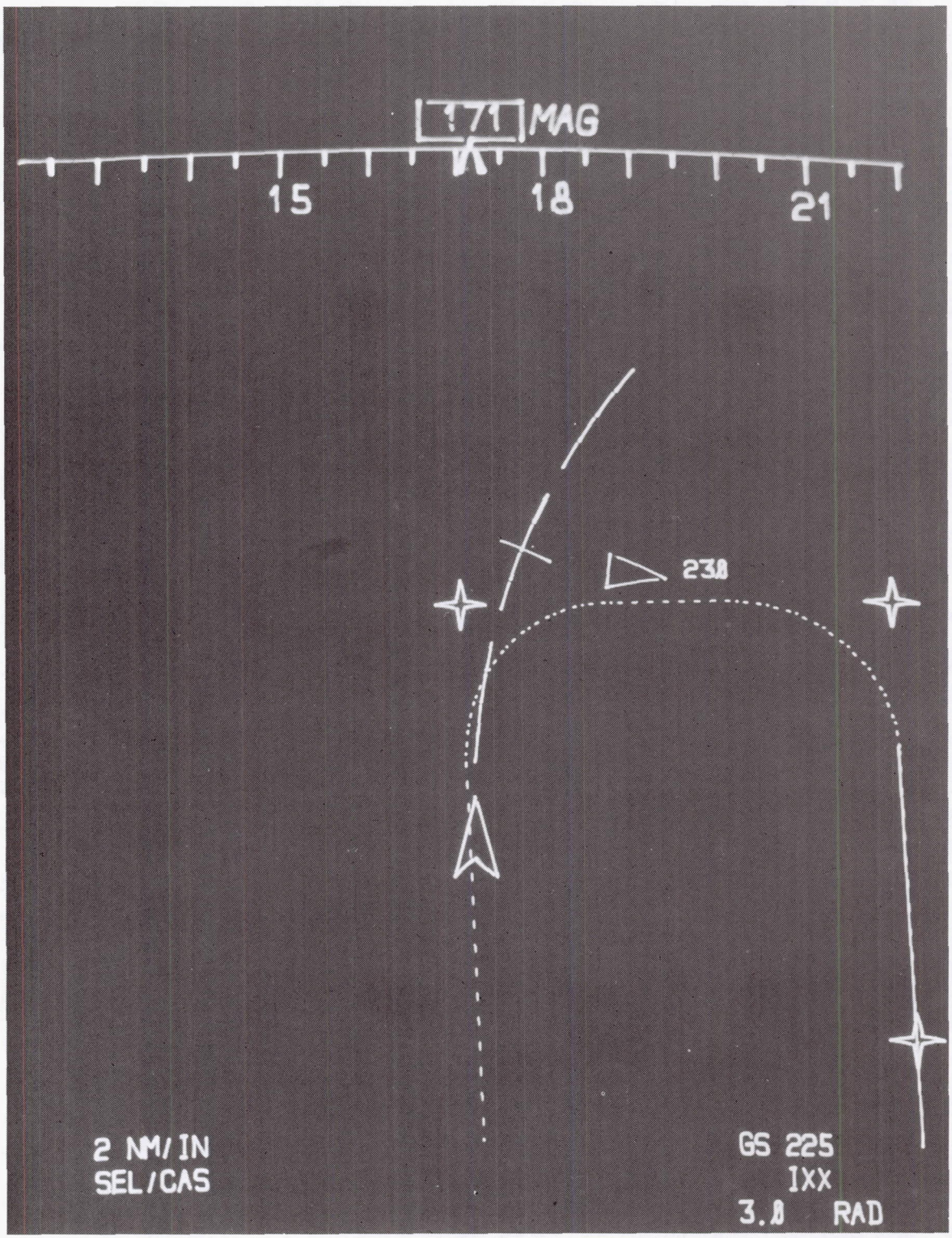

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Figure 14.- Lead aircraft on base leg with ownship on downwind leg.

