

EXPERIMENTAL STUDIES OF PILOT PERFORMANCE AT COLLISION AVOIDANCE DURING CLOSELY SPACED PARALLEL APPROACHES

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ABSTRACT

Efforts to increase airport capacity include studies of aircraft systems that would enable simultaneous approaches to closely spaced parallel runways in Instrument Meteorological Conditions (IMC). The time-critical nature of a parallel approach results in key design issues for current and future collision avoidance systems. Two part-task flight simulator studies have examined the procedural and display issues inherent in such a time-critical task, the interaction of the pilot with a collision avoidance system, and the alerting criteria and avoidance maneuvers preferred by subjects.

INTRODUCTION

To reduce flight delays and increase airport capacity, several methods of enabling closely spaced, independent parallel approaches in Instrument Meteorological Conditions (IMC) are being studied. Without specialized radar, current criteria allow independent parallel approaches to runways spaced 4300 feet or more apart; the use of new technologies to reduce this minimum separation would allow airports to effectively maintain their Visual Meteorological Conditions (VMC) capacity in IMC.

The task of ensuring adequate aircraft separation during parallel approach operations is very difficult. The aircraft are closer together than during any other airborne phase of flight, which severely limits the potential warning time should one aircraft blunder into the other's approach path. For runways at least 4300 feet apart, the controller using today's radar can ensure aircraft separation. (FAA, 1989) New technologies such as the Cockpit Display of Traffic Information (CDTI), collision alerting systems and the crosslink of aircraft state information may enable pilots, with the assistance of cockpit systems, to maintain adequate aircraft separation.

This paper summarizes two simulator studies of airborne systems for closely spaced parallel approaches in IMC. First, a baseline flight simulator study examined the pilot responses to a potential collision, both with and without the aid of an alerting system. The current Traffic Alert and Collision Avoidance System (TCAS II) was used as the baseline alerting system, although it was not intended for closely spaced parallel approaches. (Folmar, Szebrat, & Toma, 1994) The second simulator study examined the alerting criteria used by subjects in generating an alert, and how these criteria are influenced by the display of rate and trend information.

PRELIMINARY FLIGHT SIMULATOR STUDY

This preliminary simulator experiment had active airline pilots fly parallel approaches using the MIT part-task Advanced Cockpit Simulator in order to study the pilot effectiveness in avoiding encroaching traffic, both with and without the aid of an alerting system. During each approach, traffic on a parallel approach would blunder towards the subject, and the subject's response was recorded to find the allowable maneuver strength and reaction time. The study also examined several cockpit traffic display enhancements, and the relative merits of flying the approach (before any avoidance maneuver) manually or on autopilot.

The MIT Advanced Cockpit Simulator provided pilots with the relevant controls and displays of a generic glass cockpit aircraft. A Silicon Graphics workstation provided the display of the glass cockpit screens and traffic displays; it also calculated the dynamics of the simulator, which has the performance of a Boeing 737. The pilot had available a Flight Management Computer, Mode Control Panel and sidestick to control the aircraft. An experimenter acted as co-pilot, setting gear, flap and autopilot settings as commanded by the subject. A second

Silicon Graphics workstation steered the 'intruder' aircraft on an approach parallel to the subject's, and then turned the intruder into the subject at a scripted point during the scenario. This Robust Situation Generation system enabled repeatable, scripted near-collisions while allowing flexibility for varied flight paths between pilots.

The 18 subjects were qualified airline flight crew from two major airlines, with a mean of over 15,000 total flight hours. All but one were considered current on glass cockpit aircraft.

The study tested four displays:

- A TCAS traffic display integrated with the Electronic Horizontal Situation Indicator (EHSI);
- Enhancements to the current traffic display on the EHSI, including an indication of the localizer beams for both runways and a split screen;
- A display of the parallel approach traffic on the pilot's Primary Flight Display (PFD); and
- A combination of the new displays on the PFD and EHSI.

Three procedures were studied: the subject monitors an autopilot approach, and then takes manual control to follow the alerts and avoidance maneuvers shown by a TCAS II - type system; the subject manually flies the approach, and follows the alerts and avoidance maneuvers shown by a TCAS II - type system; and the subject flies the approach manually but is not shown any alerts or avoidance maneuvers.

