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Time-Based Self-Spacing Techniques Using Cockpit Display of Traffic Information During Approach to Landing in a Terminal Area Vectoring Environment

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SUMMARY

A simulation study was undertaken to evaluate two time-based self-spacing techniques for in-trail following during terminal-area-approach operations. The tests were conducted in a fixed-base cockpit simulator configured as a current-generation transport aircraft. An electronic traffic display was provided in the weather radarscope location. The self-spacing cues displayed on the electronic traffic display allowed the pilot of the simulated aircraft to follow and to maintain spacing on another aircraft which was being vectored by air traffic control (ATC) for landing in a high-density terminal area environment. Separation performance data and pilot subjective ratings and comments were obtained during the study.

Eight unique approaches representative of the aircraft vectoring used at Stapleton International Airport in Denver, Colorado, were flown and recorded in the simulator for use as target aircraft. The test subjects flew approaches following each of these prerecorded targets using constant-time-predictor and constant-time-delay spacing display formats. These time-based self-spacing techniques provided a spacing distance which was increasingly compressed as both aircraft descended and decelerated during the approach. In addition, the target aircraft left a trail of past-position dots on the electronic traffic display of the pilot's aircraft, which described the horizontal path for the pilot to follow.

Results of the study indicate that the information provided on the traffic display was adequate for the test subjects to accurately follow the approach path of another aircraft without the assistance of ATC. Pilot comments indicate that the workload associated with the self-separation task was high. Location of the traffic display in the weather radarscope position and the sensitive manual control system of the simulator contributed to the high-workload condition. Pilot comments further indicate that additional spacing command information and/or aircraft autopilot functions would be desirable for operational implementation of the self-spacing task.

Analysis of the separation performance data revealed some significant differences between the constant-time-predictor and constant-time-delay spacing techniques. The spacing cue implemented for the constant-time-delay spacing technique produced a significantly lower dispersion in displayed spacing error. Actual spacing accuracy, measured in terms of deviations from ideal spacing, was not significantly different for the two spacing techniques. The constant-time-predictor technique exhibited the inherent problem of requiring the pilot's aircraft to fly an overall slower profile than the lead aircraft. For the particular profiles flown in this study, the constant-time-predictor runs averaged 10 sec longer than the same runs using constant time delay.

INTRODUCTION

The combination of air traffic demands and airport capacity limitations has resulted in costly delays in take-off and landing for aircraft and in high workload levels for air traffic controllers. Solutions to these problems are necessary in order to improve controller productivity and to allow for the future growth of the air transportation system projected by the Federal Aviation Administration. One method which has been cited as a possible means to reduce controller workload and to improve airport capacity is to allow greater participation of pilots in the air traffic control (ATC) process.

The concept of cockpit display of traffic information (CDTI) has the potential for providing the pilot with the traffic information necessary to perform some ATC functions. Previous studies involving airborne traffic displays have identified many areas where active use of CDTI may have beneficial applications (ref. 1). Pilot control of in-trail spacing during approach to landing has been suggested as a means to increase airport capacity by reducing the dispersion in aircraft spacing at the runway threshold. Addition of spacing information to the CDTI gives the pilot the capability to perform the in-trail spacing task. The nature of this display information, the pilot's ability to successfully use the display to perform the spacing task, and the resulting effects on overall system efficiency and safety are subjects of continuing research.

The primary objective of this study was to evaluate two time-based self-spacing techniques used during approach to landing operations in a high-density terminal area environment. The spacing techniques were chosen to provide a naturally compressing spacing interval as the aircraft decelerated during the approach. The primary pilot task was to maintain the specified spacing interval behind a lead aircraft which was being vectored to the landing runway by ground ATC. Pilot performance in maintaining precise spacing intervals as well as subjective analysis of the workload associated with the self-spacing task were principal measures in the evaluation.

RESEARCH SYSTEM

Simulator Description

This study was conducted with a fixed-base cockpit simulator configured as a conventional, two-engine jet transport aircraft (fig. 1). The four throttle controls present in the cockpit were mechanically pinned together in pairs to represent the two-engine configuration. The aircraft dynamics modeled for the simulation were those of a Boeing 737. Nonlinear aerodynamic data and atmospheric effects were included in the simulation model. The host computer for the simulation was a CDC® CYBER 175 system, which contained the aircraft dynamics, navigation, and flight-director algorithms. Conventional navigation instruments, which included horizontal-situation indicators, flight director, and distance measuring equipment (DME), were provided in the cockpit. Flight instrumentation consisted of standard instruments required for manual flight control; however, no autopilot or automatic flight-control systems were provided to the pilot. In addition, no attempt was made to duplicate any specific aircraft cockpit configuration or control-force-feel characteristics.

Traffic Generation Scheme

The displayed traffic was generated from data previously recorded using the Langley Flight Simulation Computing Subsystem. Specifically, the traffic data were created by using a capability of the piloted simulation wherein flights were made along various routes that corresponded to the airway structure prescribed by the test scenarios. These individual flights were recorded and then merged into a set of data that was correlated for position and time. The output of these merged data was the representation of numerous airplanes following several flight paths. A description of the actual traffic scenarios used in this study is contained in the "Air Traffic Scenario" section.

EXPERIMENT DESCRIPTION

CDTI Description

The instrument used for the CDTI for this study was a monochrome, 875-line, raster-scan cathode-ray tube (CRT) located behind the throttle quadrant as shown in figure 1. This location corresponds to the normal location for a weather radar display on most conventionally equipped transport aircraft. The CRT measured 10 in. across the diagonal with a display area approximately 6 in. high by 6 in. wide used for the CDTI information.

The traffic information was presented on this display in a horizontal plan view superimposed on a map display. The map information provided simplified route structure and navigation way points for the approach patterns to runway 26L at Stapleton International Airport in Denver, Colorado (fig. 2). A solid line was drawn from an entry corner post toward Denver VORTAC to indicate the initial approach radial that the pilot's aircraft would be flying. Approach radials from the other three corner posts were drawn as dashed lines to indicate alternate approaches that other aircraft might be following. A second solid line was drawn along the extended centerline of runway 26L, through the outer marker (LOM) and WATKI navigation way points, to highlight the final approach path to the runway. In addition, short straight lines were drawn on the display depicting the main runway complex at Stapleton. The map display was oriented with the ground track of the pilot's aircraft being up, with apparent continuous movement of the map information about a fixed own-aircraft symbol. Six map scales, ranging from 1.0 to 32.0 n.mi./in., were available to and controllable by the test subjects.

Figures 3(a) and 3(b) illustrate the CDTI format as it appeared in the cockpit for the two spacing techniques used in this study. In these figures, the pilot's aircraft is on a downwind segment of the approach, with the extended centerline of runway 26L shown on the right side of the display. The runway complex is located in the lower right-hand corner of the display in these figures.

Traffic aircraft were displayed on the CDTI referenced to the map display. Unlike the map, the traffic data were not updated continuously but at 4-sec intervals to approximate the update interval for data obtained using a terminal area secondary surveillance radar. Between updates, the traffic symbology remained fixed on the moving map and then jumped to its new position at the update.

The traffic symbology was obtained from reference 2 and was the same as that used in references 3 and 4. Figure 4 illustrates this symbology and the information provided to the pilot concerning the aircraft traffic. Aircraft within ±500 ft altitude were considered "at" the altitude of the pilot's aircraft. The straight-line trend vector on the traffic symbol indicated where the traffic would move in 60 sec at its current ground speed and heading. The alphanumeric data blocks provided identification, beacon-reported pressure altitude, and ground-speed information for the traffic. The trend vectors and data blocks were independently selectable by the test subject at any time during a run. Selection of either option resulted in that option appearing for all the displayed traffic. The alphanumeric characters and the symbols were of constant sizes independent of map scale. It should be noted that the sizes of the alphanumeric characters in the traffic data blocks were not the same as in references 3 and 4. The numbers providing the altitude and ground-speed information were enlarged to facilitate readability. The traffic identifiers remained the smaller size in order to minimize the overall display clutter.

The lead aircraft, which the pilot's aircraft was instructed to follow, created an additional display feature on the pilot's CDTI consisting of a trail of position dots indicating the lead-aircraft ground-track history over a specified time interval. The position dots represented the location of the lead aircraft at each 4-sec update for the previous 80-sec time period. For the constant-time-delay spacing cases, a straight line perpendicular to the lead-aircraft ground track was drawn through the 80-sec-position dot on the lead-aircraft trail to provide an easy reference point for the self-spacing task. (See fig. 3(a).) A predictor vector extending from the own-aircraft symbol provided the pilot with an indication of the ground track his aircraft would follow at the current turn rate. The length of the vector was based on the distance the pilot's aircraft would travel in 80 sec at its current ground speed. For the constant-time-predictor spacing cases, an arc was drawn at the tip of the own-aircraft predictor vector for reference in performing the spacing task. (See fig. 3(b).)

Air Traffic Scenario

The air traffic approach patterns modeled in this study were based on typical approach profiles used by jet transport aircraft for landing at Stapleton International Airport as of April 1981. As with other high-density terminal area airports, Stapleton's capacity is limited at peak periods, requiring flow control, holding patterns, and high controller workload levels. Depending on wind and runway configuration in use, under visual meteorological conditions (VMC) more than 70 aircraft per hour may enter the terminal area requiring individual altitude, speed, and vectoring commands from the approach traffic controllers to land on two parallel runways. Departures are typically handled on a cross runway and are generally not a factor for approach-aircraft spacing.

Approach airspace in the Denver terminal area is divided into four approach corridors and a final approach zone, which surrounds the extended centerline for the primary landing runway. Figure 5 shows a view of a horizontal slice of this approach-airspace configuration. A vertical slice of the overall approach airspace is shown in figure 6. The accompanying table provides a brief description of the five major airspace segments an aircraft will travel through during a typical approach. It should be noted that separate air traffic controllers are responsible for the aircraft in each segment.

The "profile descent" referred to in figure 6 is a published descent procedure which specifies altitude and airspeed boundaries the aircraft must observe at the corner posts and inner way points along the approach. Once the aircraft has crossed a corner post and is in approach control airspace, the profile descent clearance is typically cancelled and the controller assumes "manual" control over the aircraft. It is in this region (segment III of fig. 6) where the traffic streams from the four corner posts must be funneled to the single final approach zone. Consequently, extensive speed control and radar vectoring of aircraft are required to smoothly mesh the arrival traffic. Even under visual conditions, aircraft are radar separated in the approach corridors until they are merged into the final approach zone, where the pilots assume visual separation responsibility.

Traffic flow into Denver follows repeatable patterns with "rush" periods of scheduled airline traffic arriving at the same times each day. Typically, these rush periods consist of long streams of traffic arriving at one or two of the corner posts with only a small number of arrivals using the other approach corridors. It is quite common for these streams of aircraft to stretch well into the en route control sectors with as many as 20 aircraft lined up in trail. Under these circumstances, the speed of each aircraft is controlled and each aircraft is vectored along a similar approach path.

For the purposes of this study, eight unique approach profiles were flown in the simulator and recorded for use as traffic aircraft. These profiles represented the four standard profiles from each corner post, as well as four extended profile patterns modeled after techniques used by controllers for merging and spacing multiple streams of traffic. Figure 7 shows the ground tracks of these eight traffic profiles. The solid lines are the standard profiles, with the dashed lines being the extended profiles. It should be noted that only the short profiles from the KIOWA and KEANN corner posts were modified for the extended profiles. Extensions to the long BYSON and DRAKO profiles would merely consist of extending the downwind segment in a "tromboning" manner, with no significant difference in the profile. Eight unique traffic scenarios were created by defining each traffic profile as the lead aircraft to be followed by the test subjects and selecting three or four of the other profiles to be included as background traffic. The background traffic profiles were carefully merged with the lead aircraft profile to provide a realistic flow of the traffic to final approach with minimum aircraft spacing at the runway threshold. Departing aircraft traffic were not included in the simulated traffic scenarios.

Task Description

The basic piloting task in this study was a manual instrument approach into a terminal area environment. The test subjects were instructed to follow and maintain a specified separation on a lead aircraft which was being directed for landing by typical altitude, speed, and vectoring instructions from ATC. The only instructions the test subjects required from ATC were altitude clearances. The descriptions of the piloting task, initial conditions, and specific ground rules provided to the test subjects are given in appendix A. The test subjects consisted of three NASA research pilots and an Air Force research pilot assigned to NASA Langley Research Center. All test subjects had attended an airline training school and were experienced at flying the Boeing 737 aircraft.

As described previously, the simulator used for this study was a fixed-base, partial-workload cockpit. It was, therefore, impossible to simulate the full-workload environment associated with actual operations. Previous experience had indicated that using the standard two-pilot crew in partial-workload simulations of this type resulted in unrealistically low workload levels. For this reason, a test subject in this study was required to function essentially as a single pilot performing all decision-making functions and traffic display monitoring while exercising total manual control of the simulated aircraft. The only tasks not required of the test subjects were manual operation of landing gear and flaps, tuning of radios to proper navigation frequencies, and changes in traffic display formats. These functions were performed by the test engineer at the verbal requests of the subject pilot.

Air traffic control communications were simulated by having the test engineer relay pertinent ATC commands to the test subjects. This was done by determining the elapsed time from the start of the simulation run until the lead aircraft would need to receive a command from ATC. The times and events were tabulated and used by the test engineer for relay to the test subject at the proper times during the run. Only ATC instructions to the lead aircraft, as well as the subject pilot's altitude clearances, were relayed to the test subjects. This method was chosen as a compromise between a full-party-line ATC simulation and not providing any information at all.