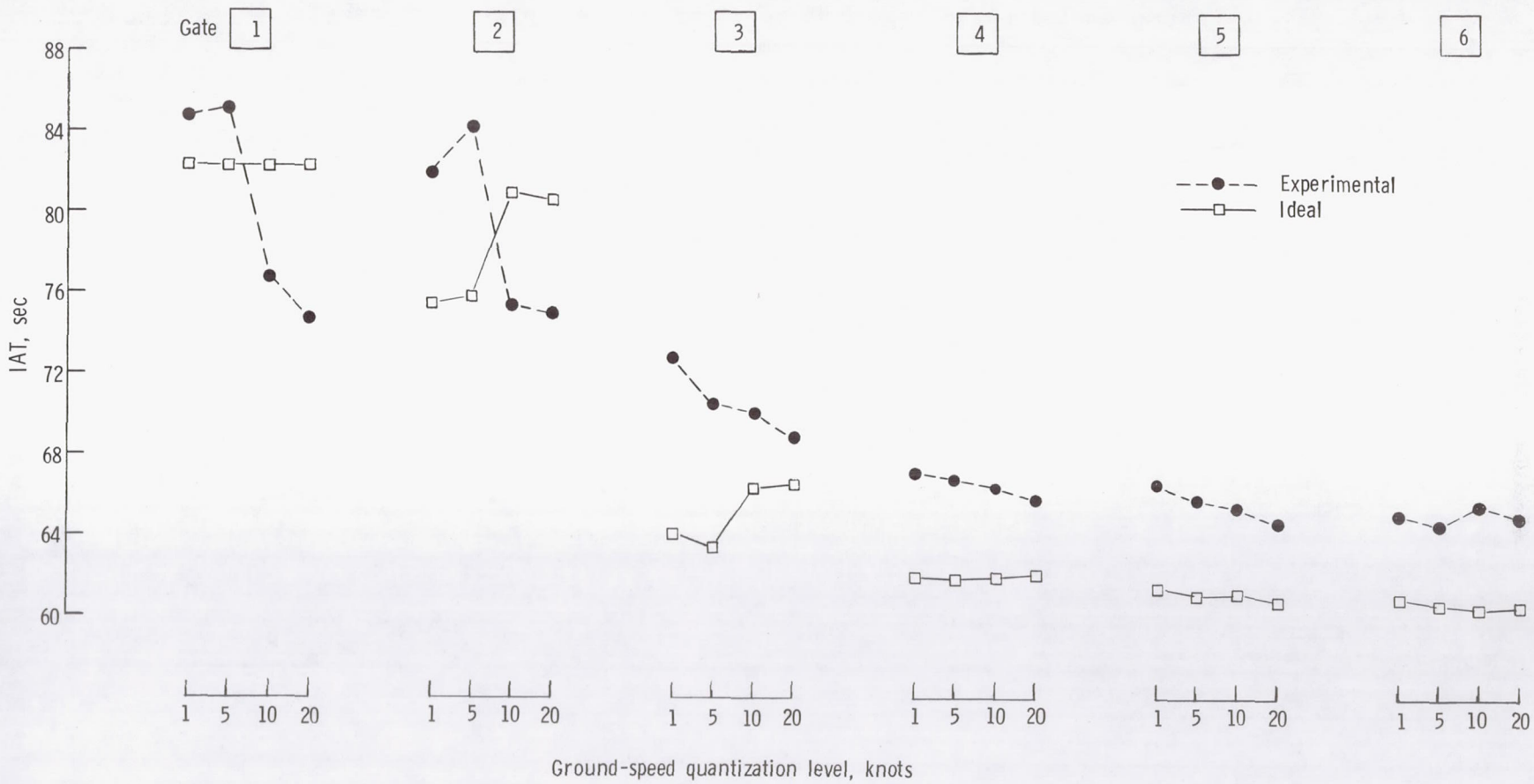


Figure 15.- Effect means for ground-speed quantization level in phase I test series.

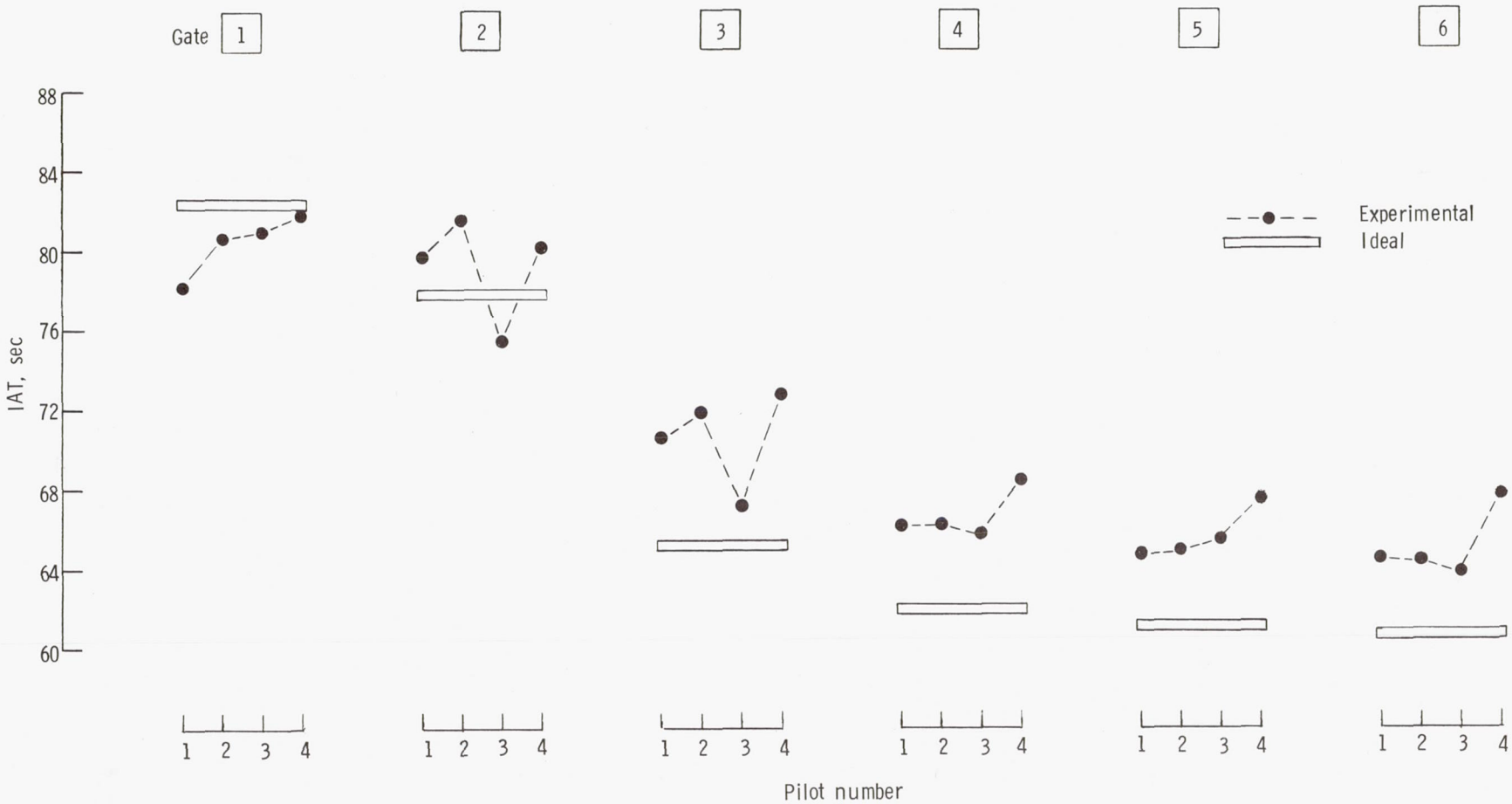


Figure 16.- Effect means for pilot factor in phase I test series.