Within each test block, the subjects flew three approaches. These three approaches were each of a different type, scripted to represent a variety of traffic situations, both hazardous and non-hazardous. Multiple scenarios of each type were implemented to prevent the subjects from becoming familiar with any specific collision geometry.

Altogether, each subject flew a total of 36 approaches. These approaches were flown in 12 blocks of three. Each of the 12 blocks were flown under a different condition, representing all the combinations of four different traffic displays and three different procedures. The test matrix was counter-balanced against any learning effects.

The primary goal is to ensure adequate separation between aircraft on parallel approaches. Therefore, the first measurement of interest is the resulting miss distance between aircraft. Overall, the intruder and subject aircraft came within 500 feet of each other 4% of the time, and within 1000 feet of each other 20% of the time. These percentages were found to be significantly lower when the approach was flown on autopilot and significantly higher when TCAS avoidance maneuvers were not displayed. These percentages are highly scenario-dependent and may not be indicative of pilot collision avoidance performance in all situations.

The presentation of the TCAS alerts and avoidance maneuvers correlated with a significant improvement in aircraft miss distance. However, TCAS maneuvers are generated with the assumption that the pilot will follow them, both by reacting within five seconds, and then by matching or exceeding the TCAS pitch command. (RTCA, 1983) However, examination of the trajectories has shown that the actual maneuvers flown by the pilots, when the TCAS maneuvers were shown, did not conform to the commanded vertical maneuver in 40% of the cases. As shown in Figure 1, the full benefit of the alerting system was not achieved due to non-conformance.

No single causal factor of the low conformance rate can be isolated. Pilot reaction time alone does not show a strong effect. 66% of the pilots reacted within the five second allowance assumed by the TCAS system, and of these only 61% matched the displayed TCAS maneuver. Of the pilots who acted shortly before the alert or after the five second allowance (13% and 20% respectively), a significant number of pilots still matched what the TCAS guidance commanded (71% and 33% respectively).

Conformance to the (vertical) TCAS maneuver may be affected by the turning maneuvers that the pilots often performed at the same time. Overall, pilots did not turn in 32% of the approaches (i.e. the maximum bank angle after the alert was less than five degrees); 34% of the time the pilots turned away from the intruder, 11% of the time pilots turned toward the intruder, and 23% of the time pilots turned one way and then another. Pilots who did not follow the TCAS maneuver turned away significantly more often than those who followed the TCAS maneuver. This may suggest that the pilots, by executing a turn, felt a vertical maneuver was no longer required.

Pilots, given the enhanced traffic displays tested in this experiment, conformed significantly less often than when they were given the current TCAS II type traffic display. This may also suggest that pilots, given a more explicit traffic picture, may have felt a vertical maneuver was no longer required. This perception may have been erroneous, however, as more near-misses happened with these new displays.

Other possible factors for the low conformance rate have also been investigated. Examining the aircraft trajectories for the approaches where the pilots were not shown any TCAS alerts or maneuver guidance, the pilots' reactions only satisfied what the TCAS would have commanded in 25% of the approaches, suggesting that the TCAS maneuver is not what the pilots would do instinctively. Further analysis suggested that these problems