Spacing Criteria

The self-spacing task for this study involved maintaining an indicated (displayed) spacing interval behind a lead aircraft throughout an approach to landing. Selection of a suitable spacing criterion is critical to the successful implementation of such a task. The criterion must ensure safe separation throughout the approach without excess separation, which would reduce the traffic flow rate into the terminal area. In addition, the display of the spacing criterion should be easy to implement and readily understood by the pilot. Finally, the spacing criterion must be achievable within the maneuvering capabilities of the trailing aircraft.

Past simulation studies involving CDTI self-spacing tasks have typically used a constant-distance criterion for spacing. This technique provides a representation of the required spacing interval that is simple, direct, and easy to implement. The major drawback to constant-distance spacing stems from the decelerating speed profiles inherent to landing approach operations. In order to maintain a constant-distance spacing interval, a trailing aircraft must begin to decelerate at the same time the lead aircraft starts to decelerate. Assuming both aircraft have the same landing approach speed, the trailing aircraft will reach this speed at the same time as the lead aircraft but at a distance farther from the runway. This situation is undesirable from an operational efficiency standpoint, since the trailing aircraft would be required to lower flaps earlier than desired, take longer to fly the same approach, and therefore use more fuel. An obvious solution might be to provide a series of constant-distance spacing intervals which would allow a decrease in separation resulting from the deceleration profile of the lead aircraft. This becomes difficult to implement and results in a spacing technique which is dependent on the lead aircraft following a prescribed deceleration profile. For these reasons, it was decided that constant-distance spacing techniques would not be suitable for the approach profiles used in this study.

A time-based spacing criterion that has been used in previous self-spacing simulation studies is the constant-time-predictor technique. This technique accounts for the deceleration of the approach speed profile by basing the required spacing interval at any instant on the current ground speed of the trailing aircraft multiplied by a time constant. The time constant is chosen to provide a minimum safe separation distance at the slowest speed the aircraft will be flying during the approach. This technique is consistent with current electronic horizontal-situation displays, which present time-based predictor vectors indicating where on the map display the aircraft will be after a given time interval at the current ground speed. A possible drawback to this spacing technique is the potential confusion resulting from the change in length of the time-predictor spacing vector on the CDTI as the ground speed of the pilot's aircraft changes. Earlier studies (e.g., ref. 5) have indicated no significant problem with the constant-time-predictor spacing technique, so it was decided to evaluate this technique further in this study.

The second time-based spacing criterion used in this study is referred to as the constant-time-delay technique. This concept essentially provides the pilot with a moving reference mark which defines the desired horizontal location of his aircraft at any given time. The reference mark is a representation of where the leading aircraft had been located on the horizontal map a constant time interval earlier. In effect, by following this moving reference, the pilot's aircraft tracks the same speed profile as the lead aircraft with a time delay in deceleration equal to the selected constant-time-delay interval. Figure 3(a) illustrates the display format used for this spacing technique. The spacing reference mark, referred to as the spacing command bar, was a perpendicular line drawn through the desired point on the path of the lead aircraft where the pilot's aircraft should be located. To the side of this line were numbers representing the previous altitude and ground speed of the lead aircraft at that point on the approach path. The time predictor vector extending from the own-aircraft symbol was retained as an aid in horizontal path following.

RESULTS AND DISCUSSION

A total of 84 simulated approaches were flown by the 4 test subjects in this study. Of these approaches, 20 were practice runs, 59 were good data runs, and 5 runs were lost because of various problems encountered which were not related to the CDTI or to the piloting task. Table I shows the matrix of test conditions, with the 59 runs which were used in the data analysis indicated.

The results obtained from this study are divided into two basic categories, namely, the tracking performance achieved by the test subjects throughout the approach and the accuracy with which the aircraft was delivered to the runway threshold by use of the CDTI self-spacing techniques. The discussion of these results considers the performance achieved by the test subjects in conducting the in-trail following task, the comparison of the two spacing techniques, the pilot opinions of the CDTI display formats, and the implications on pilot workload. The part-task nature of the simulation precludes any detailed analysis of full-mission operational factors or effects on ground-based ATC resulting from the CDTI self-spacing task.

Tracking Performance

Analysis of the tracking performance achieved by the test subjects required an accurate measure of both longitudinal spacing between aircraft and the lateral deviation of the pilot's aircraft from the desired horizontal path. Since the test subjects had been instructed to follow the horizontal ground track of the lead aircraft, lateral deviation is defined as the shortest distance between the pilot's aircraft and the trailing path of the lead aircraft. The distance (projected in the horizontal plane) along the trailing path from the location of the lead aircraft to the point on the path nearest to the pilot's aircraft is defined as the longitudinal spacing. The spacing numbers used in the data analysis thus represent a projected spacing along a defined path rather than the straight-line distance between the aircraft. Defining spacing in this manner provides a more representative measure of spacing performance for path-following situations and facilitates analysis of multiple approaches along the same described path.

The time-based spacing techniques used in this study provided the pilot with a single spacing cue throughout the entire approach. This cue was a graphical indication of the spacing situation presented on the CDTI. Figure 8 illustrates the actual spacing, desired spacing, and spacing error for the constant-time-predictor and constant-time-delay spacing techniques. As noted previously, these distances are measured along the horizontal ground track of the lead aircraft.

A statistical analysis was performed on the spacing error and lateral tracking error data from all the runs in order to compare the performance achieved using the two spacing techniques. For this analysis, each approach profile was divided into three segments corresponding to the type of lateral navigation guidance provided the test subjects during that segment. These segments are described as follows:

Segment 1 - Extends from entry corner post to the point on the approach where the initial turn is encountered. Lateral guidance is provided by the trailing path of the lead aircraft plus the straight-line radial drawn on the CDTI map.

Segment 2 - Extends from the initial turn until roll-out onto final approach. Lateral guidance is provided solely by the trailing path of the lead aircraft.

Segment 3 - Extends from the end of segment 2 until the lead aircraft crosses the runway threshold. Lateral guidance is provided by instrument landing system (ILS) localizer indications on the flight director.

An example of the three segments of the approach from the BYSON corner post is shown in figure 9.

Position and velocity data for both the pilot's aircraft and the lead aircraft were recorded at 1-sec intervals throughout each approach. These data were then processed to provide average and root-mean-square (rms) values for the spacing and lateral tracking errors during each of the three segments of each approach. For a given spacing technique (constant time predictor (CTP) or constant time delay (CTD)), the values of average and rms spacing and lateral tracking errors obtained from the same segment of all the approaches were assumed to follow approximate normal distributions when pooled together. This allowed calculation of mean and standard deviation values which were used for statistical t-test comparisons of the two spacing techniques. (See ref. 6 for statistical methods used.)

Figure 10 presents the confidence intervals calculated for the mean of the average spacing errors and for the mean of the rms spacing errors during each of the three approach segments. The intervals were calculated at the 95-percent confidence level using the equations for a standard t-distribution with sample sizes of 32 for the constant-time-predictor data and 27 for the constant-time-delay data.

The average spacing errors for the two spacing techniques, presented in figure 10(a), are essentially the same with overlapping confidence intervals centered roughly at 0.1 n.mi. positive error. The results of a t-test on the average spacing data revealed no significant difference between the means of the average spacing errors for the two spacing techniques (table II). The positive values of the average spacing errors indicate an average spacing greater than the desired spacing for both the criteria. This result agrees with data obtained from previous self-spacing studies (refs. 3 and 4) showing a pilot tendency to hold a spacing interval which is slightly greater than commanded.

The rms spacing error values for the two spacing techniques, presented in figure 10(b), are noticeably different. The 95-percent confidence intervals for the means of the rms values for the two spacing techniques do not overlap during segments 1 and 3 and only slightly overlap during segment 2 of the approach. The results of a t-test on the rms spacing error clearly indicate a significant difference between the mean values of the rms spacing errors for the two spacing techniques during all three segments (table II). Constant-time-delay spacing results in lower rms values of spacing error, indicating more accurate spacing performance achieved using this technique.

The confidence intervals calculated for the mean of the average lateral tracking errors and the mean of the rms lateral tracking errors during the three approach segments are presented in figure 11. Once again, the intervals were calculated at the 95-percent confidence level in the same manner as the spacing error confidence intervals.

Table III presents the results of t-tests of the lateral tracking error data for the two spacing techniques. No significant differences between the two techniques are indicated in either average lateral tracking error or rms lateral tracking error. The rms lateral tracking error during segment 2 has the largest t-value. Figure 11(b) also indicates a larger confidence interval for the mean of the rms lateral tracking error for the CTD technique in that segment. These results suggest a possible difference in lateral tracking accuracy during segment 2; however, the data from this study do not indicate any significant differences.

Pilot comments and ratings of the display formats were obtained following each simulated approach. The pilots were asked to rate the suitability of the display format for performing the path-following and self-spacing tasks using the rating scale given in appendix A. A rating of 3 or less indicated the display format was satisfactory, with a rating of 1 being the most desirable. A rating of 4 to 6 indicated the display was still acceptable, although modifications would be required to make it satisfactory. A rating of 7 or greater indicated major shortcomings resulting in a totally unacceptable display.

The results of the pilot ratings of display suitability for the self-spacing and path-following aspects of the tracking task are presented in figures 12 and 13. The constant-time-delay format received better overall ratings for the self-spacing task, with the constant-time-predictor format having a slight edge for the path-following task. Both display formats received acceptable ratings; however, a large percentage of the ratings indicate some unsatisfactory aspects of the displays. Pilot comments and responses to the questionnaire given in appendix A were obtained to determine reasons behind the subjective ratings.

A major objection raised by two of the test subjects was the lack of guidance information present in the display. They would have preferred a spacing cue that told them what to do (e.g., slow down or speed up) rather than merely what the spacing error was. The constant-time-predictor format was cited as especially needing this type of guidance since changes in the pilot's ground speed directly affected the displayed spacing error, and proper spacing strategy was not always obvious. The other two test subjects liked the situational presentation of the spacing cues; however, they agreed the workload involved with that type of display was high when coupled with the manual flight-control task.

Minor objections to the displays involved clutter and the excessive time required to extract the desired information from the display. Color coding of the symbology was cited as a method to improve the display and to enhance readability. The discrete update of traffic positions at 4-sec intervals was cited as a prime factor in the excessive dwell time required to extract spacing information from the display. This problem was especially noticeable because the display was located in the weather radar position and thus outside the pilot's primary scan. A faster update interval for the traffic was suggested as a method to lower the CDTI dwell time requirements. Pilot comments further indicated that the constant-time-delay format focused their attention on their own-aircraft symbol and reduced the amount of predictive path information obtained from the display.

At this point it should be noted that many of the pilot objections were related to the manual control system of the simulator. The primary objection was to the highly sensitive nature of the control system, which required a very minor control input to produce a response. Although the high sensitivity of this system had been somewhat of a problem in previous studies, the added workload resulting from the characteristics of this control system was considered a positive factor in those studies because it compensated for reduced workload stemming from the part-task nature of the simulation. In the current study, the approach task was more complicated than in the previous self-spacing studies, and the sensitivity in the simulator control system presented the pilot with a very high workload. At the conclusion of the study, pilot comments were solicited concerning the effect of the control system on their performance. These comments indicated that the overall piloting workload did not preclude assessment of the display formats or of the self-spacing task. There was some concern about the absolute spacing and tracking performance achieved being worse than would be the case under two-crew-member operations with a good airplane control system. All the test subjects stressed the need to evaluate CDTI self-spacing under more realistic conditions.

Delivery Accuracy

The delivery accuracy achieved using the self-spacing techniques was measured in terms of the time interval between the lead aircraft crossing the runway threshold and the trailing aircraft arriving at the runway threshold. This time interval, referred to as interarrival time (IAT), is frequently used as a parameter in defining arrival capacity for a particular runway. More specifically, the less the IAT varies from the mean IAT, the shorter the mean IAT can be for an equivalent level of safety. Figure 14 illustrates this effect of IAT dispersion on runway arrival capacity. As shown, for a given minimum allowable IAT, the mean IAT of a distribution of times with a low dispersion can be less than the mean of a distribution with a higher dispersion. Since a shorter mean IAT results in an increase in arrival capacity, it is desirable to minimize the dispersion of IAT (ref. 7).

The self-spacing techniques evaluated in this study provided the pilots with time-based spacing cues. The time constant associated with the spacing cues is directly related to the desired IAT between the lead aircraft and the pilot's aircraft. The time-delay interval of the constant-time-delay spacing technique (80 sec in this study) is equal to the desired mean IAT, assuming both aircraft fly the same final approach speed. Aircraft with different approach speeds would need to adjust the time-delay spacing interval in order to achieve a consistent mean IAT. The lead and the trailing aircraft in this study flew the same final approach speed, thus simplifying the analysis of delivery accuracy for the constant-time-delay spacing runs. For the constant-time-predictor spacing technique, the time constant is also equal to the IAT, assuming the aircraft maintains its final speed after the lead aircraft crosses the threshold. Therefore, the desired IAT for all approaches in this study is equal to the time constant of 80 sec used for both self-spacing techniques.