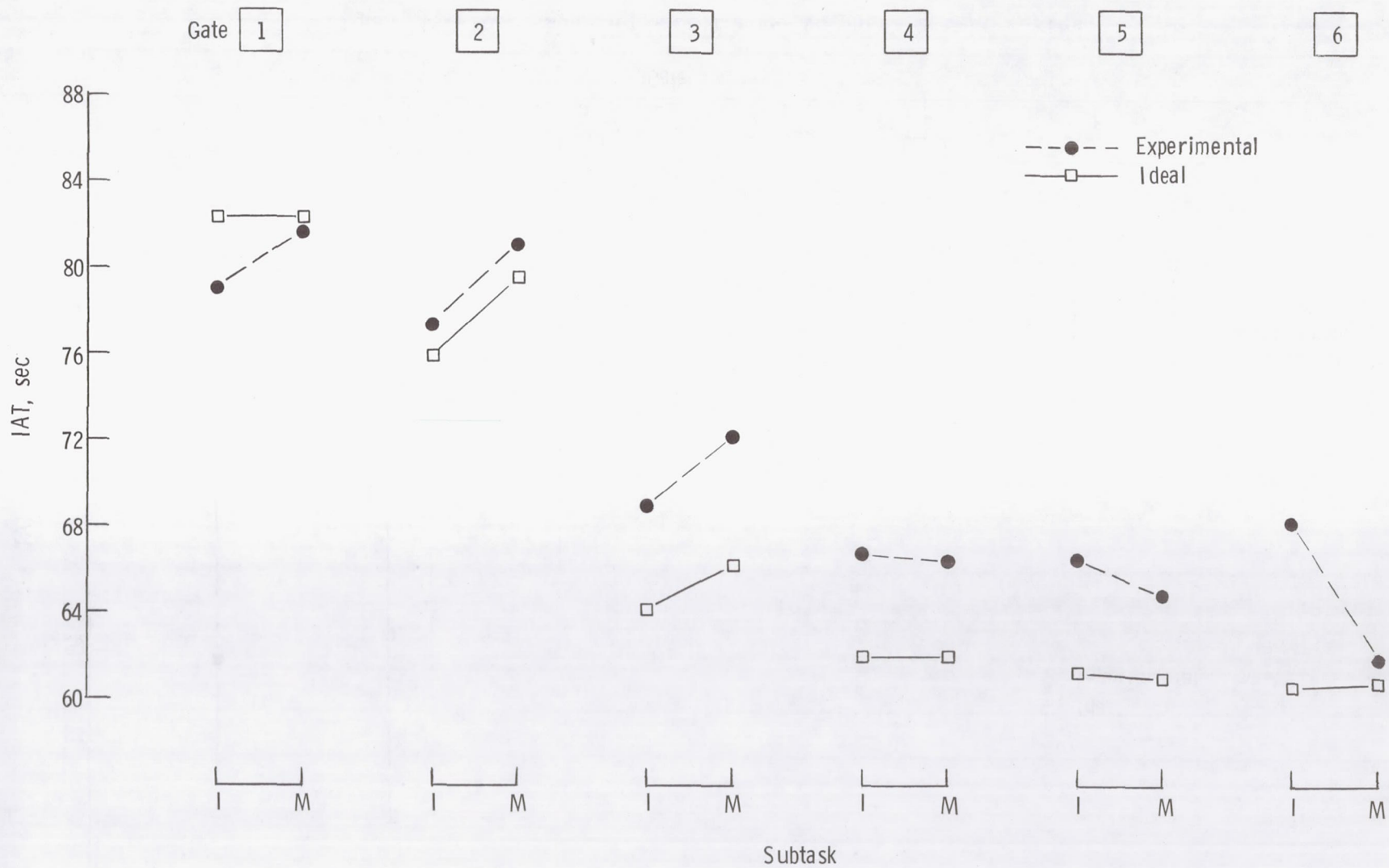


Figure 17.- Effect means for subtask factor in phase I test series. I signifies in-trail; M signifies merge.