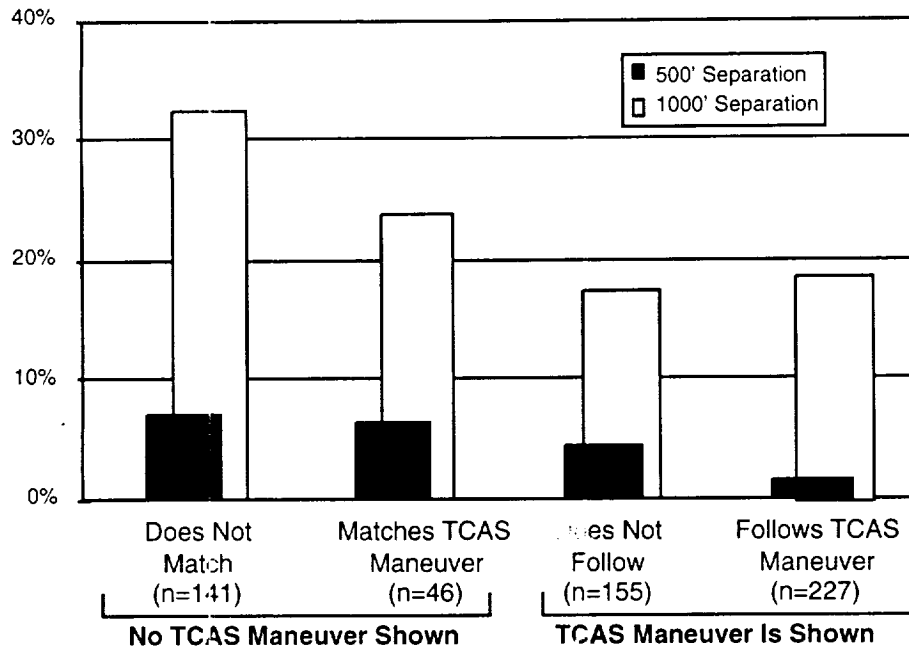


Figure 1. Frequency of Incidents by Presentation of Alerts & Avoidance Maneuvers, and Pilot Conformance

may stem from the pilots' use of a different and less effective alerting algorithm for deciding when to generate alerts. The across-track deviation of the intruding aircraft appears to have been a major determinant in the decision to react, a conclusion also supported by pilot comments about their decisions to alert.

However, this type of alert generation logic -- based on intruder lateral deviation -- has been shown to be ineffective: it can generate a false alarm when the parallel traffic oscillate around their localizer during a normal approach, and it may not trigger an alert until the intruding aircraft has already established a high rate of convergence.

The enhanced displays tested in the previous experiment provided pilots with a fiducial marker indicating the cross-track position of a normal approach. All pilots indicated they liked this feature; some commented that it freed them from monitoring the convergence rate of the other aircraft. Therefore, this feature may have unintentionally encouraged a range-only alerting logic.

SIMULATOR STUDY OF ALERTING CRITERIA AND AVOIDANCE MANEUVERS PREFERRED BY SUBJECTS

Based on the results from the prior experiment, it was hypothesized that the traffic display features can, and should, support a more sophisticated mental model for pilots to use in generating alerts and selecting avoidance maneuvers. This should provide for better pilot confidence in, and following of, automatically displayed avoidance maneuvers (when available), and reduce erroneous pilot reactions. To test this hypothesis, a follow-on flight simulator experiment was conducted. This experiment had the following two objectives: 1) provide a preliminary study of how the display features of a cockpit traffic display affect a person's mental 'alert generation logic', used to assess when an avoidance maneuver is necessary and what the avoidance maneuver should be, and 2) ascertain how display features affect a user's ability to detect a conflict.

The experiment runs each consisted of three sequential parts:

- *The Flight* The subjects were told they were flying an approach, and should press a red button on the sidestick as soon as they thought the other aircraft was blundering towards them, as evidenced by the traffic display.
- *The Maneuver Selection* Once the subject indicated the parallel approach traffic was deviating towards them, the traffic display was blanked and six possible maneuvers were graphically shown to the subjects. The subjects were asked to select the maneuver considered best for maintaining inter-aircraft separation.

- *Numerical Simulation* The simulator then predicted the miss distance resulting from the selected avoidance maneuvers, providing a first order measurement of the subjects' decision making.

The simulator used a Silicon Graphics Indigo 2 workstation for the displays and aircraft dynamics computations. A sidestick was connected for the flying task. The aircraft dynamics used point-mass calculations with performance constraints representative of air transport aircraft. The pitch and heading acquisition models used a critically damped controller, while the localizer acquisition controllers were slightly under damped, modeling the actual wavering about the approach path of the aircraft.

In total, nineteen subjects flew the experiment. The basic characteristics of the subjects varied widely. Two were airline flight crew, four were Certified Flight Instructors (CFI) in general aviation aircraft (one with jet fighter experience), two held Private Pilot Licenses, and the remaining eleven were students without piloting experience.

Five displays were tested. All were based on a moving map type display, with a top-down view, heading-up orientation, iconic presentation of the other aircraft's positions and a text presentation of the other aircraft's altitudes. Traffic information was updated once per second, a technically feasible rate with current datalink systems.