Histograms of the actual IAT's obtained from the simulated approaches are presented in figure 15. The distribution of times from the constant-time-delay spacing runs exhibit a mean IAT of approximately 1 sec greater than the desired time of 80 sec, with a standard deviation of 8 sec. The constant-time-predictor distribution has a shift of nearly 11 sec in mean IAT with a standard deviation of approximately 7 sec. Applying a two-tailed t-test to the IAT distributions reveals a statistically significant difference between the mean IAT's of the two spacing techniques. Pooling the standard deviations of the two distributions results in a t-value of 5.208 compared with a table value of 2.665 for the two-tailed t-test at a significance of 1 percent. This shift in the mean IAT for the constant-time-predictor spacing technique prompted a closer evaluation of the two spacing techniques.

Speed profiles and the resultant spacing time histories for ideal following of the same lead aircraft using both constant-time-delay and constant-time-predictor spacing techniques were calculated for each of the eight lead aircraft profiles. Appendix B describes the equations used for calculating these ideal profiles. Figure 16 presents an example of the speed-profile and spacing time histories for ideal following of a typical lead aircraft for both spacing techniques. The ideal constant-time-delay speed profile is identical to the profile of the lead aircraft with a shift in time equal to the spacing time constant (80 sec in this case). The ideal constant-time-predictor speed profile, on the other hand, is characterized by early deceleration with relatively smooth and shallow deceleration rates. As a result, when the lead aircraft crosses the runway threshold, the trailing aircraft, following the speed profile for ideal constant-time-predictor spacing, is at a higher speed and has a greater spacing interval than would be the case with the constant-time-delay spacing. The aircraft using constant-time-predictor spacing must continue to the runway threshold at this final value of ground speed in order to arrive at the desired IAT. Since the aircraft is constrained to a specified landing speed, it must depart from the ideal profile and decelerate to landing approach speed. The resulting increase in time is a problem which is inherent to operational use of the constant-time-predictor spacing technique.

Operationally required ideal speed profiles were calculated for constant-time-predictor following of the eight lead aircraft profiles used in this study. These "ideal" profiles were identical to the profiles calculated with the equations in appendix B up to the time when the lead aircraft crossed the runway threshold. At this point, the aircraft were assumed to make a nominal 1 knot/sec deceleration to final approach speed. From these profiles, "operationally ideal" IAT's were calculated. The table below gives these IAT's for both the constant-time-predictor and the constant-time-delay spacing techniques for the eight lead aircraft profiles.

Lead aircraft	Operationally ideal IAT, sec, for –	
	Constant-time-delay technique	Constant-time-predictor technique
1	80.0	85.7
2	↓	92.1
3	↓	91.7
4	↓	87.5
5	↓	87.0
6	↓	87.6
7	↓	90.5
8	↓	86.4

The inherent increase in IAT with constant-time-predictor spacing is clearly evident in this table. The IAT data presented in figure 14 were reanalyzed in terms of these operationally ideal times. An IAT error, defined as actual IAT minus ideal IAT, was calculated for each approach. These error values are plotted in histogram form in figure 17 for both spacing techniques. The large shift in mean IAT, present in the constant-time-predictor data in figure 15, has been almost entirely eliminated. Both constant-time-predictor and constant-time-delay techniques exhibit a slight shift in mean IAT error, with constant-time-predictor mean error being approximately 1.5 sec greater than the constant-time-delay mean error. The pooled standard deviation for the two IAT-error distributions is 7.6 sec. The t-value from the two-tailed t-test for these IAT-error distributions is 0.80, which indicates no significant difference in mean IAT's between the two distributions. These results indicate the inherent increase in IAT present in the constant-time-predictor spacing technique is responsible for the bulk of the mean IAT shift noted in figure 15.

The dispersions in arrival time errors shown in figure 17 indicate a slightly lower standard deviation for the constant-time-predictor technique. This result appears to be contradictory to the results presented in the "Tracking Performance" data analysis section. That analysis revealed a statistically significant advantage in spacing accuracy using the constant-time-delay technique (fig. 11(b) and table II). The reason for this apparent contradiction is the manner in which spacing error was defined in the spacing performance analysis. In figure 8, the spacing error values were referenced to the displayed spacing cues. The spacing error for the constant-time-delay technique represents the actual error in distance from the ideal spacing location. For the constant-time-predictor technique, the displayed spacing error represents the actual error in distance from the ideal spacing location only if the trailing aircraft is at the speed for ideal following as defined by equation (5) in appendix B. Therefore, any variations in speed from the speed profile for ideal following would result in variations of displayed spacing error which do not represent errors from the ideal spacing location. Since the dispersions in IAT errors shown in figure 17 indicate actual spacing errors from ideal spacing, it would be inappropriate to compare these results with the displayed spacing error results for the constant-time-predictor spacing technique. In addition, the comparison of spacing performance for the two spacing techniques presented in figure 11 and table II is applicable only to displayed spacing performance and does not represent a comparison of spacing performance in terms of actual spacing errors as represented by delivery accuracy. Such a comparison can be made by defining ideal spacing error as the difference between actual spacing location and the desired spacing location resulting from ideal following.

An analysis of the spacing performance referenced to ideal spacing was performed in the same manner as the analysis of displayed spacing performance presented in the "Tracking Performance" section. Figure 18 shows the 95-percent confidence intervals calculated for the means of the average ideal spacing errors and of the rms ideal spacing errors during each of the three approach segments. The t-values for the t-test between the two spacing techniques are given in table IV. The results of this analysis reveal no significant differences in spacing performance between the two spacing techniques when the spacing error is referenced to the ideal spacing profile. Therefore, although there is a significant difference in the displayed spacing accuracy achieved using the two spacing techniques, there appears to be no significant difference in actual delivery accuracy achieved using either the constant-time-predictor or the constant-time-delay spacing.

CONCLUSIONS

A piloted simulation was conducted to evaluate two time-based self-spacing techniques using a cockpit display of traffic information (CDTI) during approach to landing in a terminal area vectoring environment. The following conclusions are based on the results of this study:

1. The information provided by the CDTI proved to be adequate for the test subjects to follow the approach path of a preceding aircraft in a high-density terminal area without the assistance of ground air traffic control.

2. Pilot comments indicated that the 4-sec update interval of the traffic locations on the CDTI, coupled with the location of the display out of the pilot's primary scan, resulted in an increase in dwell time on the CDTI which would not be necessary if the traffic were updated at a faster rate. Further comments suggested that an autopilot and/or additional spacing guidance information are desirable to lower the overall workload associated with the approach and self-spacing tasks.

3. The spacing cue implemented for the constant-time-delay spacing technique was found to produce a significantly lower dispersion in displayed spacing error. Actual spacing accuracy, measured in terms of deviations from ideal spacing, was not significantly different for the two spacing techniques. The pooled standard deviation of interarrival times at the runway threshold for the two spacing techniques was 7.6 sec.

4. The mean interarrival time achieved at the runway threshold using the constant-time-delay spacing technique was 80.9 sec with a standard deviation of 8.0 sec. The ideal interarrival time was 80.0 sec.

5. The constant-time-predictor spacing technique, as implemented, produced an inherent slow down in the overall speed profile of the trailing aircraft. The result was a mean interarrival time of 91.0 sec with a standard deviation of 6.9 sec. The desired interarrival time was 80.0 sec.

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Hampton, VA 23665
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APPENDIX A

PILOT INSTRUCTIONS AND QUESTIONNAIRE

Pilot Instructions

You are flying a twin-engine jet transport (B-737) on an IFR approach into Denver Stapleton Airport. Your task is to utilize a CDTI mounted in the weather radar location to follow and maintain separation on a preceding aircraft while manually controlling your own aircraft. The aircraft you are following is being directed by altitude, speed, and vectoring instructions from Air Traffic Control in a manner representative of current Denver approach procedures. ATC will monitor your approach and provide you with altitude clearance as necessary.

Initial Conditions

Your aircraft is trimmed in an idle thrust descent crossing into Denver TRACON airspace at one of the four corner-post locations. You have been cleared to descend and maintain 11 000 ft altitude while following and maintaining a separation of 80 sec (time predictor or time delay) on the aircraft preceding you.

Specific Ground Rules

1. Your primary task is to follow the path of the preceding aircraft while maintaining a specified separation on that aircraft. Path deviations to adjust spacing are not permitted unless required to prevent a hazardous situation.

2. A test engineer will serve as your copilot during this study. His functions will be limited to the manual tasks of operating the flaps and gear at your request and informing you of ATC instructions, both to you and the aircraft you are following. He will not assist you in monitoring the CDTI or flight instruments.

3. Landing gear and flap airspeed limitations should be strictly observed.

4. Every effort should be made to fly the aircraft in a manner which you feel would be acceptable for airline operations.

Pilot Rating Scale

Use the following scale to rate the suitability of the display format for the path-following and self-spacing tasks following each simulation run.

Category	Description	Numerical rating
Satisfactory	Excellent Good, negligible deficiencies Fair, mild deficiencies	1 2 3

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Category	Description	Numerical rating
Unsatisfactory	Minor deficiencies, moderate pilot compensation required	4
	Moderate deficiencies, considerable pilot compensation required	5
	Very objectionable deficiencies, extensive pilot compensation required	6
Unacceptable	Major deficiencies, required information is too difficult to extract	7
	Major deficiencies, required information is not provided	8
	Major deficiencies, displayed information is misleading	9
Hazardous	Major deficiencies, displayed information will result in a hazardous situation	10

Pilot Questionnaire

Display Questions

1. Did the trail of past position dots left by the aircraft you were following provide you with adequate information to accurately follow the path of that aircraft?

2. Comment on the shortcomings of the display for the path-following task and improvements you feel would be beneficial.

3. Did the time predictor spacing criteria provide you with adequate information to accurately self-space on the target aircraft? Comment.

4. Did the time delay spacing criteria provide you with adequate information to accurately self-space on the target aircraft? Comment.

5. Do you feel a display such as this would be acceptable for operational self-spacing and following in a terminal-area environment? Elaborate.

Piloting Task and Workload Questions

1. What effect did the location of the CDTI have on your ability to carry out the piloting task?

2. Do you think the workload associated with flying a manual approach in this simulator was representative of that associated with flying a B-737 on an ILS approach into a terminal area such as Denver? If not, explain the difference.

APPENDIX A

3. Did the fixed-base (i.e., no motion cues) nature of the simulator adversely affect your performance? Explain.

4. Do you think an operational autopilot, such as the one available on the B-737, would have made a significant difference in your performance? Explain.

5. What suggestions do you have for improving future display studies utilizing a simulator such as the one used in this study?

APPENDIX B

IDEAL SPACING PERFORMANCE

The self-spacing task in this study involved maintaining a specified time-based spacing interval behind a preceding aircraft. For a given lead aircraft speed profile there is a corresponding unique speed profile for the trailing aircraft which allows maintenance of the desired spacing time interval throughout the entire approach. The purpose of this appendix is to present the basic equations which were used with the constant-time-predictor and the constant-time-delay spacing techniques to calculate the speed profiles for ideal following of the eight lead aircraft used in this study.

Constant Time Predictor

The desired spacing interval for the constant-time-predictor spacing technique at any point along the approach is equal to the distance the aircraft would travel at its current ground speed for the time interval specified by the spacing time constant. The actual spacing interval is equal to the horizontal distance between the two aircraft along the common ground track they are following. These spacing intervals can be written mathematically as functions of time as follows:

$$S_d(t) = T_c\, V_o(t) \tag{1}$$

$$S_a(t) = r_t(t) - r_o(t) \tag{2}$$

where

$S_d(t)$	desired spacing interval
T_c	spacing time constant
$V_o(t)$	ground speed of pilot's aircraft
$S_a(t)$	actual spacing interval
$r_t(t)$	ground range of target aircraft from common reference point
$r_o(t)$	ground range of pilot's aircraft from common reference point

Ideal spacing is achieved when the actual spacing interval is equal to the desired spacing interval, as follows:

$$S_d(t) = S_a(t) \tag{3}$$

Then,

$$T_c\, V_o(t) = r_t(t) - r_o(t) \tag{4}$$

Differentiating equation (4) and arranging terms yields

$$\frac{dV_o(t)}{dt} + \frac{1}{T_c} V_o(t) = \frac{1}{T_c} V_t(t) \tag{5}$$

where

$$V_o(t) = \frac{dr_o(t)}{dt}$$

$$V_t(t) = \frac{dr_t(t)}{dt}$$

Equation (5) is now a linear first-order differential equation which can be solved for $V_o(t)$. Since the speed profiles of the target aircraft are known, time histories of $V_o(t)$ can be generated through a simple numerical solution of equation (5).

This technique was used to generate a unique speed profile for ideal constant-time-predictor following of each target aircraft used in this study. Once the target aircraft crossed the runway threshold, the pilot's aircraft continued at its final value of ground speed until it reached the runway threshold.

Constant Time Delay

Speed profiles for ideal constant-time-delay following are much simpler to obtain. The desired spacing interval is solely a function of the approach profile of the target aircraft. The separation equations for this case are given by

$$S_d(t) = r_t(t) - r_t(t-T_D) \tag{6}$$

and

$$S_a(t) = r_t(t) - r_o(t) \tag{7}$$

where T_D is the spacing time constant. Setting actual spacing equal to desired spacing yields

$$S_d(t) = S_a(t) \tag{8}$$

and

$$r_t(t) - r_t(t-T_D) = r_t(t) - r_o(t)$$

Therefore,

$$r_o(t) = r_t(t-T_D) \tag{9}$$

Differentiating yields

$$V_o(t) = V_t(t-T_D) \tag{10}$$

The speed profile for ideal constant-time-delay spacing described by equation (10) is seen to be simply the speed profile of the target aircraft shifted in time by the spacing time constant. Ideal speed profiles for constant-time-delay following of each of the target aircraft in this study were determined in this manner.