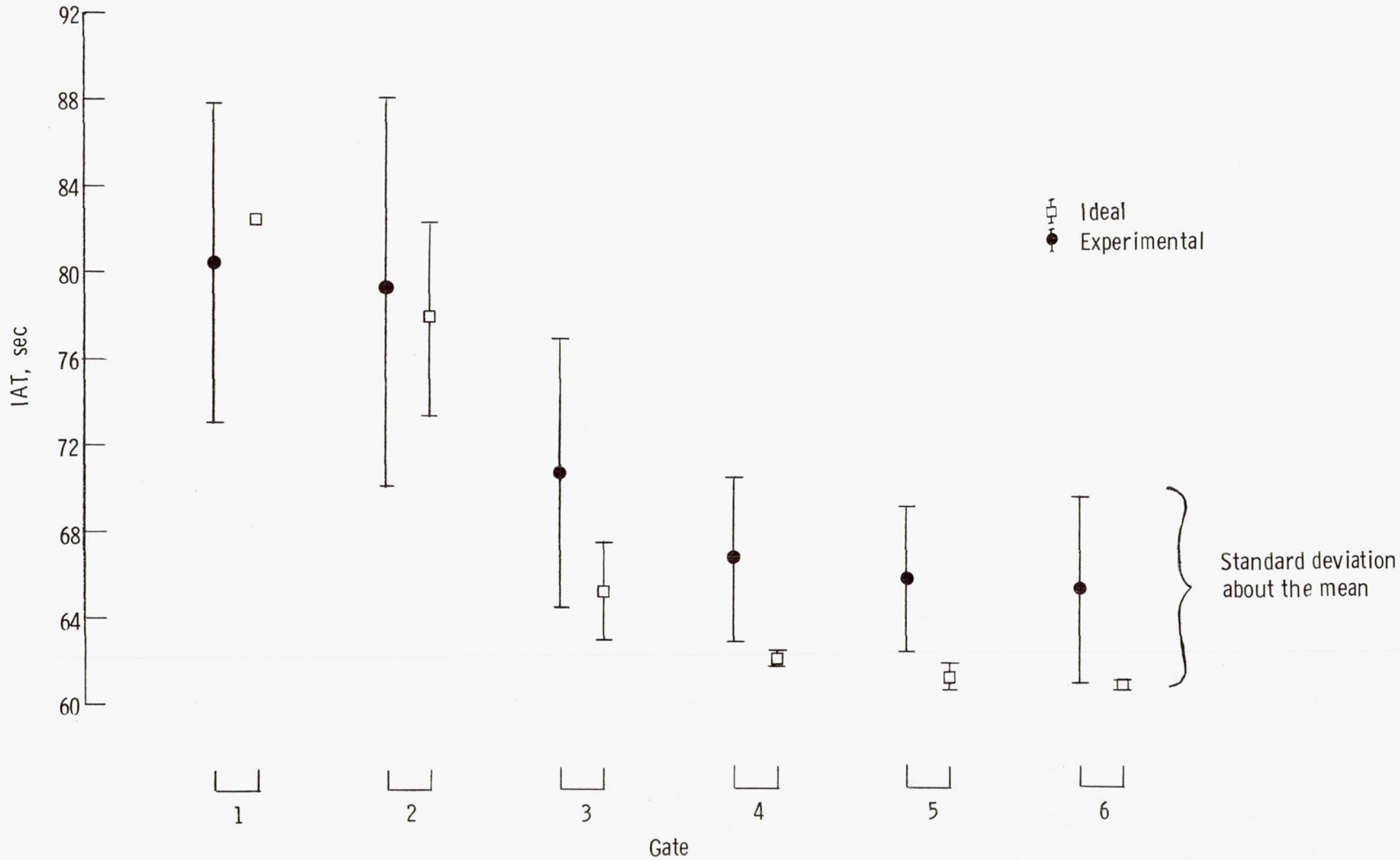
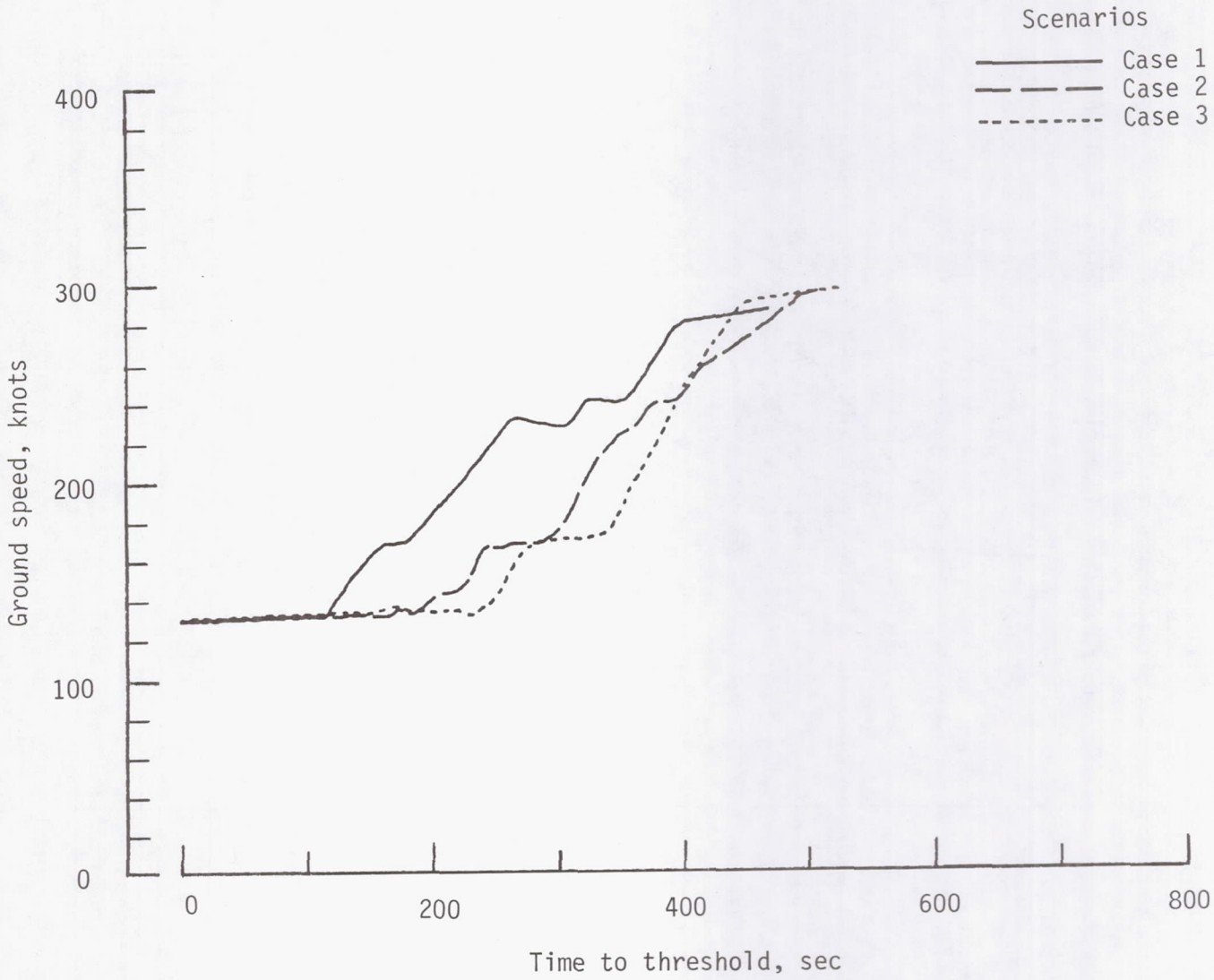
