TWO STUDIES OF PAIRED APPROACHES

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ABSTRACT

At airports with closely-spaced parallel runways, the inability to conduct simultaneous approaches in all weather conditions is a cause of significant delay. One concept for reducing delay is paired approaches, where two aircraft on closely spaced approaches are 'paired', and the 'trail' aircraft stays within a safe zone relative to the 'lead'. This positioning guarantees that neither aircraft risks loss of separation and that neither aircraft will be affected by the other's wake. This operation is being investigated through two studies. The first documents how the safe zone may be calculated and explores its size, location and movement in response to operational factors. The second study is a piloted simulator evaluation of cockpit display and procedural issues.

INTRODUCTION

At airports with closely-spaced parallel runways (i.e. spaced less than 2500 feet apart), the inability to conduct simultaneous approaches is a cause of significant delay. Because the ceiling and visibility required for visual approaches are typically quite high, the weather does not need to be very bad to demand single runway operations.

One concept for reducing delay is paired approaches, where two aircraft on closely spaced parallel approaches are 'paired', and the 'trail' aircraft maintains position within a safe zone relative to the 'lead' aircraft.[1,2,3] As shown schematically in Figure 1, such a position guarantees that neither aircraft will be in danger of loss of separation should the other depart its approach path, and that neither aircraft will be affected by the other's wake.

This approach is novel for several reasons: it is preventive in nature, in that it spaces the aircraft so that separation is guaranteed, rather than reacting to intrusions; it provides trail aircraft with the assurance that they will be safe if they *do not* execute an avoidance maneuver in the face of a blunder; it requires the trail aircraft to maintain a position relative to the lead aircraft, adding a new task to the pilots' approach duties; and it requires the trail aircraft to be *in front of*, rather than behind, the lead aircraft's wake, putting the aircraft closer together than any other current airborne civilian operation.

Several studies have examined paired approaches, suggesting possible procedures,[4] methods of calculating the safe zone,[5] and a simulator assessment of cockpit traffic displays.[6]

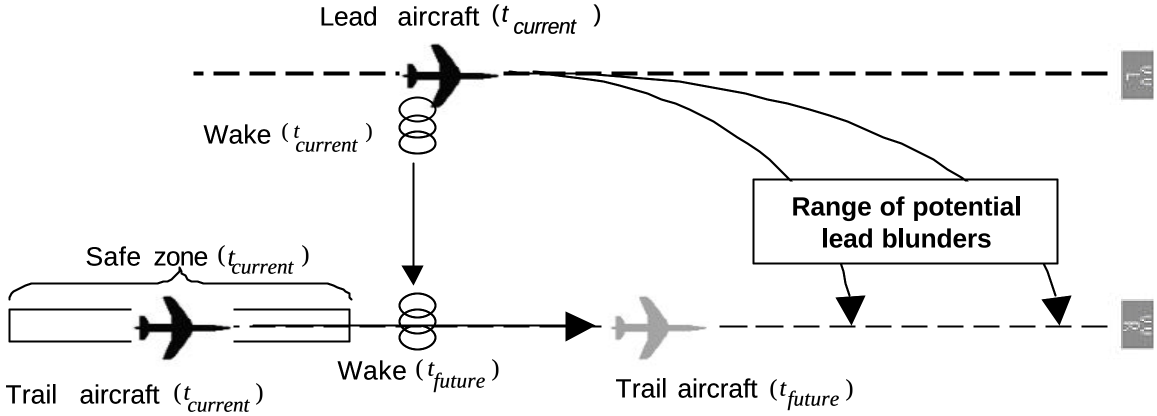

Figure 1. Schematic of the safe zone at the current time to guarantee collision and wake avoidance at future times

However, many issues are outstanding; therefore, we are conducting the two studies outlined in this paper. The first explores the size, location and movement of the safe zone as a function of various blunder profiles, alerting times, runway separations, procedural restrictions, etc. The second study is a piloted flight simulator evaluation of cockpit display and procedural issues in paired approaches. This paper will discuss the results of these studies to date, and outline their implications for technologies and procedures suitable for implementing paired approaches.