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TABLE I.- MATRIX OF TEST CONDITIONS

Traffic profile	Pilot 1		Pilot 2		Pilot 3		Pilot 4	
	Constant time predictor	Constant time delay	Constant time predictor	Constant time delay	Constant time predictor	Constant time delay	Constant time predictor	Constant time delay
1	X	X	X	X	X	X	X	X
2	X	X	X	X	X	X	X	X
3	X	X	X	X	X	X	X	X
4	X	X	X	X	X	X	X	X
5	X	X	X	X	X	(a)	X	X
6	X	X	X	(a)	X	(a)	X	X
7	X	X	X	X	X	(a)	X	X
8	X	X	X	X	X	(a)	X	X

[a]Data from this condition were not obtained.

TABLE II.- t-VALUES FOR SPACING PERFORMANCE COMPARISON

Approach segment	CTP spacing		CTD spacing		t-value[a]
	Mean	Standard deviation	Mean	Standard deviation	
Average spacing error, n.mi.					
1	0.082	0.200	0.079	0.108	0.073
2	.158	.337	.117	.243	.541
3	.152	.295	.114	.206	.580
rms spacing error, n.mi.					
1	0.280	0.134	0.164	0.083	[b]4.060
2	.424	.218	.303	.190	[c]2.278
3	.356	.175	.237	.119	[b]3.092

[a]Assumes unequal population variances (ref. 6).
[b]Indicates 1-percent significance level.
[c]Indicates 5-percent significance level.

TABLE III.- t-VALUES FOR LATERAL TRACKING PERFORMANCE COMPARISON

Approach segment	CTP spacing		CTD spacing		t-value[a]
	Mean	Standard deviation	Mean	Standard deviation	
Average lateral tracking error, n.mi.					
1	0.002	0.091	0.011	0.091	-0.378
2	-.030	.080	-.037	.079	.337
3	.005	.027	.002	.011	.575
rms lateral tracking error, n.mi.					
1	0.105	0.051	0.103	0.051	0.150
2	.152	.050	.186	.110	-1.482
3	.016	.037	.013	.017	.410

[a]Assumes unequal population variances (ref. 6).

TABLE IV.- t-VALUES FOR IDEAL SPACING PERFORMANCE COMPARISON

Approach segment	CTP spacing		CTD spacing		t-value[a]
	Mean	Standard deviation	Mean	Standard deviation	
Average spacing error,[b] n.mi.					
1	0.036	0.105	0.079	0.108	-1.543
2	.102	.252	.117	.243	-.232
3	.115	.277	.114	.206	.016
rms spacing error,[b] n.mi.					
1	0.123	0.079	0.164	0.083	-1.932
2	.264	.169	.303	.190	-.826
3	.249	.174	.237	.119	.313

[a]Assumes unequal population variances (ref. 6).
[b]Referenced to ideal profile.

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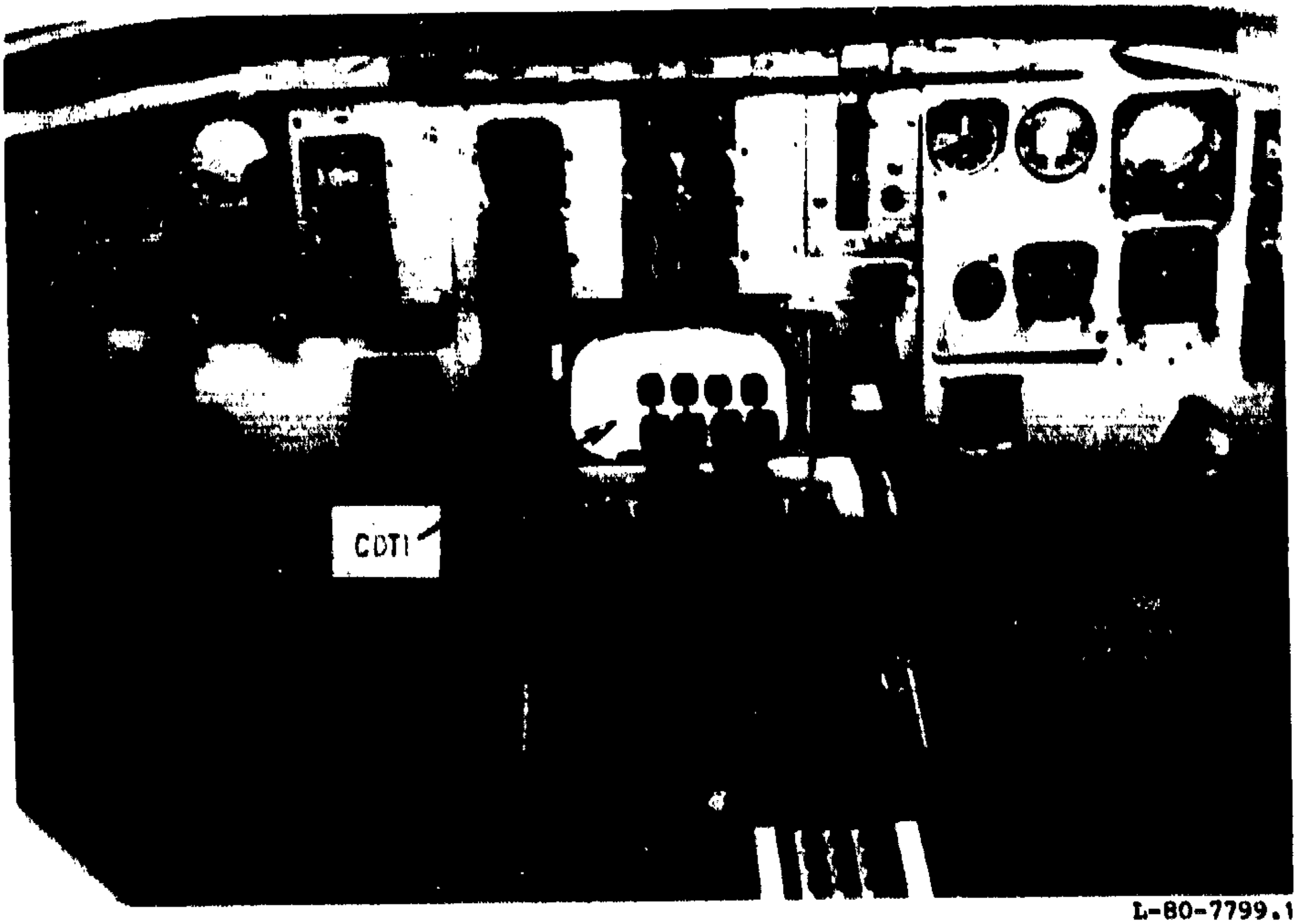

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Figure 1.- Simulator cockpit with cockpit display of traffic information (CDTI).

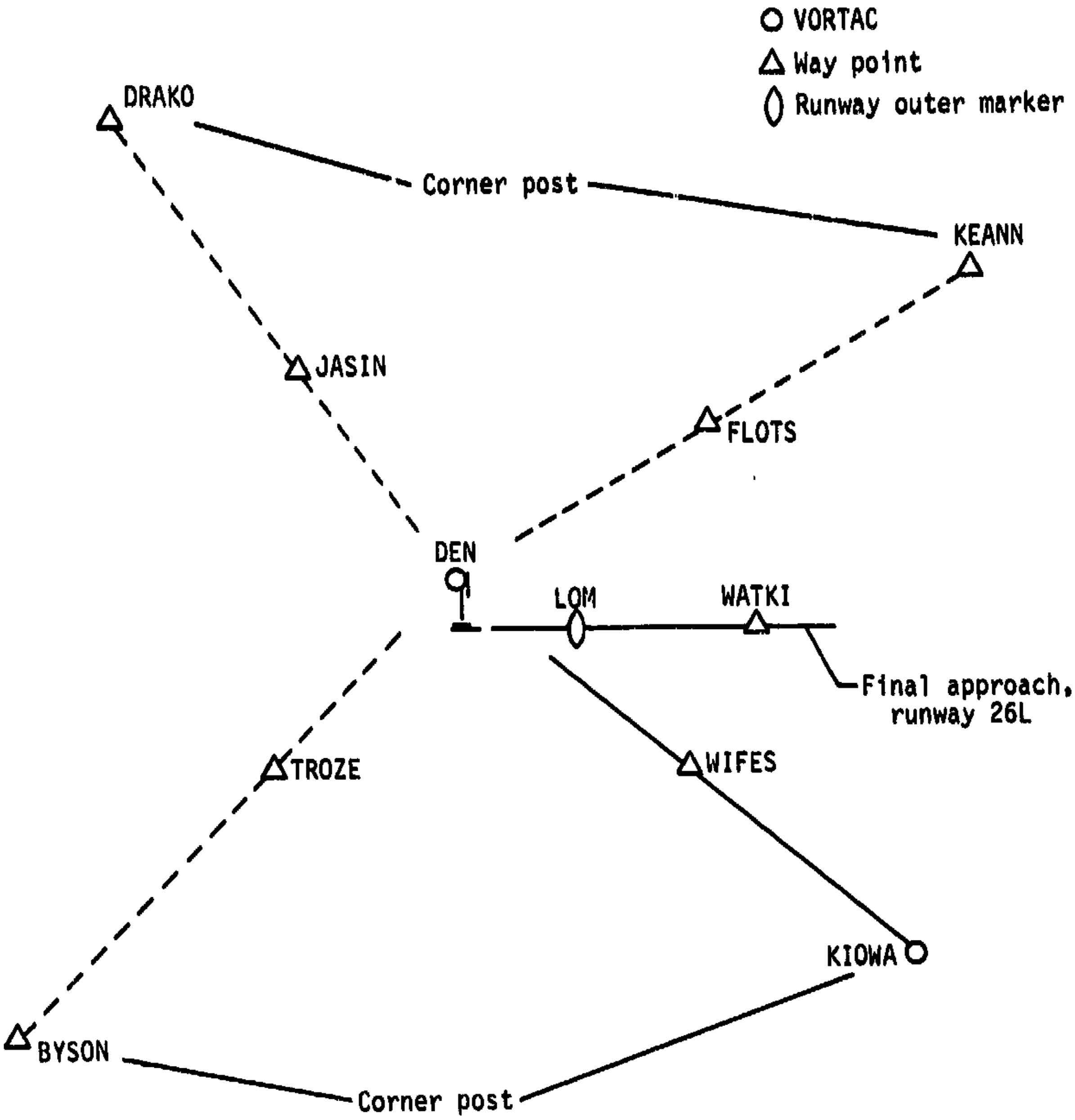
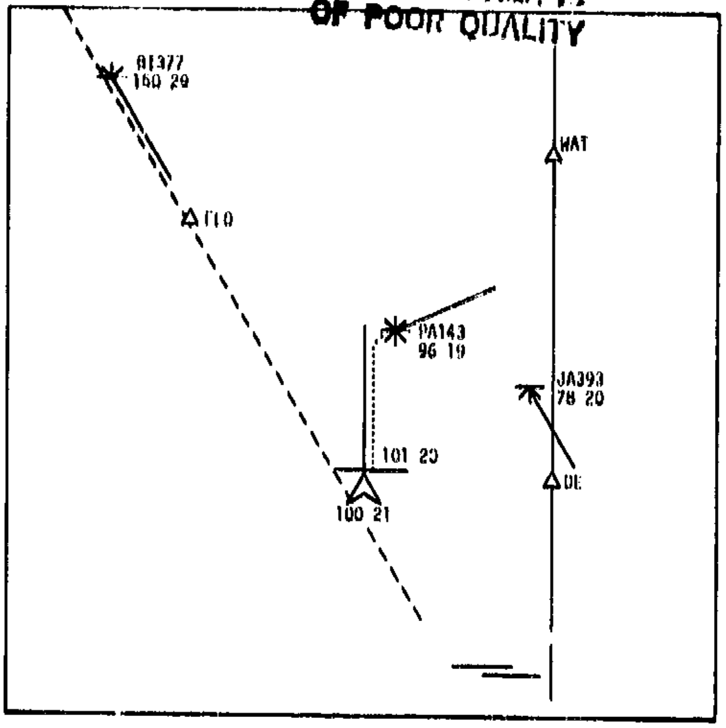
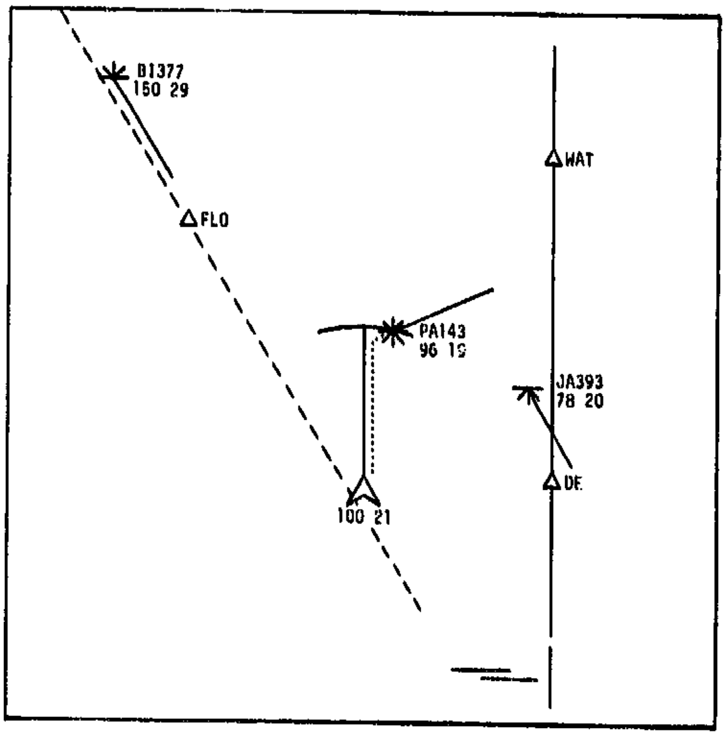


Figure 2.- Map display format.