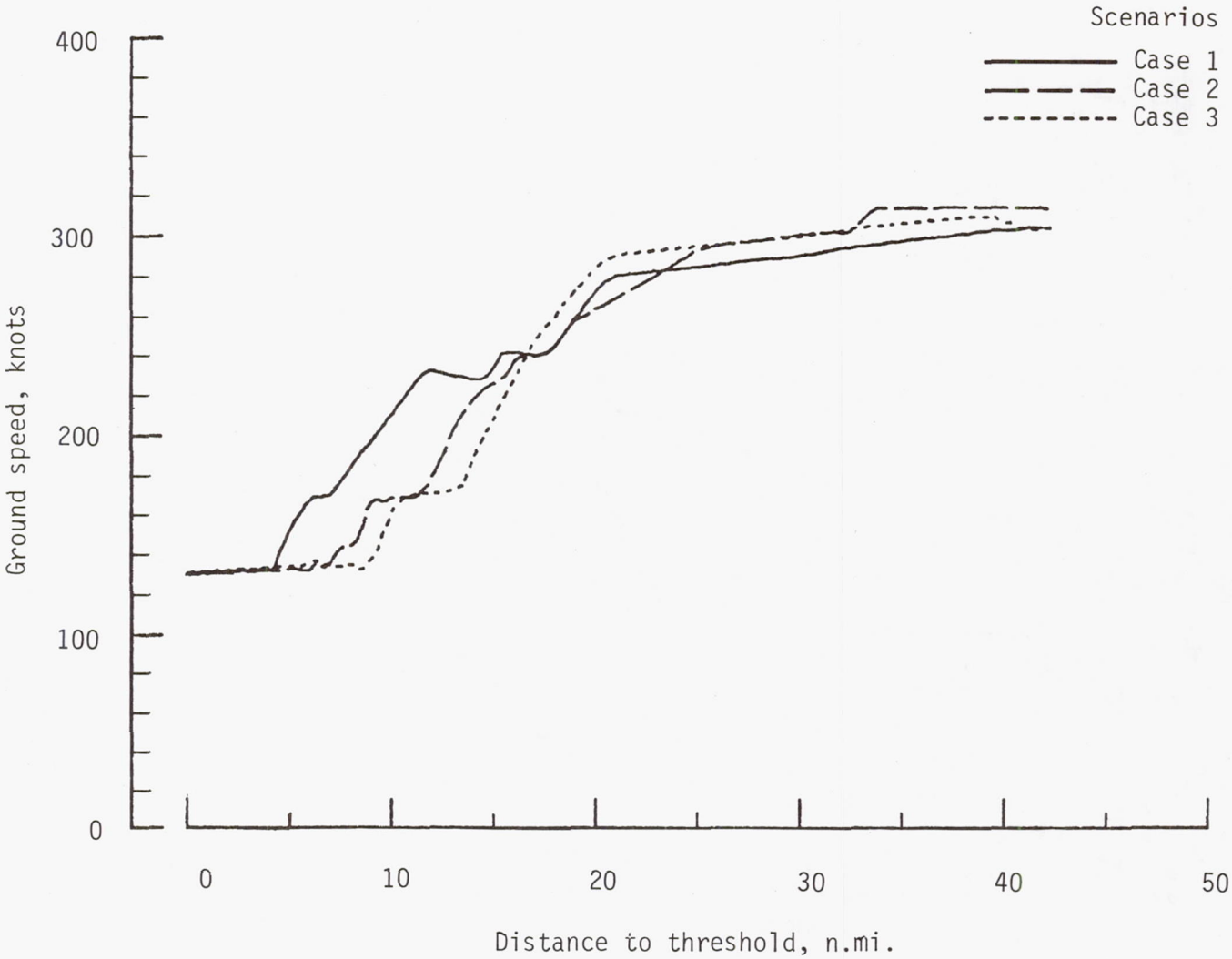