STUDY ONE

Method

The front of safe zone is the current location of the trail aircraft that can guarantee no loss of separation can occur within a given protection time; i.e. this is the minimal value for current longitudinal separation providing separation in all allowable future conditions within the protection time. The location of the safe zone can be found analytically from examination of potential future trajectories and current positions of the two aircraft. Since vertical position can vary quickly, separation can not be guaranteed in the vertical plane. Instead, the front of the safe zone provides separation between the two aircraft in the horizontal plane. We assumed the blunder heading change rate is achieved instantly, an assumption that was tested and found to have negligible consequences.

The distance the trail aircraft can fly while the wake crosses between the aircraft is the maximum allowable in-trail distance. The back of the safe zone is therefore determined by the lateral separation between aircraft, the crosswind (assumed to be the transport speed of the wake),[7] and the speed of the trail aircraft.

In summary, the size and location of the safe zone is determined by the variables listed in Table 1. The calculations used here do not consider uncertainty about parameters; rather, solutions can be found for worst-case values given knowledge of their uncertainty.

Current longitudinal separation
Current lateral separation between aircraft
Lead and trail aircraft speeds
Blunder heading change
Blunder heading change rate
Protection time cap of safe zone
Crosswind

Table 1. Front of Safe Zone Variables

Results

This study explored how the front and back of the safe zone change with the variables list in Table 1. To understand how the front of the safe zone changed as each parameter was varied, the location of the front and back of the safe zone was calculated for lateral separations of 750 feet to 3000 feet, lead and trail speeds of 100 to 230 knots, heading changes of up to 45 degrees, and up to infinite heading change rates. Findings of interest are detailed here.

<u>Impact of Aircraft Ground Speed</u>

The speed of both the lead and trail aircraft can have a significant impact on the position of the front of the safe zone. For example, Figure 2 shows its location as the minimum allowable distance in trail for a range of aircraft speeds. Two insights should be noted. The first is the overall sensitivity of the location of the safe zone to speed. Second, there may be some conditions where the ‘trail’ aircraft can safely be in front of the ‘lead’ aircraft – specifically, when the lead aircraft is faster – as shown by negative allowed distances in trail.

<u>Effect of Blunder Headings</u>

We examined how the front of the safe zone is impacted by requiring protection against blunders of greater and lower severity; these results are shown in Figure 3 for blunder heading change. The most restrictive safe zone is one where its front is further back. This figure shows that, if the aircraft are allowed to fly a range of speeds, the blunder of concern is one where the lead aircraft is flying slower than the trail, and where the blunder is caused by a small heading change; large heading changes are not a determinant of safe zone location. A similar analysis examining blunder heading change rate (i.e. rate of turn used to acquire a blunder heading) found similar results; i.e. it is the small – not the large – heading change rates that can determine safe zone location.

However, blunders with small heading changes can take a long time to create a separation hazard. Therefore, we also examined the impact of capping the amount of protection time provided by the safe zone. As shown in Figure 4, capping the protection time moves the front of the safe zone forward significantly.