- *Baseline Display*: emulated the current TCAS display.
- *Fiducial Mark Display*: added the reference indication of the parallel approach path, emulating the enhanced EHSI display tested in the baseline experiment.
- *Heading Display*: added a graphic indication of the other aircraft's heading.
- *Noisy Projection Display*: added a graphic indication of heading rate and projected position for the next 15 seconds; the projection was based on the noisy measurement of the other aircraft's bank that sensors can provide.
- *Smooth Projection Display*: added a graphic indication of heading rate and projected position within the next 15 seconds; the position projection used theoretical knowledge of heading rate to give a more smooth projection.

Subject workload was also varied to test its effect on subject's decisions. The subjects were told their primary task was to keep their wings level despite turbulence, using a side-stick. To do this, bank angle was shown on an artificial horizon drawn approximately three inches away from the edge of the traffic display. The turbulence was set to two different levels, generating two different levels of workload. The subjects were not briefed on these qualities.

Four scenarios were flown, in random order, within each test block. These scenarios were designed to represent a variety of collision trajectories, with high and low convergence rates. One of the four was not hazardous; in another scenario, the 'other' aircraft never varied from its approach path.

The complete test matrix was three dimensional, with five displays, four types of scenarios and two workload levels being varied. Most subjects had 40 experiment runs, fully combining all types of displays, workload levels and scenarios, allowing for within-subject comparisons; four subjects did not have runs with the smooth predictor display. The scenarios were flown in blocks of four; each included all runs for each display-workload combination.

The collision avoidance system available in the previous experiment, TCAS II, uses convergence rate to estimate time remaining to collision as a basis for generating an alert. The subjects' reactions, however, did not have a consistent time to point of closest approach at their reactions, as shown in Figure 2. The time to point of closest approach ranged from -13.39 seconds (the subject reacted after the point of closest approach) to 34.32 seconds, with a mean of 14.37 seconds. The wide spread suggests the subjects' alerting criteria does not take into account convergence rate, differing from the alerting criteria used by TCAS.

The subjects' reactions were instead consistent with a criteria based on range or lateral separation. The distribution of the lateral separation between the aircraft at the time of the reaction is shown in Figure 3. A Chi-Squared goodness-of-fit test found its distribution approximates a normal distribution with a high probability ($p > 99\%$). The mean lateral separation at the time of the reaction is 1346 feet, with a standard deviation of 345 feet. These statistics were similar for both high and low convergence rate scenarios. For comparison, in the high convergence rate blunders, the aircraft lateral separation could decrease 200 feet between every one second update of information about the other aircraft. Therefore, the variance of this distribution is comparable to that expected from a standard deviation of 1.75 seconds in reaction time around an alerting criteria based purely on lateral separation.

Although the newer displays were purposefully designed to give indications of relative convergence rate and trend before an abnormal lateral position was reached by the intruder, no differences can be found in the method used by the subjects to generate alerts with each of the different displays.

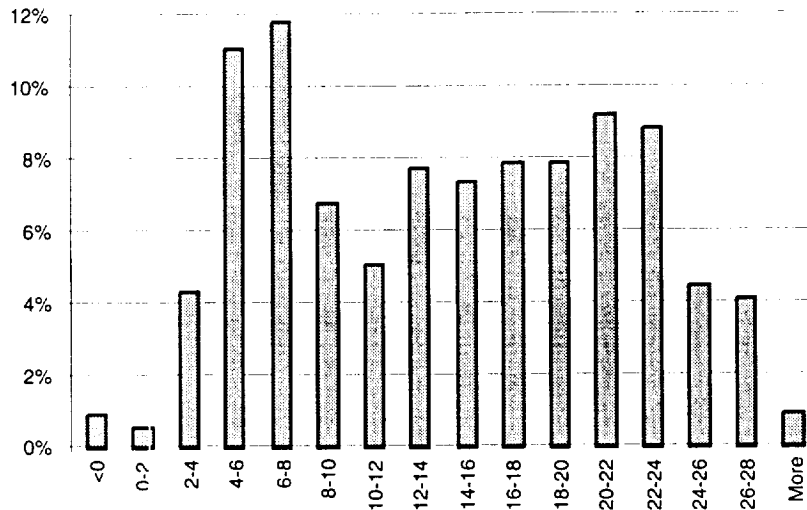


Figure 2. Distribution of Time Remaining to Point of Closest Approach (Seconds) When the Subjects Reacted (n = 546)