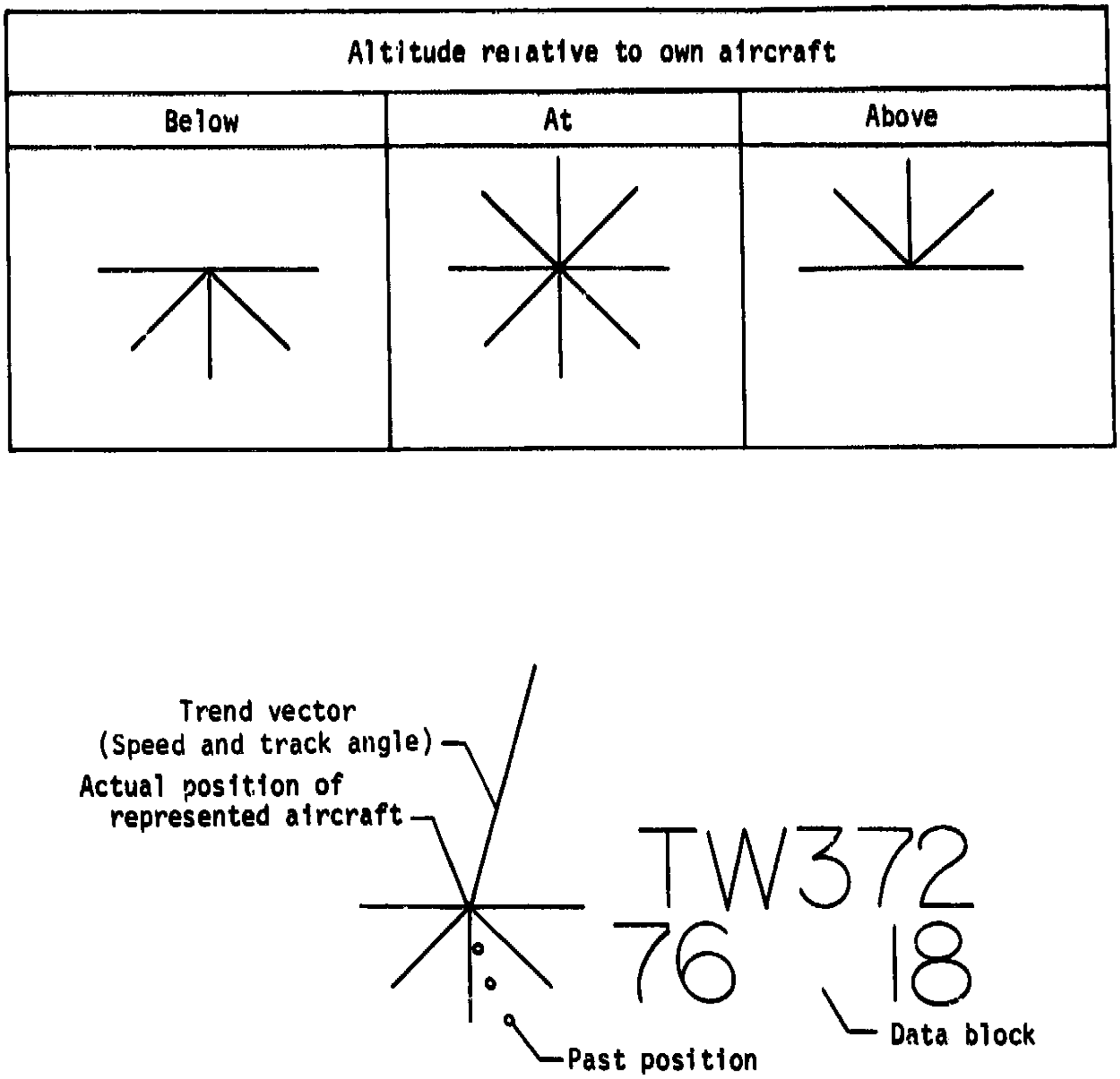


(a) Constant-time-delay spacing.



(b) Constant-time-predictor spacing.

Figure 3.- CDTI formats for the spacing techniques.



Data-block format
Identifier
Altitude/100 Speed/10

Figure 4.- Traffic symbology for information provided to pilot.

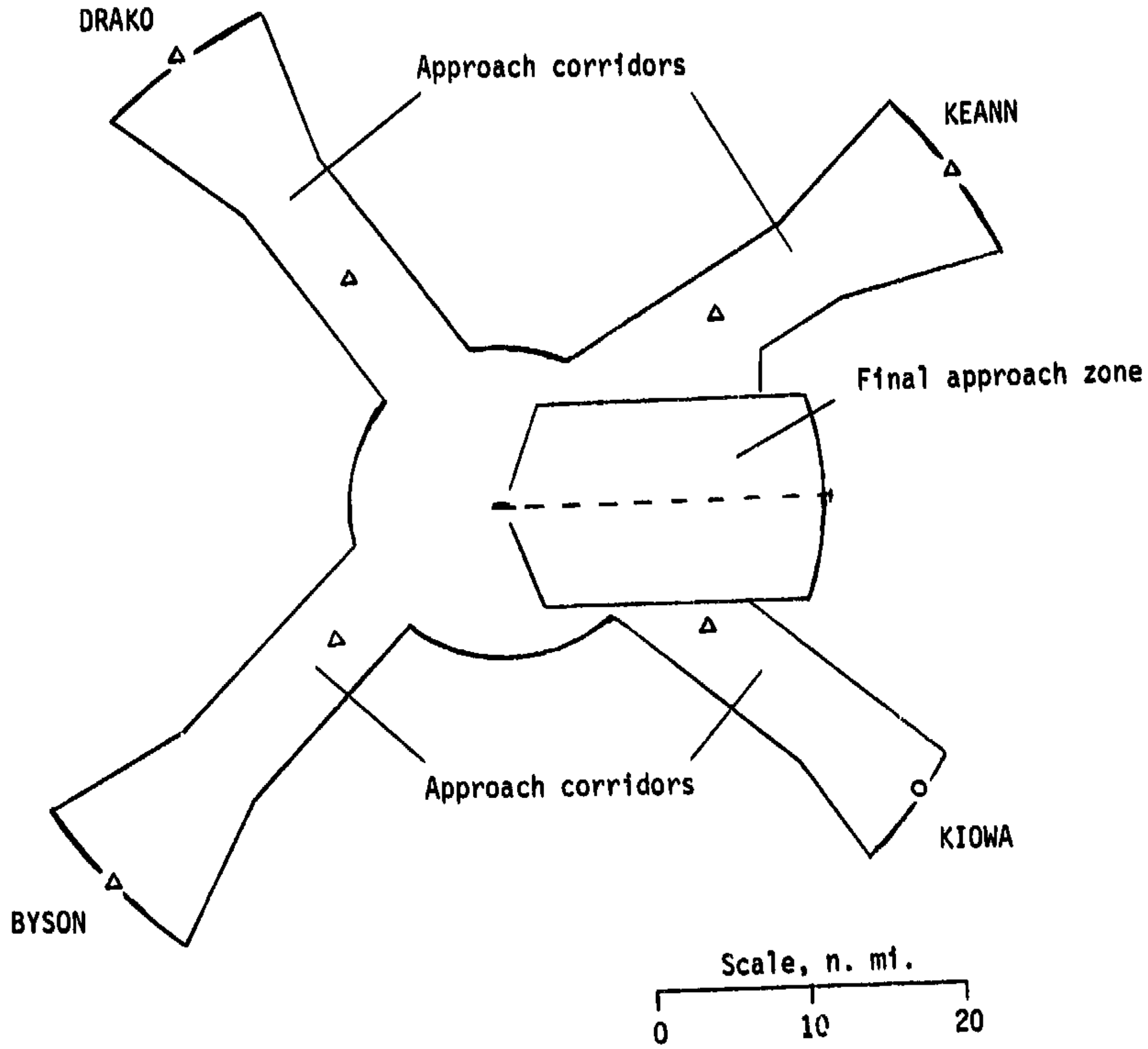


Figure 5.- Horizontal slice of test scenario approach airspace configuration.

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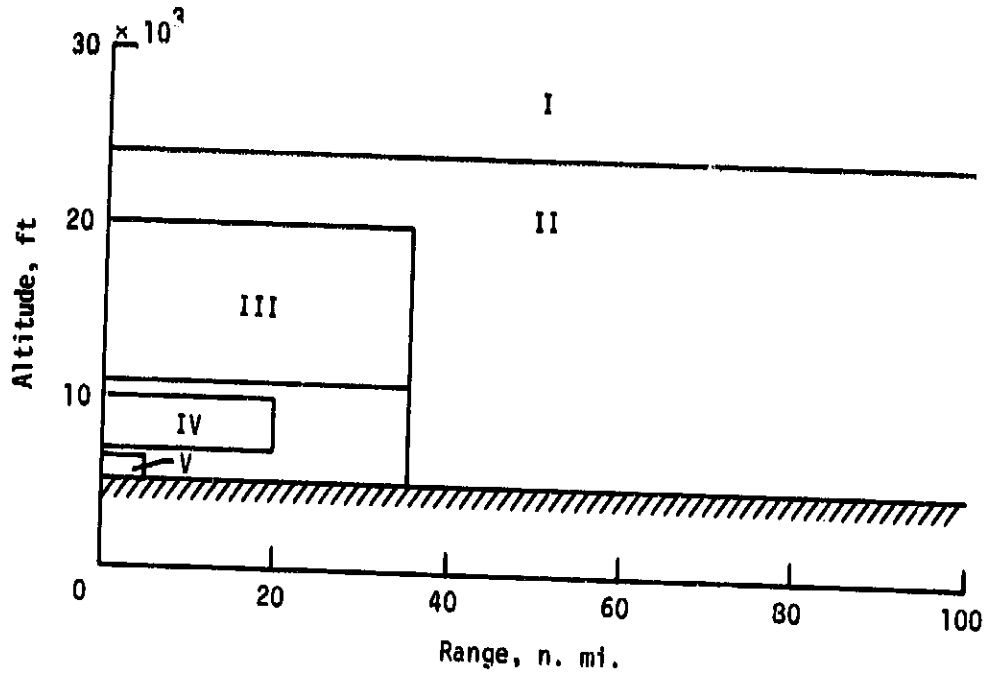

Approach airspace segment	Altitude; Typical distance from runway; Responsible controller	Significant events
I	Above 24 000 ft; Greater than 80 n. mi.; High altitude en route	Descent clearance
II	20 000 to 24 000 ft; Greater than 35 n. mi.; Low altitude en route	Profile descent clearance into Denver terminal area
III	11 000 to 20 000 ft; 10 to 35 n. mi.; Approach control	Vectored to final approach zone
IV	7 000 to 10 000 ft; 5 to 20 n. mi.; Final approach control	Vectored to ILS
V	Ground to 6 500 ft; 0 to 5 n. mi.; Local control	Landing clearance

Figure 6.- Vertical slice from airport eastward of test scenario approach airspace segments.