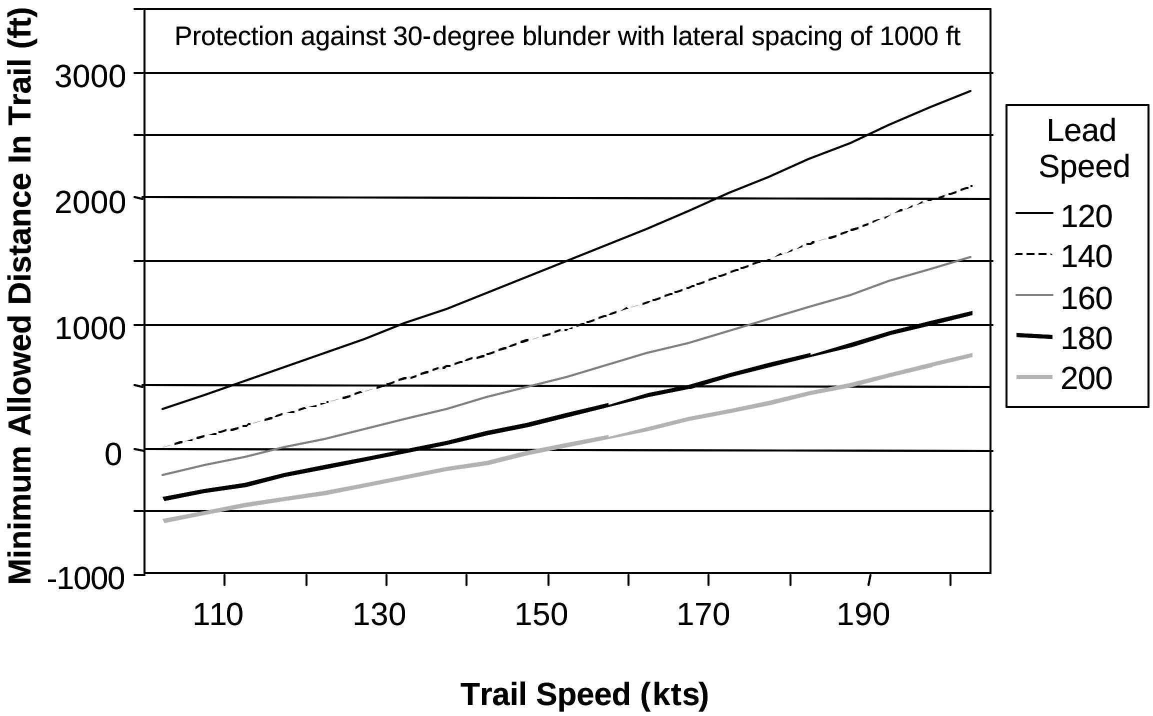

Figure 2. Impact of trail and lead aircraft ground speed on location of the front of the safe zone

<u>Comparison of Lead, Trail, and Dual Blunders</u>

The position and size of the safe zone is also dependent upon which aircraft blunders, shown in Figure 5 for blunders by the lead and by the trail aircraft at two different speed differences. Regardless of which aircraft blunders, the front of the safe zone, as computed here, is a relative position, based upon whichever blundering aircraft (lead or trail) provides the furthest in-trail requirement for the trail aircraft. In some conditions in Figure 5 (lateral separations less than 1100 feet when the trail aircraft is 50 knots faster than the lead; lateral separations less than about 2000 feet when the trail is 20 knots faster), for example, the safe zone that the trail aircraft must stay within is actually defined by the blunder that it could create, rather than by the lead aircraft's blunder.

The possibility of both aircraft blundering must also be considered. A comparison between both aircraft blundering and a single aircraft blundering is shown in Figure 6. This figure shows that the solutions for dual blunders result in lower minimum in-trail distances than for single blunders. Therefore, it is more conservative to protect against a single blunder by either aircraft.

<u>Back of the Safe Zone</u>

Lateral separation and trail speed, along with crosswind speed, determine the back of the safe zone, as shown in Figure 7 for a range of crosswind speeds. The back of the safe zone has a greater dependence on lateral separation than the front of the safe zone. If the lateral separation between the aircraft goes to zero (as can be the case during a blunder), the back of the safe zone moves up to the lead aircraft, i.e. the safe zone collapses to zero length.

<u>Feasible Solutions</u>

The length of the safe zone goes to zero in some cases, particularly with low lateral spacing, high protection times, and large speed differences. These combinations are confined to near 750-foot lateral separation, very low lead speed (below 110 knots), and very high trail speed (above 190 knots), as shown in Figure 8. The safe zone lengthens rapidly away from these combinations.