Figure 18.- Self-spacing performance in phase I test series.



(a) Ground speed as function of time to go to runway threshold.

Figure 19.- Lead-aircraft ground-speed characteristics in phase II test series.



(b) Ground speed as function of distance to go to runway threshold.

Figure 19.- Concluded.

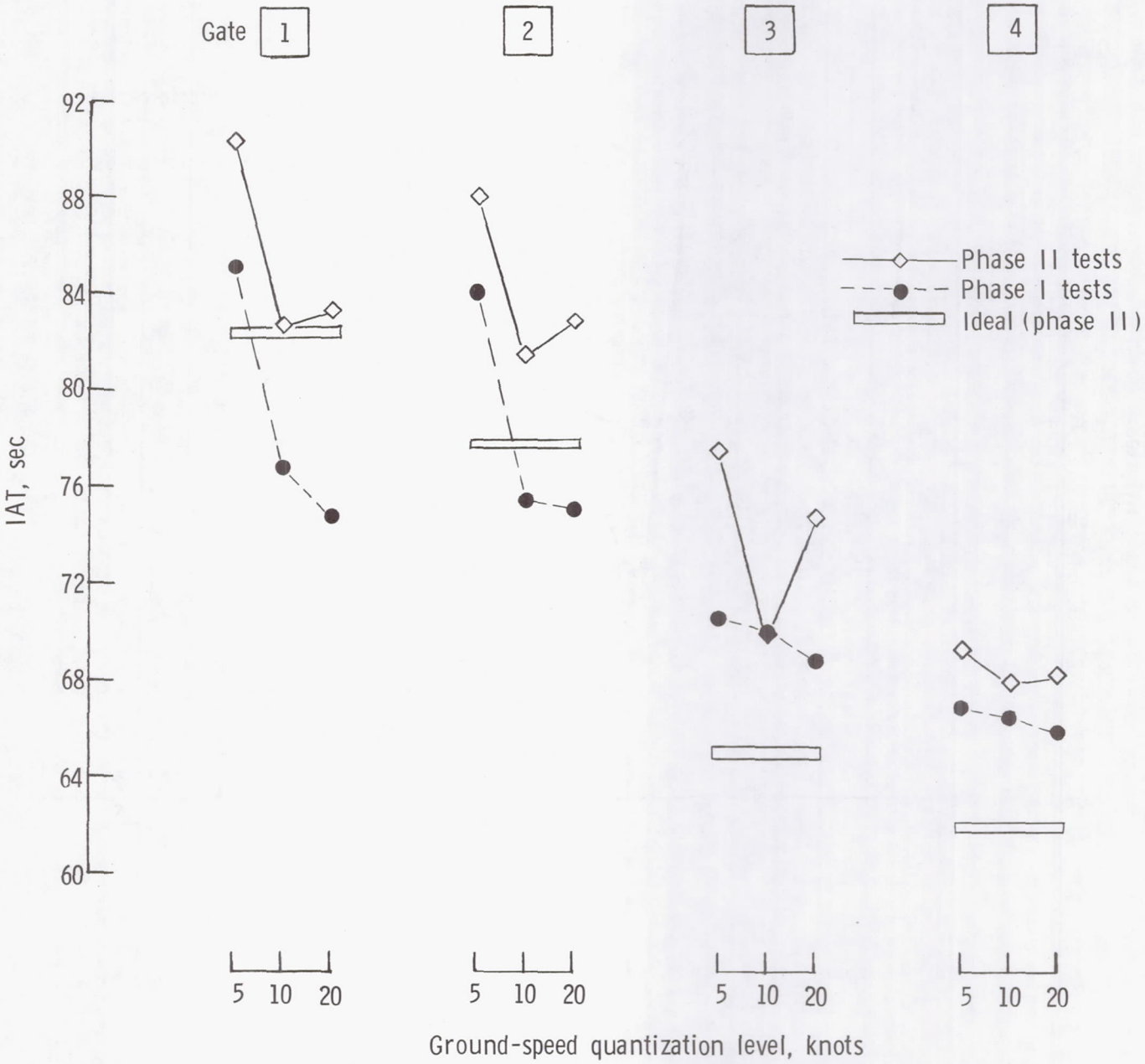


Figure 20.- Effect means for ground-speed quantization level in phase II test series.

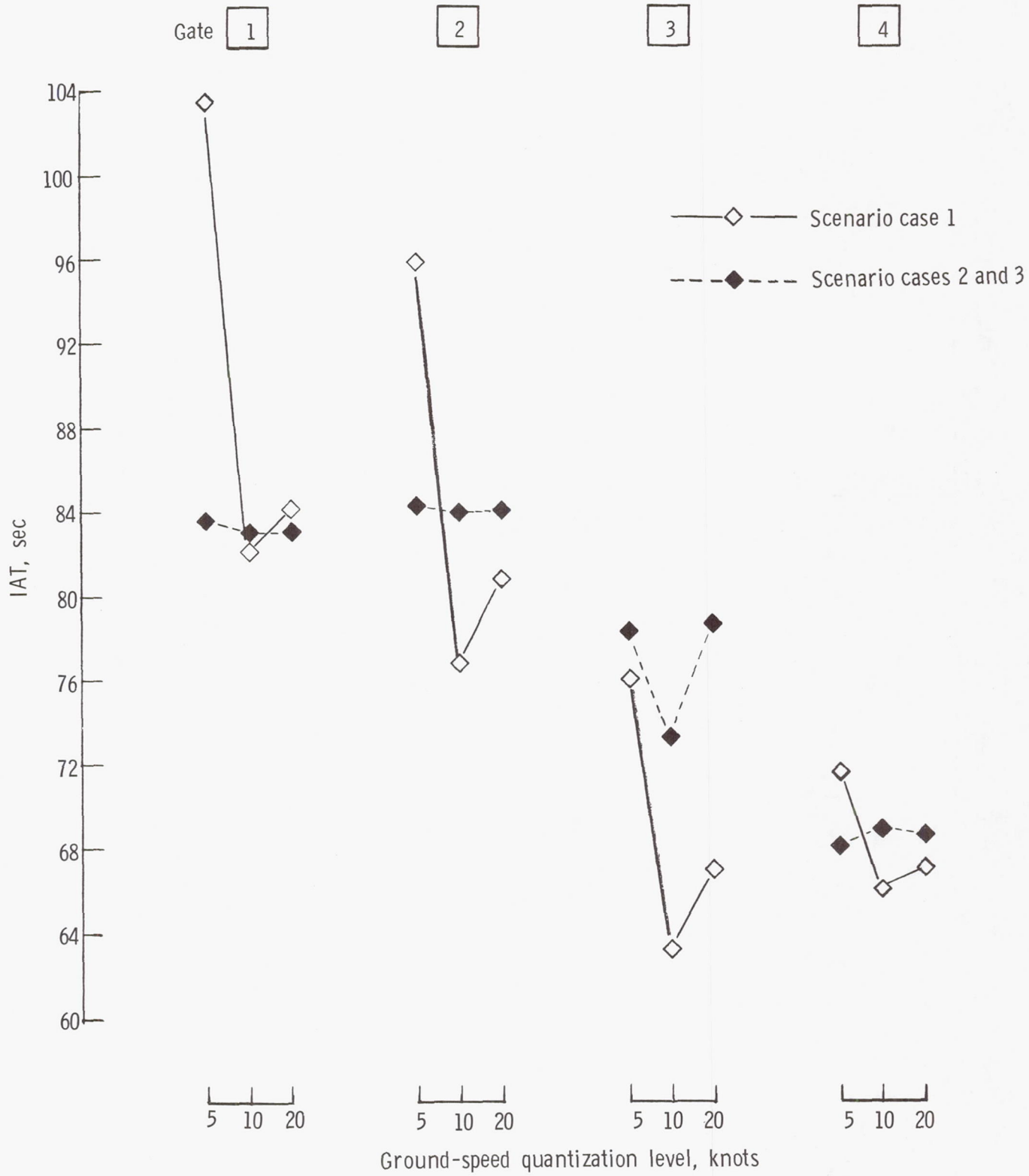


Figure 21.- Effect means for interaction of scenario and ground-speed quantization level in phase II tests.