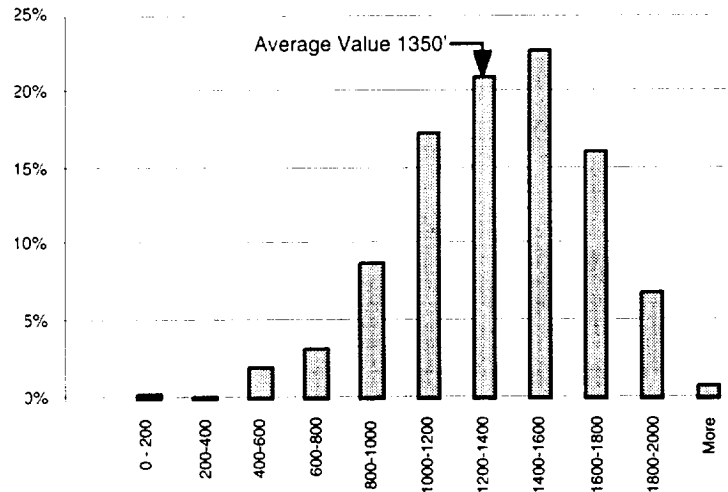


Figure 3 Distribution of Lateral Separation (Feet) Between the Aircraft When the Subjects Reacted (n = 546)

The largest determinant of predicted collision avoidance performance was the convergence rate of the intruding aircraft. In scenarios with a high convergence rate, subject's reactions were too late for an effective avoidance maneuver in 42% of the cases, highlighting the need for a collision avoidance system or for subjects to use a more effective alerting strategy.

In addition to the timing and validity of the subject's alerting decisions, the performance of the subjects in selecting a safe direction of flight for an avoidance maneuver was measured. The most popular maneuvers were Turn Away and Climb (55%), and Turn Away while maintaining altitude (36%). Each maneuver appeared to be selected the same amount, regardless of display. However, these maneuvers were not always effective.

SUMMARY OF RESULTS AND DISCUSSION

A preliminary flight simulator evaluated the need for a collision avoidance system and tested several features of cockpit traffic displays. The need for a collision avoidance system was demonstrated by the fewer instances where adequate aircraft separation was lost when automatic alerts and avoidance maneuvers were displayed. Pilots also indicated a preference for an alerting system.

However, the full benefit of an alerting system was not always attained because of pilot non-conformance. Pilots did not conform to displayed avoidance maneuvers 40% of the time. This non-conformance rate, and a resulting decrease in collision avoidance performance, was found to have an unanticipated correlation with the pilot preferred enhanced traffic displays; these displays may have encouraged different alerting and avoidance strategies.

A follow-on simulator experiment asked subjects to identify potential collisions without any form of automatic assistance other than displays of the intruder aircraft's current state. The primary objective of this experiment was to measure the characteristics of the subjects' reactions. Subjects' reactions appeared consistent with an alerting strategy using the lateral separation between themselves and the intruder as a primary criterion; this type of alerting strategy is prone to false alarms, while it may not always give sufficient warning for an effective avoidance maneuver. The display of heading and trend information did not appear to encourage different, more effective alert logic schemes. Subjects picked 'Turn Away' and 'Turn Away and Climb' avoidance maneuvers 91% of the time. These maneuvers did not always generate a safe aircraft separation. The type of maneuvers selected also did not appear to be affected by the different traffic displays.

These results provide insight into the type of strategies used by subjects at these types of tasks. The subjects' reactions were consistent with simple criteria, based upon comparison of the position of fixed graphical fiducial markers on the traffic display. The display of more information about the other aircraft's trend did not promote the use of more accurate alerting strategies; this may have been caused by a lack of awareness by the subjects of their own low performance, or it may have been an indication that the subjects were not capable, in the time-available, of performing the extra computations required by more sophisticated strategies. Therefore, these results seem to emphasize a tendency of the subject to need a simple comparison upon which to base an alert.

These experiments suggest that subjects may disagree with the alerts and avoidance maneuvers made by more efficient alerting systems, such as the TCAS II system used in the preliminary experiment. Pilot conformance has been demonstrated to have a significant effect on pilot performance at collision avoidance. Therefore, methods of encouraging pilot conformance may require explicit consideration in the design, evaluation and implementation of collision avoidance systems.

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