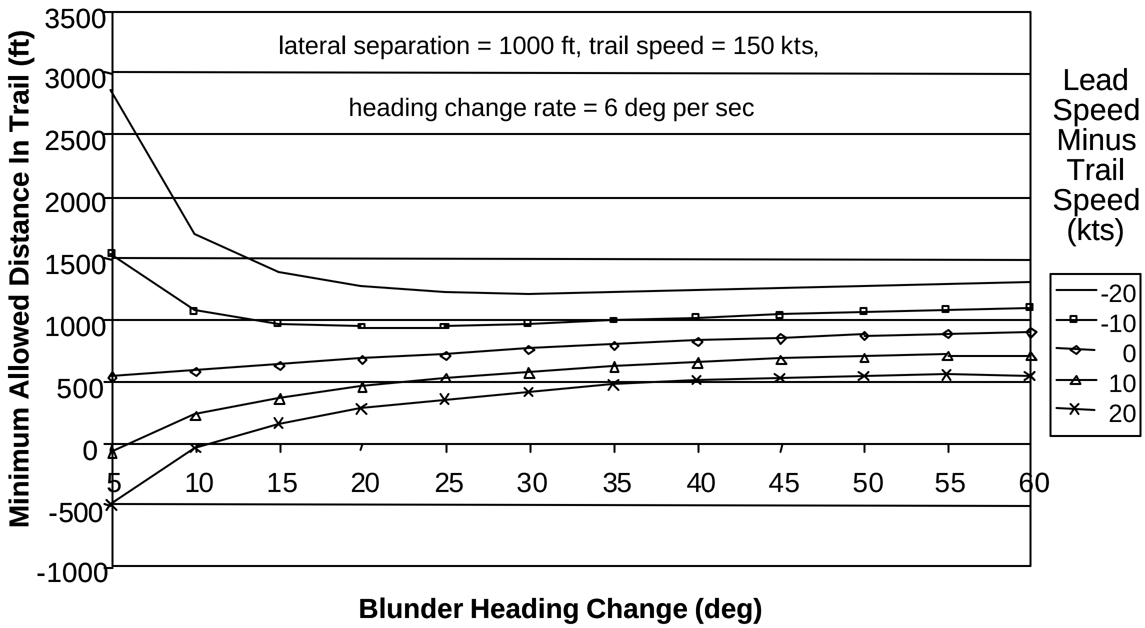

Figure 3. Location of front of safe zone as a function of maximum possible blunder heading change, without a protection time cap

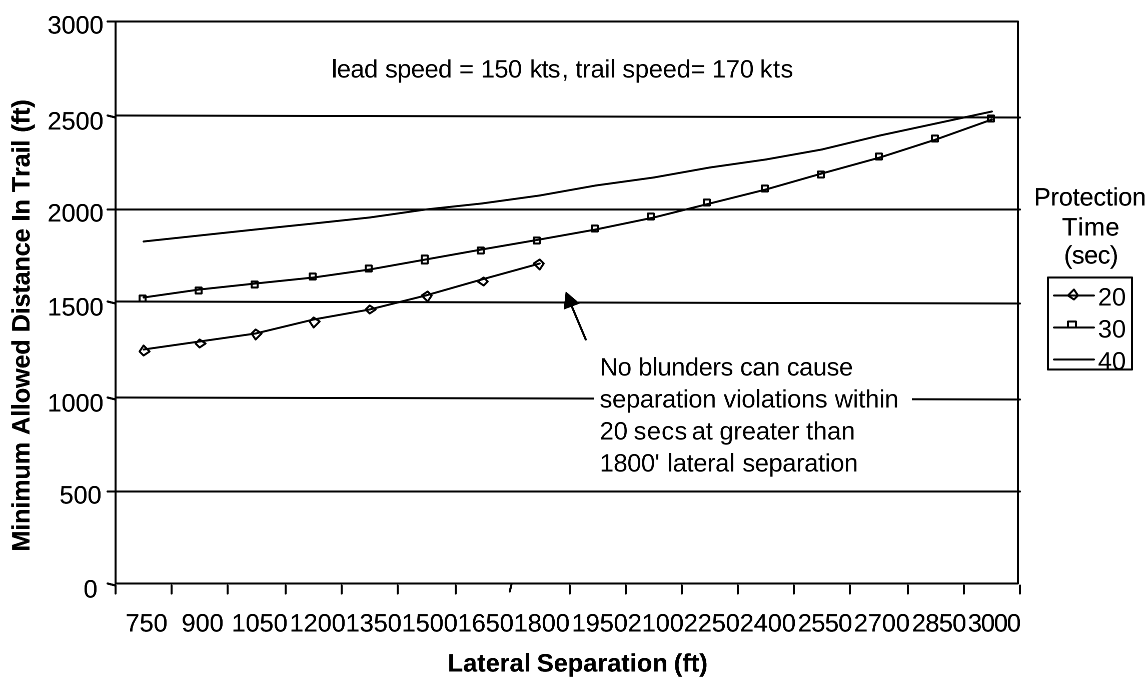

Figure 4. Location of the front of the safe zone with different protection time caps and lateral separations