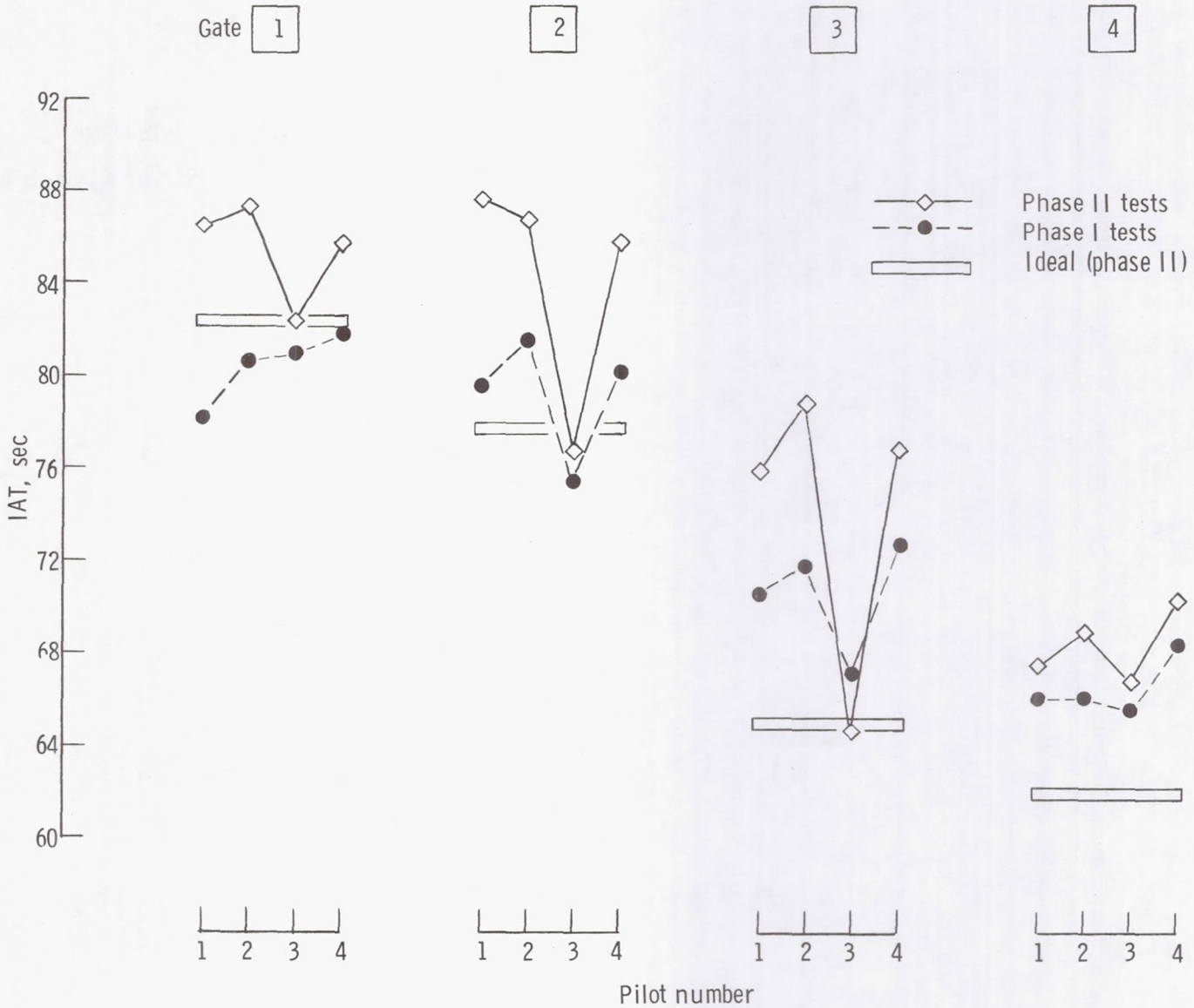


Figure 22.- Effect means for pilot factor in phase II test series.