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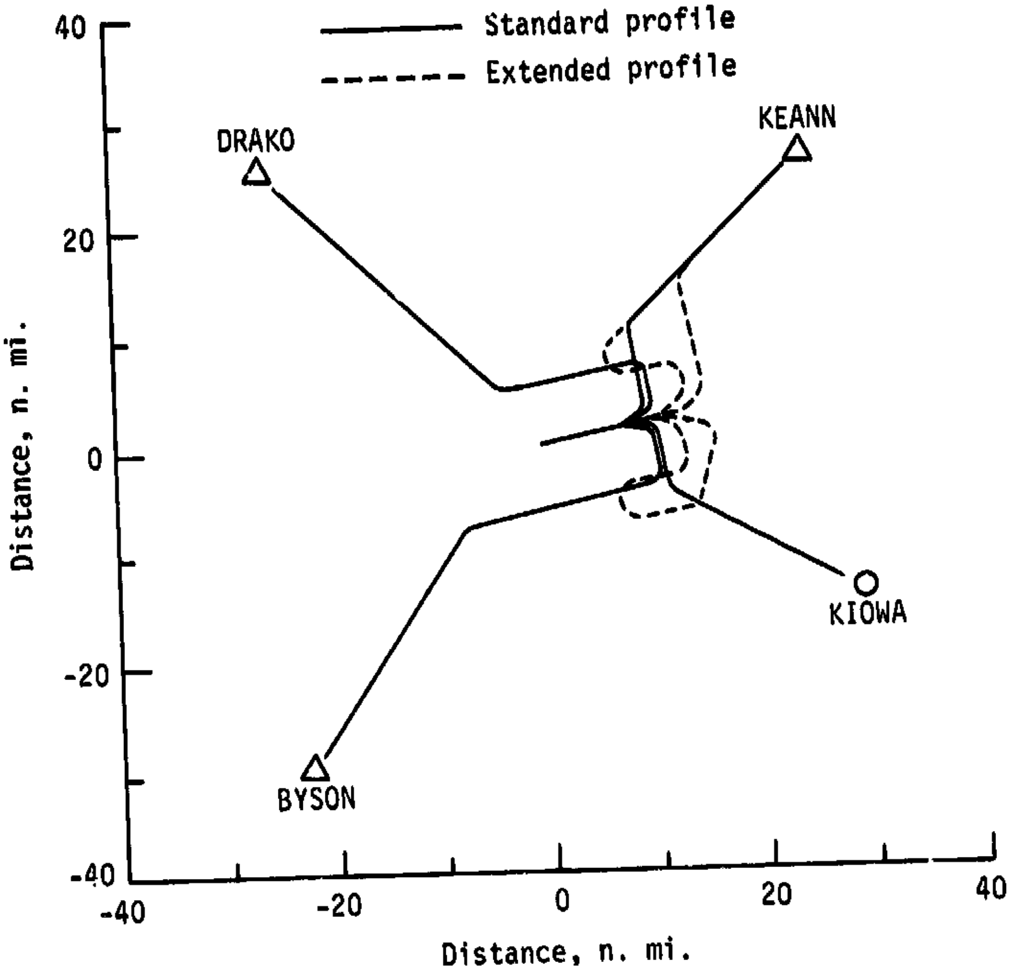
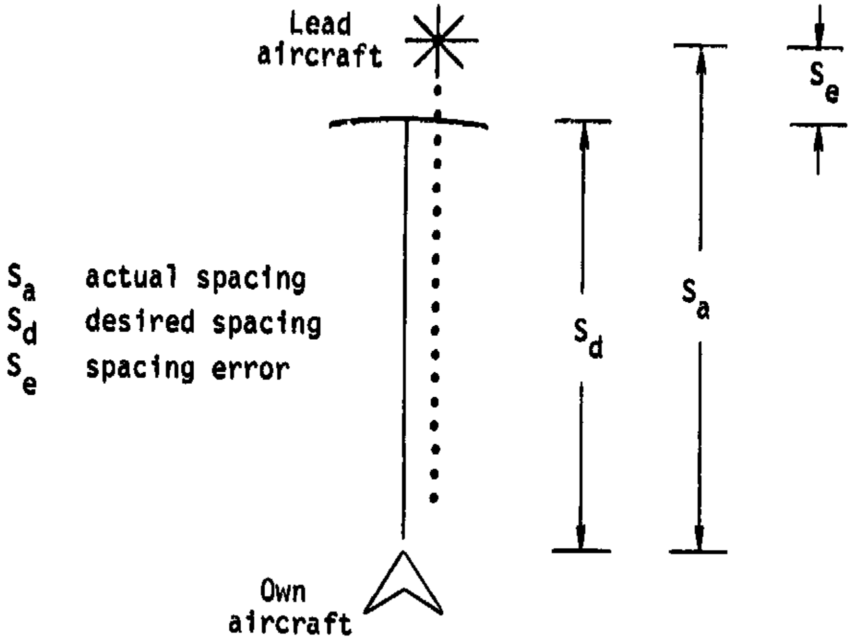
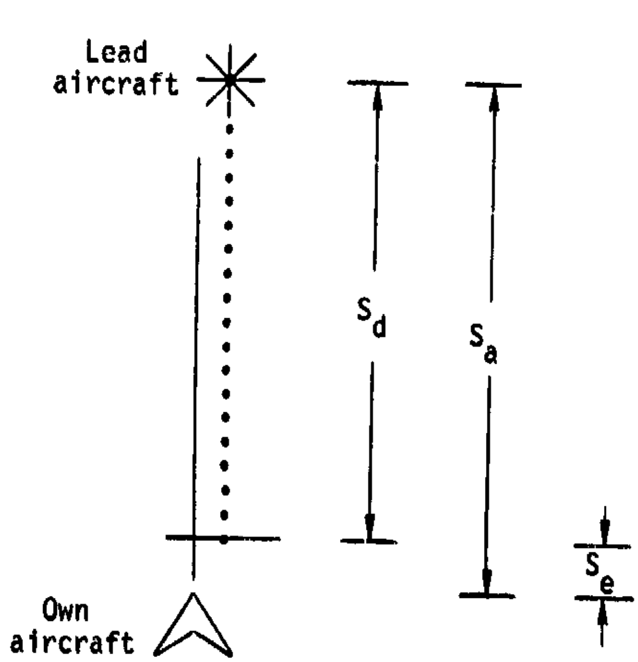


Figure 7.- Ground tracks of lead-aircraft approach profiles.



(a) Constant-time-predictor spacing.



(b) Constant-time-delay spacing.

Figure 8.- Illustration of actual spacing, desired spacing, and spacing error for two spacing techniques.

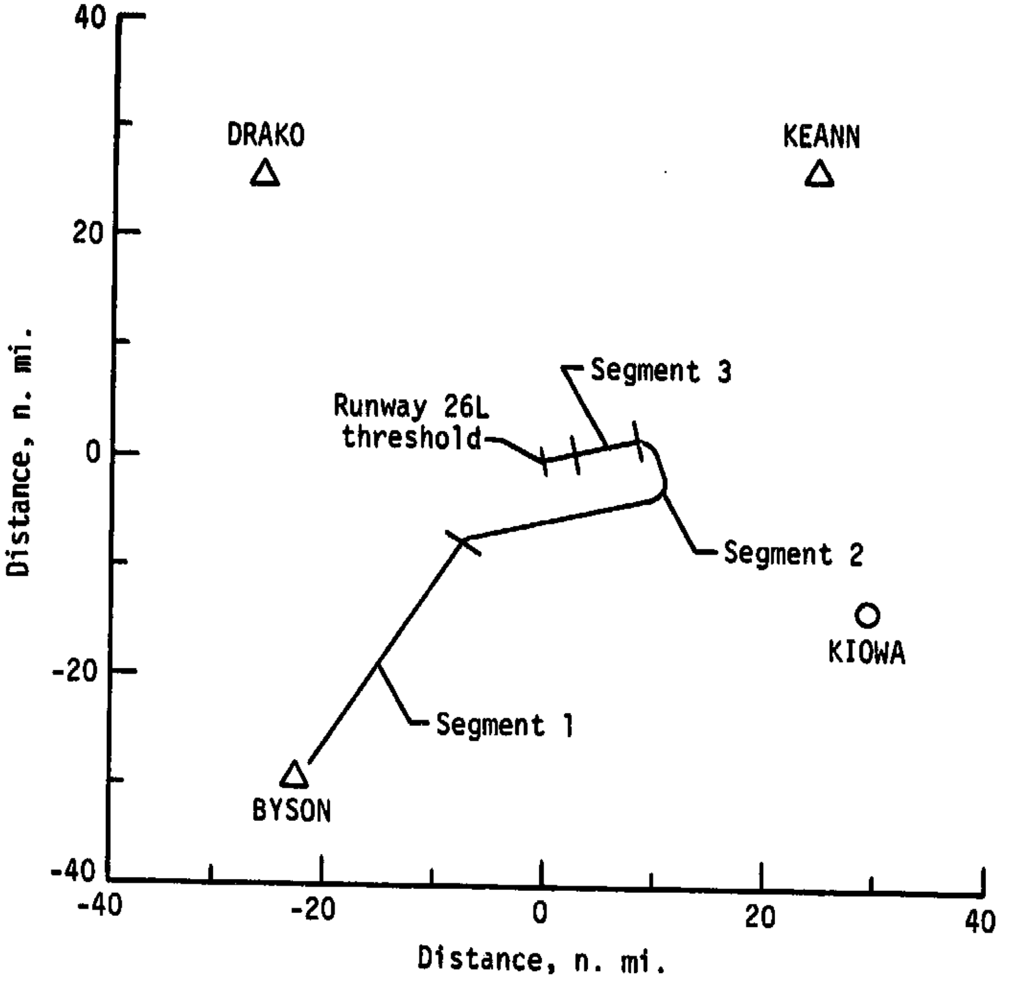


Figure 9.- Illustration of three approach segments used for statistical analysis of tracking performance.

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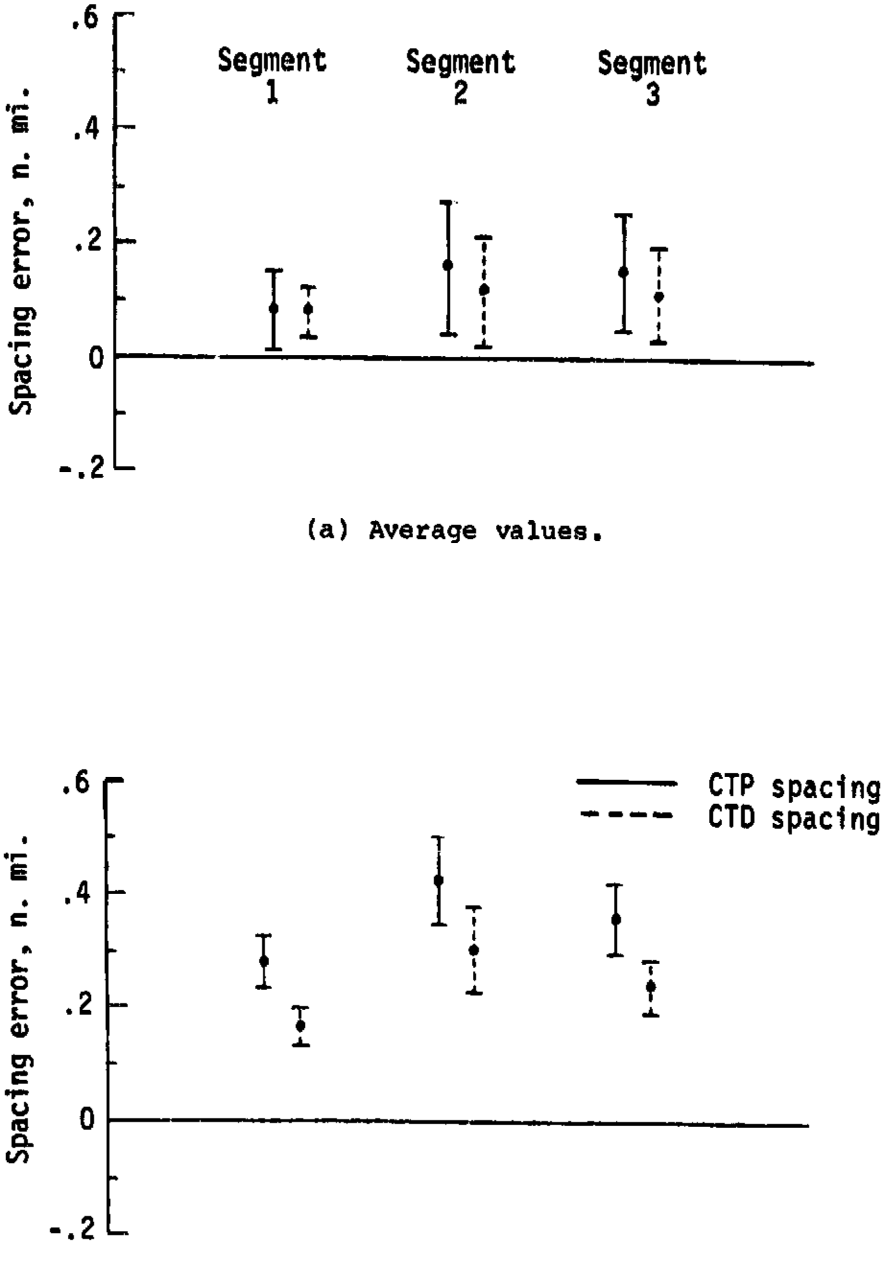

(a) Average values.

(b) rms values.

Figure 10.- Spacing performance represented by mean values of average and rms displayed spacing error with 95-percent confidence intervals.