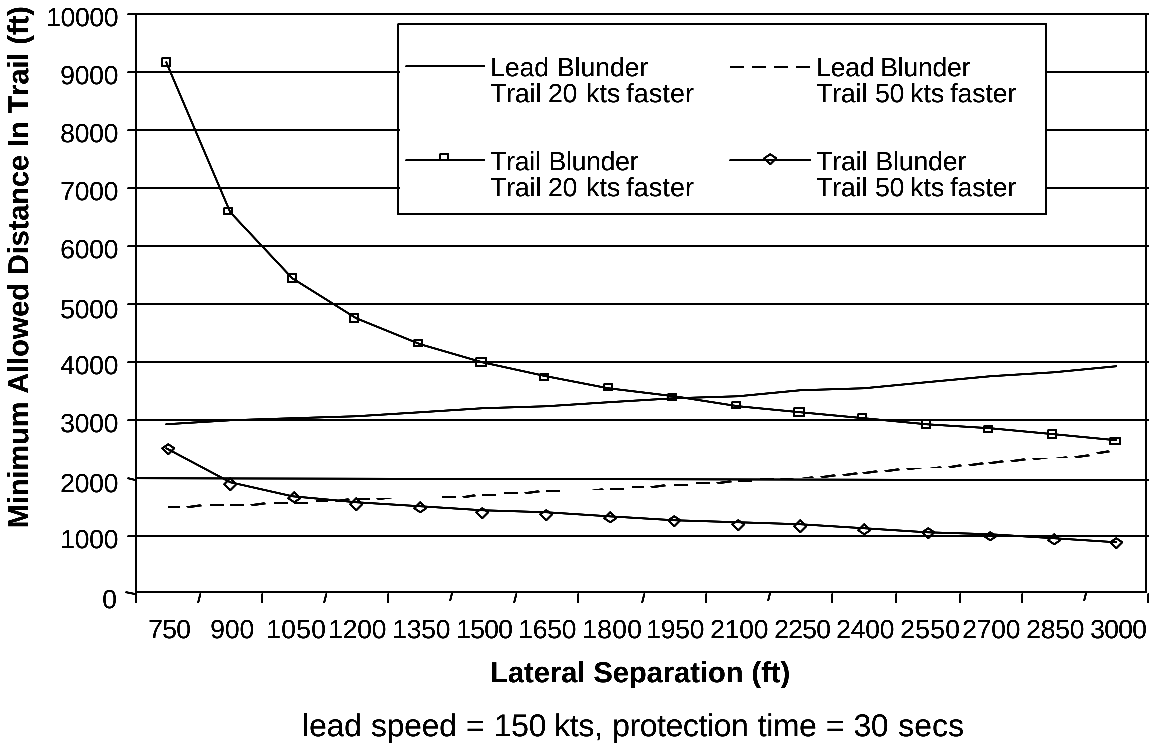

Figure 5. Comparison of the front of the safe zone for lead blunders and trail blunders