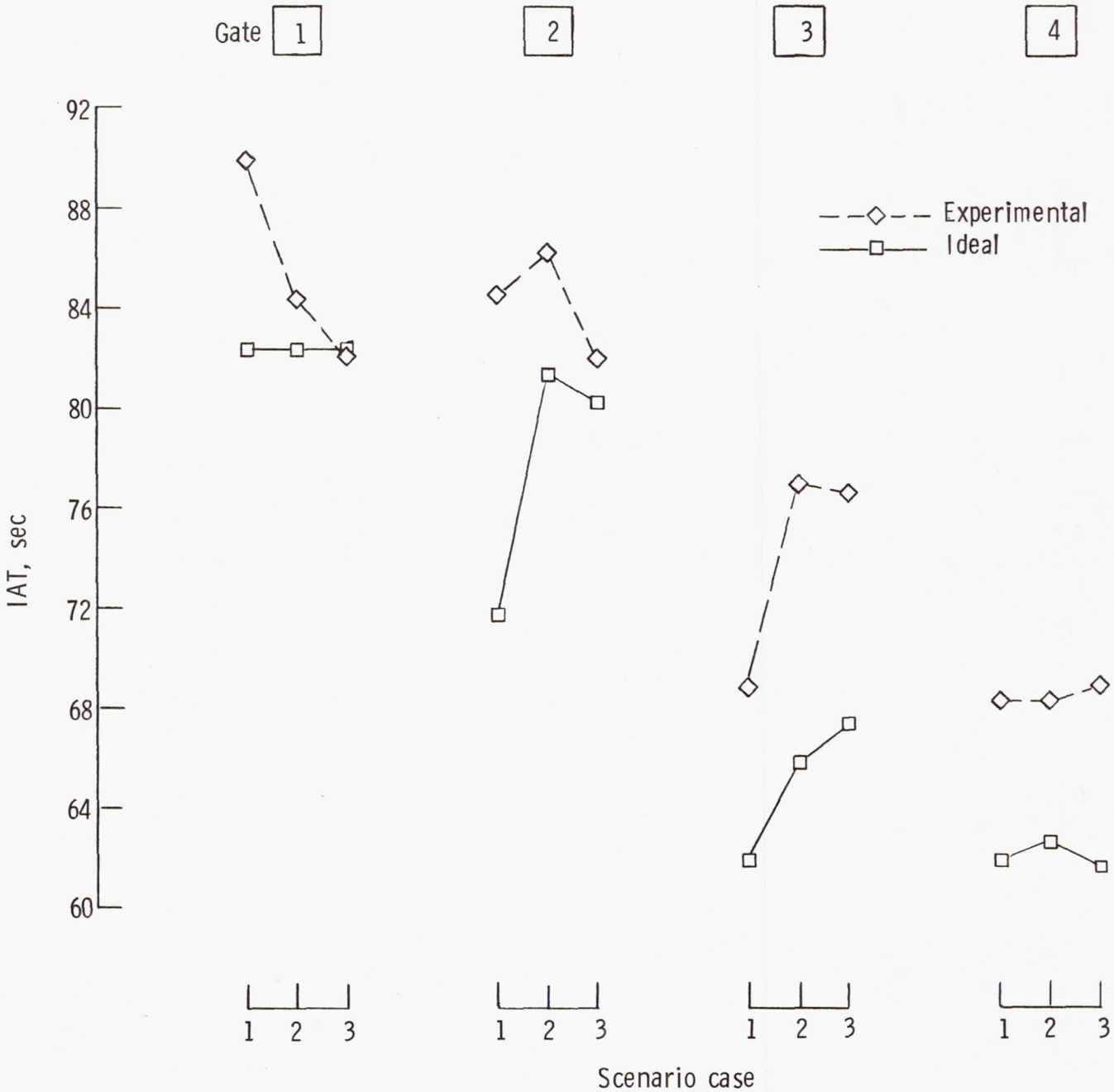


Figure 23.- Effect means for scenario factor in phase II test series.

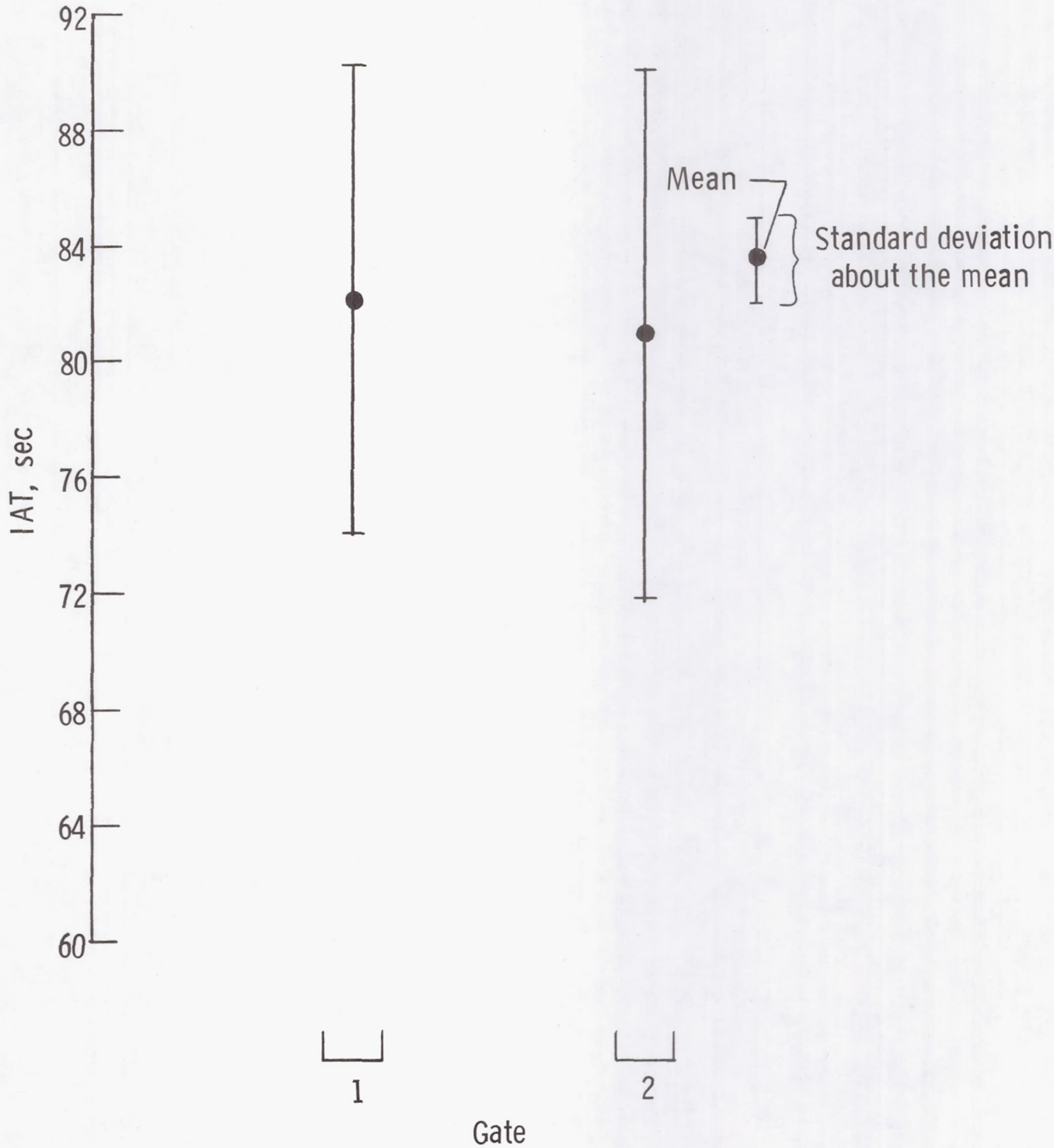


Figure 24.- Overall spacing performance.

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15. Supplementary Notes

16. Abstract

A simulator investigation was conducted to determine the effect of the lead-aircraft ground-speed quantization level on self-spacing performance using a Cockpit Display of Traffic Information (CDTI). The study utilized a simulator employing cathode-ray tubes for the primary flight and navigation displays and highly augmented flight control modes. The pilot's task was to follow, and self-space on, a lead aircraft which was performing an idle-thrust profile descent to an instrument landing system (ILS) approach and landing. The spacing requirement was specified in terms of both a minimum distance and a time interval. The results indicate that the ground-speed quantization level, lead-aircraft scenario, and pilot technique had a significant effect on self-spacing performance. However, the ground-speed quantization level only had a significant effect on the performance when the lead aircraft flew a fast final approach.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Cockpit display of traffic Cockpit traffic display Traffic situation display Aircraft separation CDTI	Unclassified - Unlimited Subject Category 06

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