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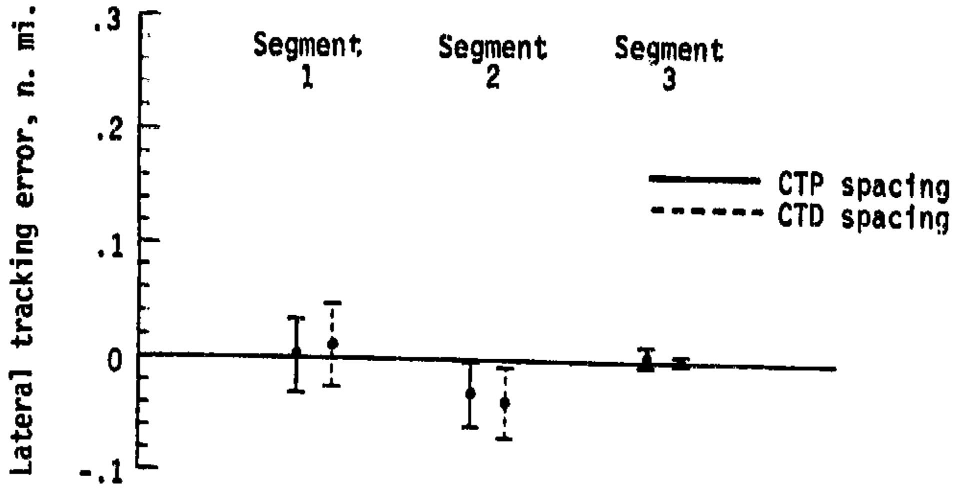
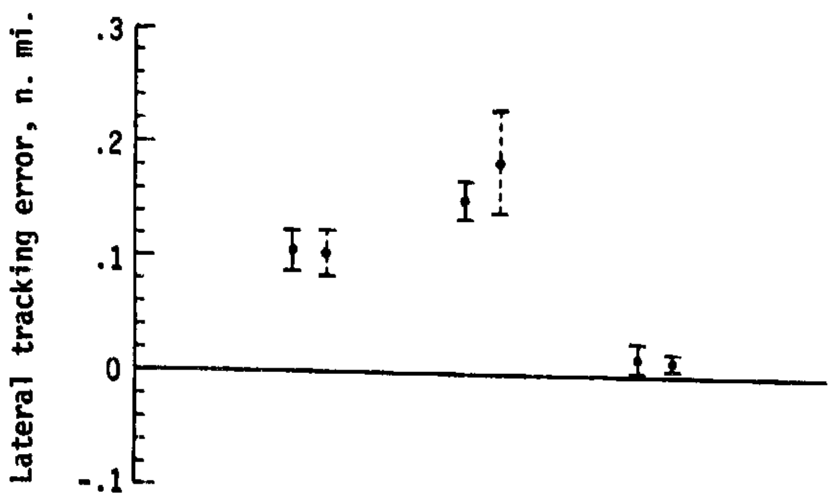
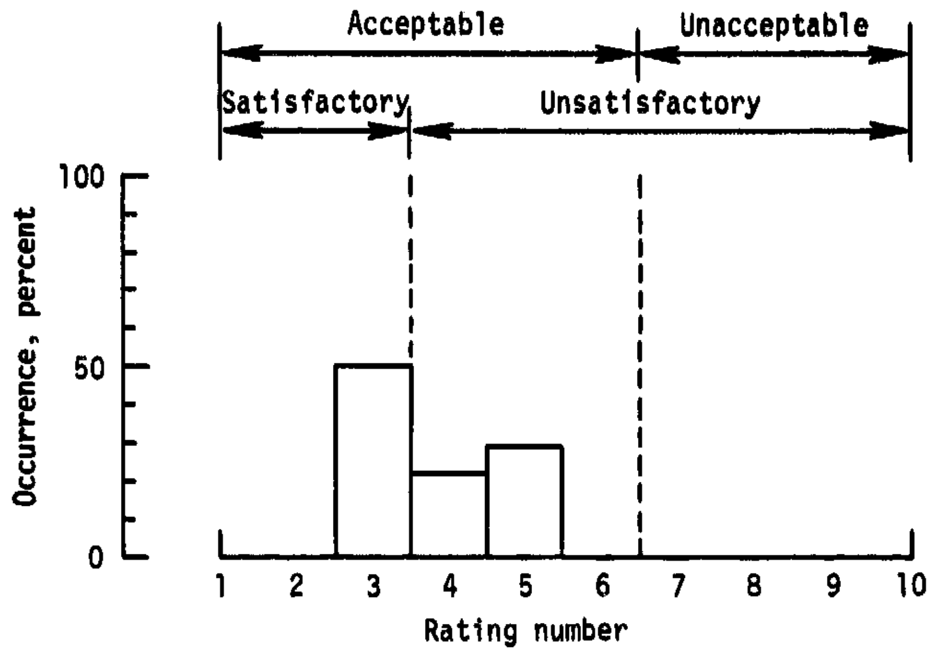


(a) Average values.

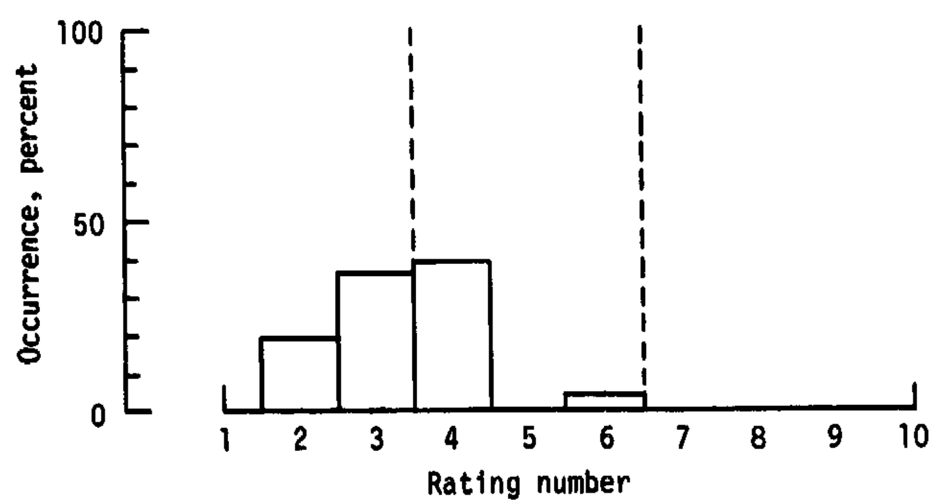


(b) rms values.

Figure 11.- Lateral tracking performance represented by mean values for average and rms lateral tracking error with 95-percent confidence intervals.



(a) Constant time predictor.



(b) Constant time delay.

Figure 12.- Pilot rating of display suitability for self-spacing task.

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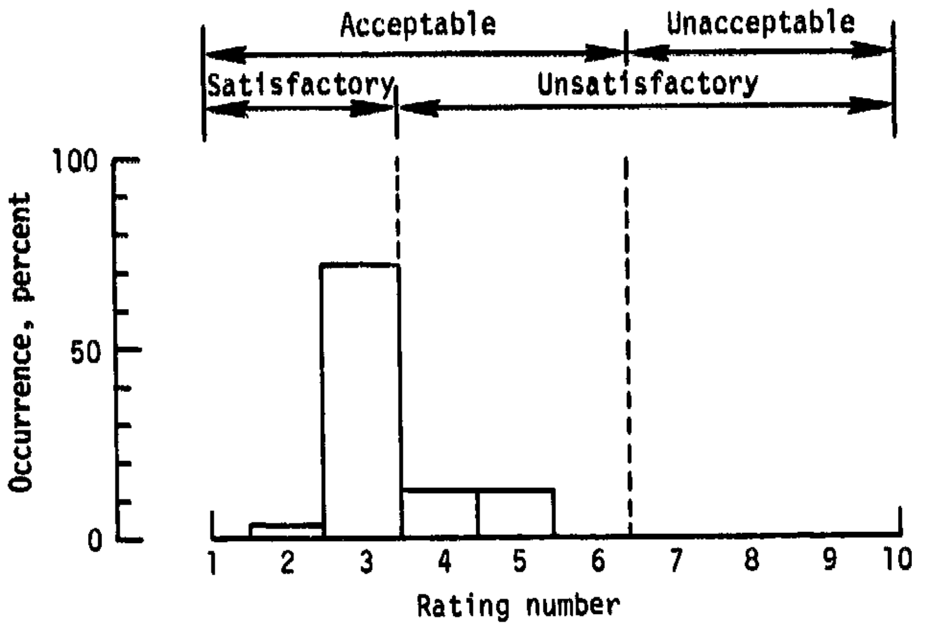
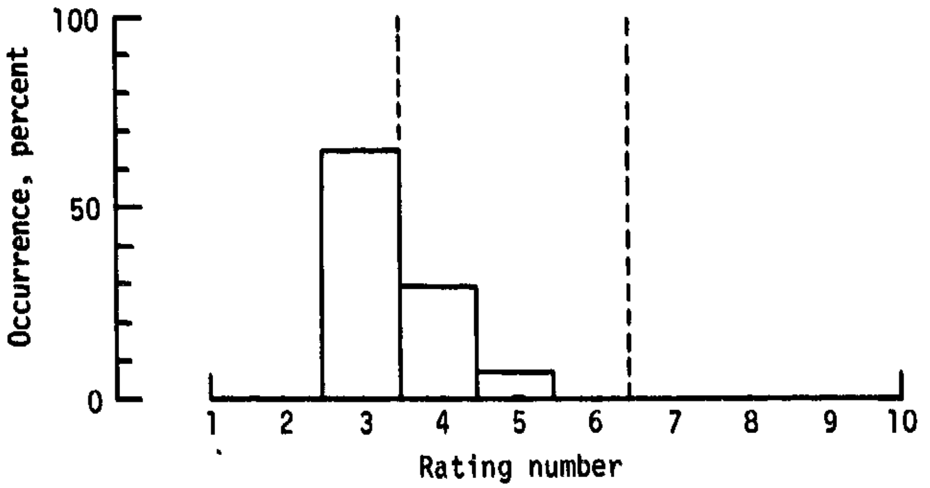


(a) Constant time predictor.



(b) Constant time delay.

Figure 13.- Pilot rating of display suitability for path-following task.

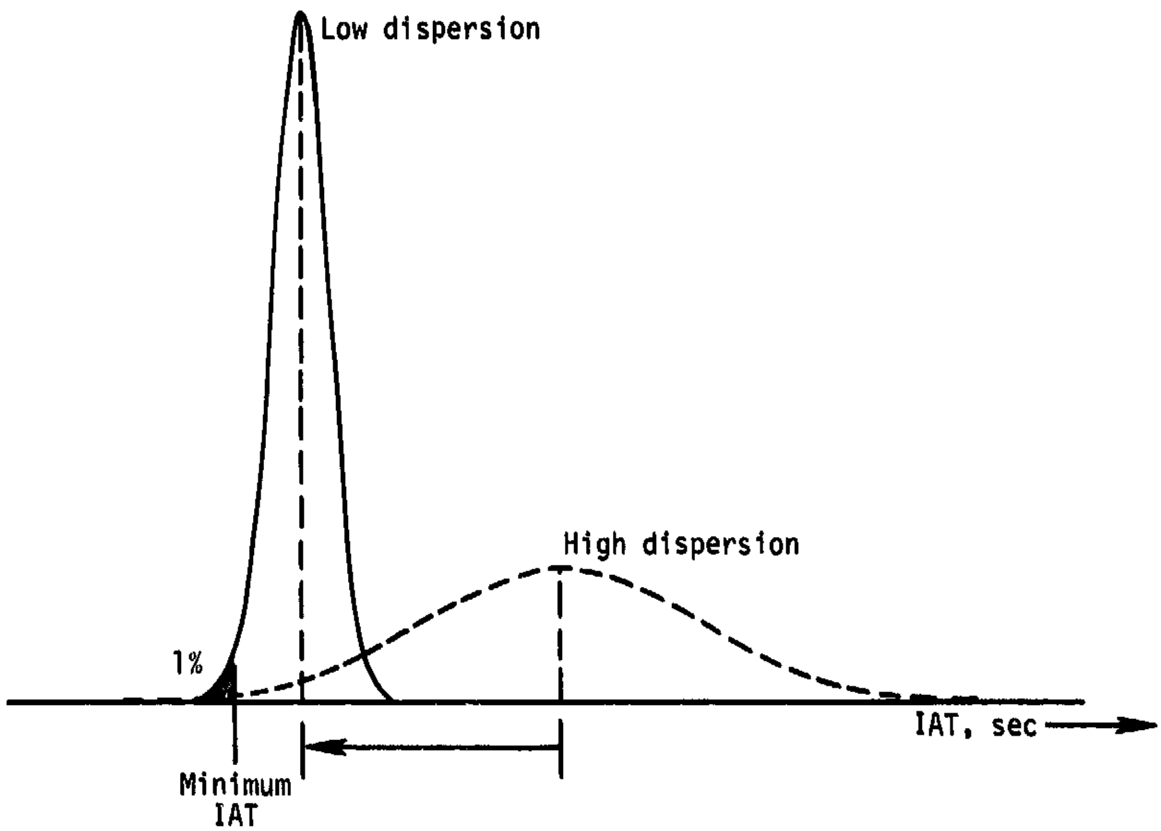
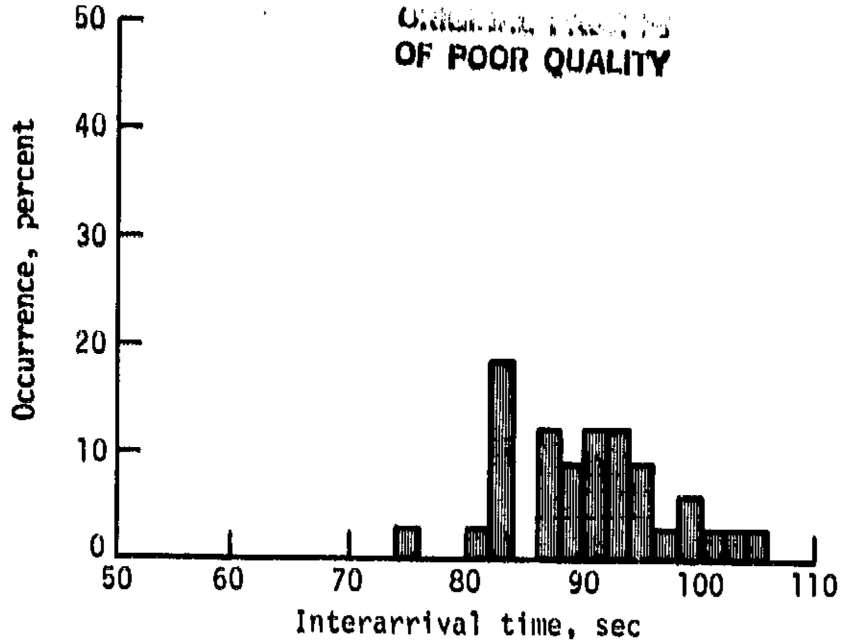
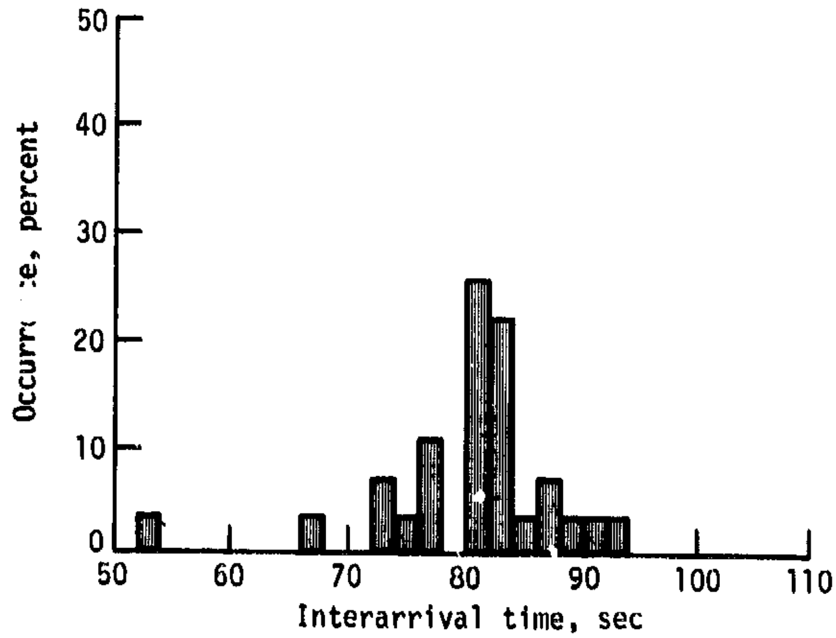


Figure 14.- Illustration of effect on mean IAT resulting from lower IAT dispersion.



(a) Constant-time-predictor technique; Mean = 91.0 sec; Standard deviation = 6.9 sec.



(b) Constant-time-delay technique; Mean = 80.9 sec; Standard deviation = 8.0 sec.

Figure 15.- Histograms of interarrival times achieved using constant-time-predictor and constant-time-delay spacing techniques.

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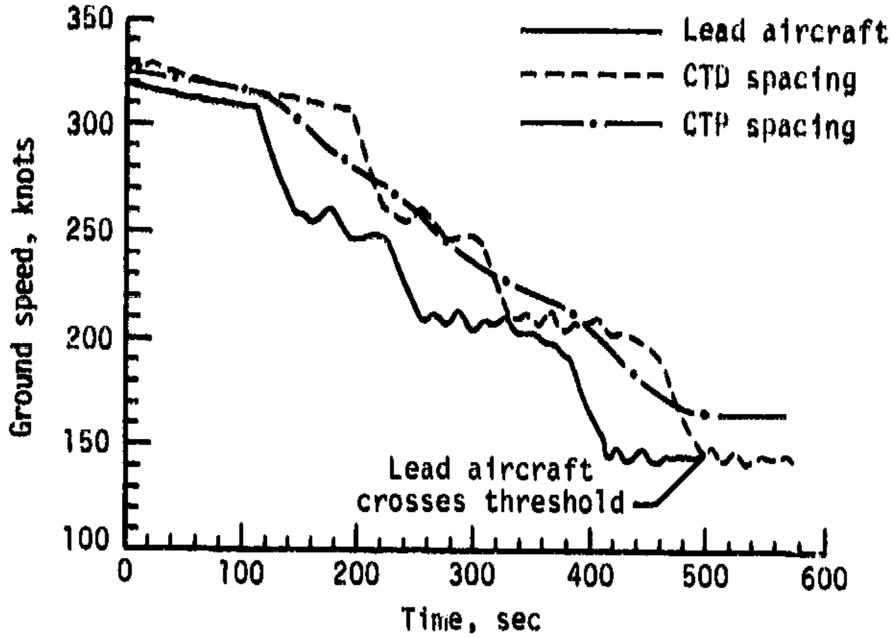
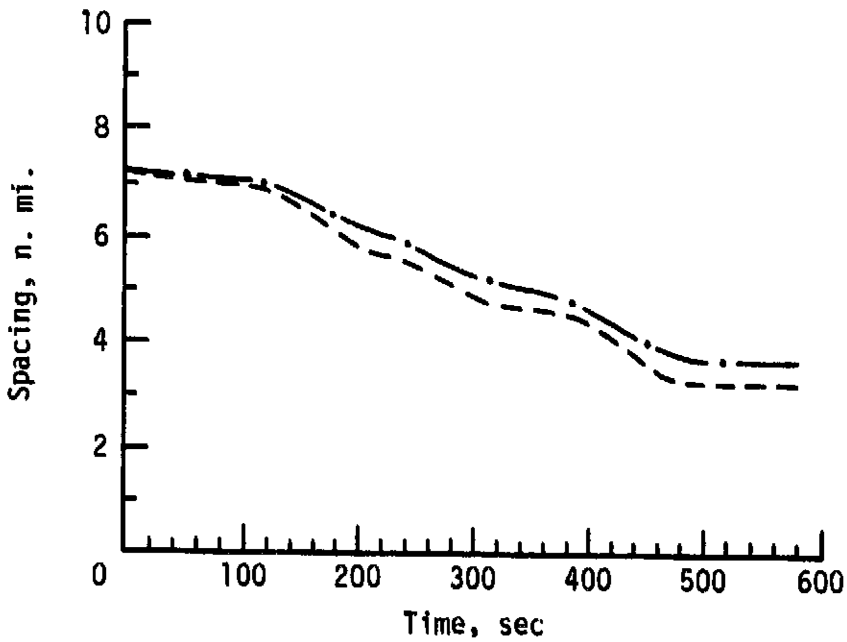
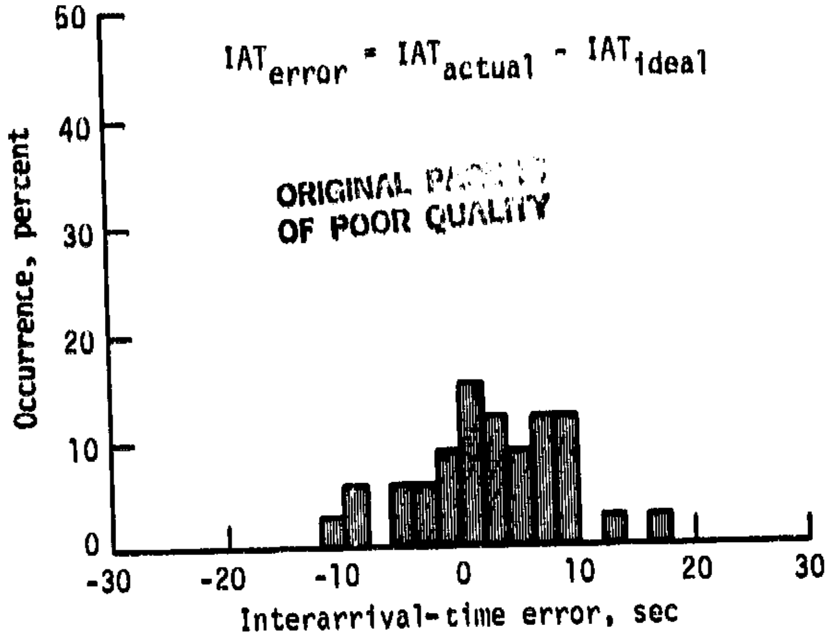


(a) Speed profiles.

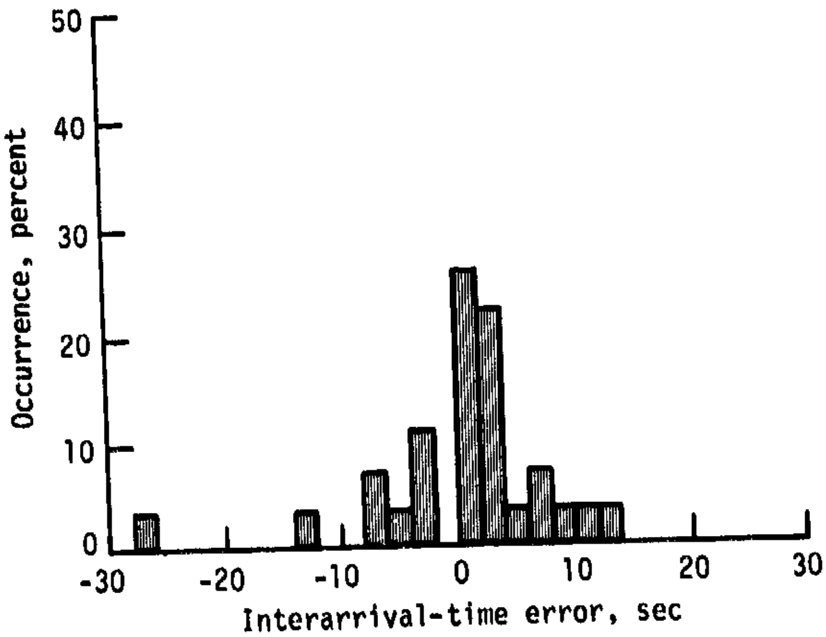


(b) Spacing.

Figure 16.- Examples of ideal speed and spacing time histories for constant-time-delay and constant-time-predictor spacing techniques for following same lead aircraft.

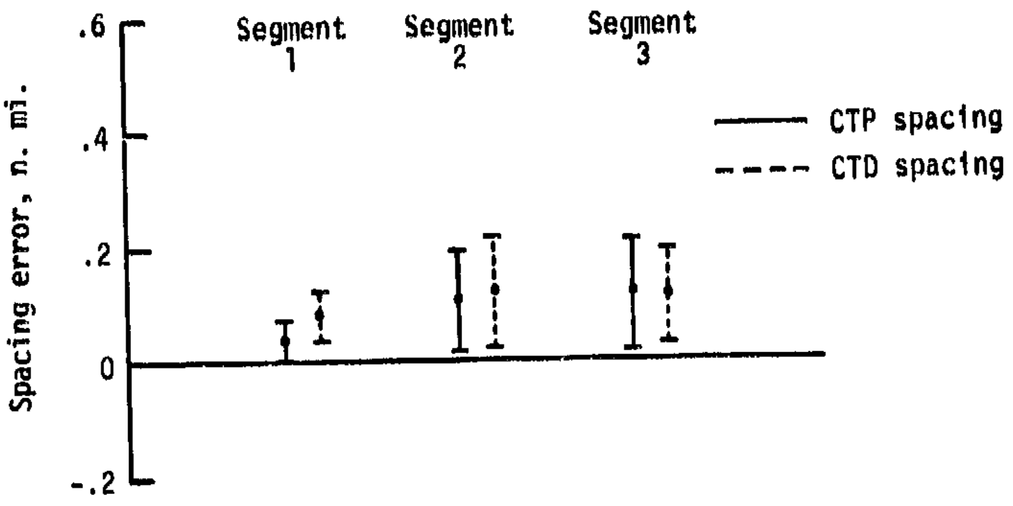


(a) Constant-time-predictor technique; Mean = 2.4 sec; Standard deviation = 6.4 sec.

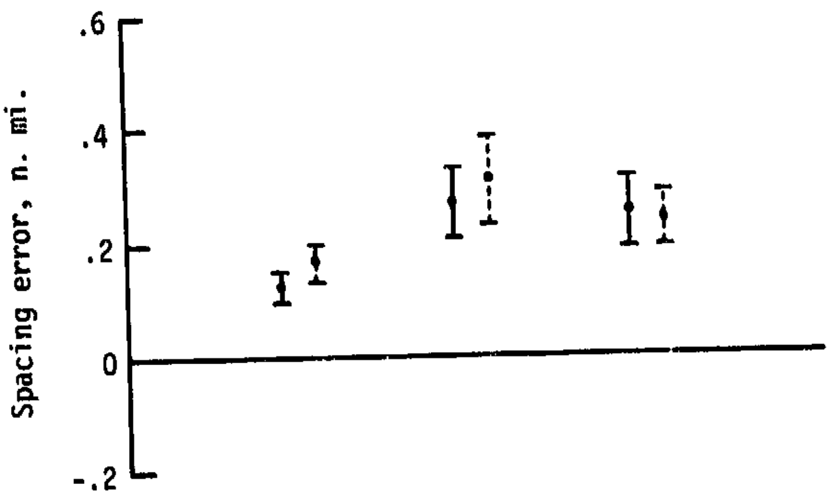


(b) Constant-time-delay technique; Mean = 0.9 sec; Standard deviation = 8.0 sec.

Figure 17.- Histograms of interarrival-time error for constant-time-predictor and constant-time-delay spacing technique.



(a) Average values.



(b) rms values.

Figure 18.- Ideal spacing performance represented by mean values for average and rms errors from ideal spacing with 95-percent confidence intervals.