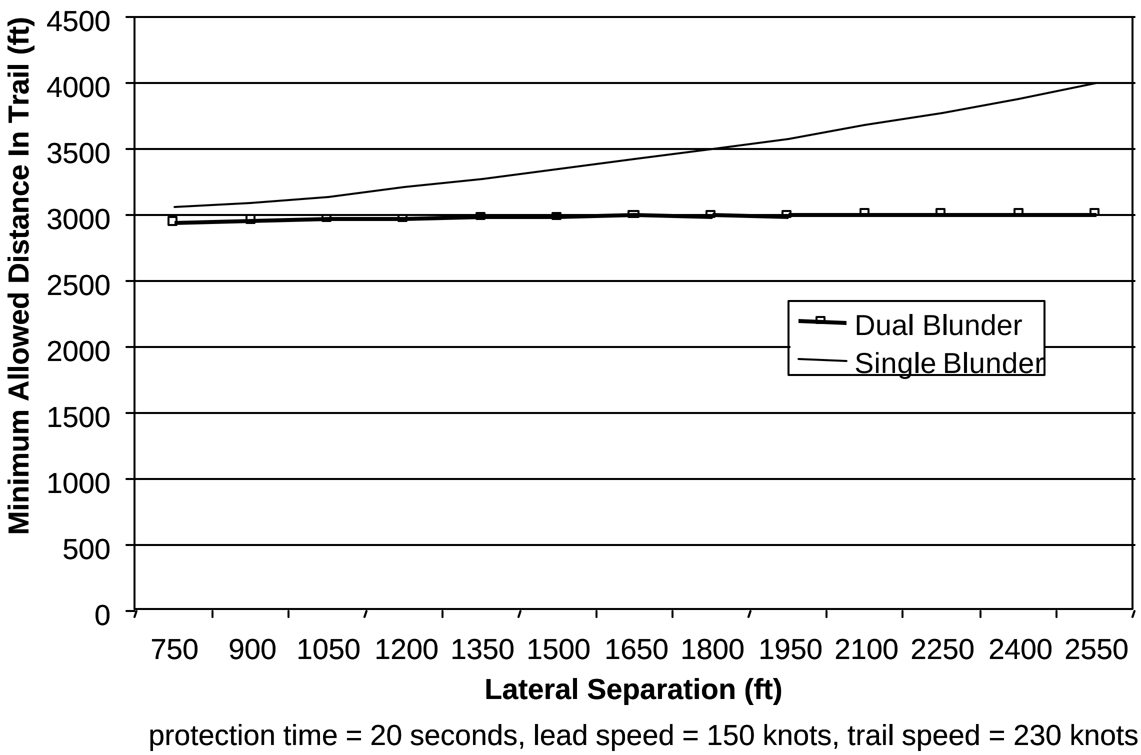

Figure 6. Comparison of dual and single blunders

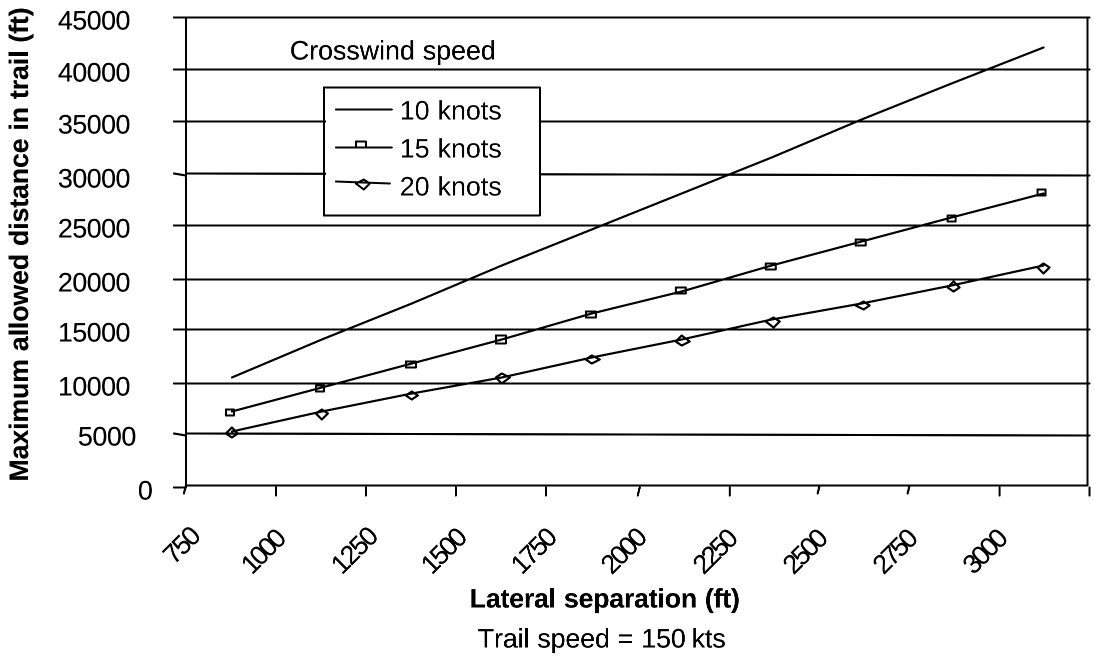

Figure 7. Effect of crosswind speed on the back of the safe zone

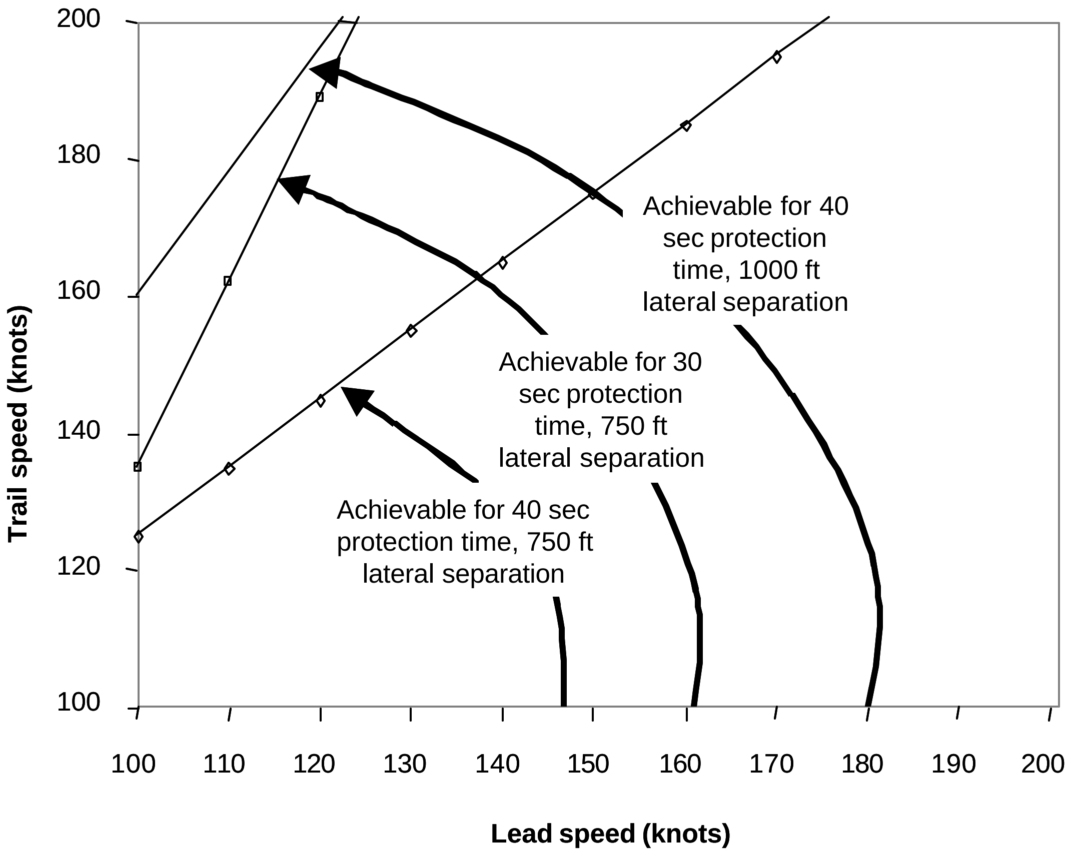

Figure 8. Range of conditions in which safe zone exists and paired approaches is feasible

STUDY TWO

Objectives

A vital element in paired approaches is the cockpit traffic display, which the pilot must use both to maintain position within the safe zone and to detect off-nominal conditions. Before detailed decisions can be made about symbology and format, we must understand the display's information requirements. Specifically, previous studies have demonstrated that un-aided pilots appear to be poor detectors and resolvers of potential collisions on parallel approaches.[2,8]

Therefore, a mechanism is needed to portray the fundamental dynamics of this operation, which include elements at several levels of abstraction. Low-level elements include the positions of both aircraft, and how they are changing. At a more conceptual level, information includes knowing where the safe zone is, and how the 'own' aircraft is moving relative to it, and movements in the safe zone in response to the lower-level aircraft states.

In this experiment, we examine portraying the more conceptual elements of information – the safe zone – directly to the pilot, as compared to studies which have examined traffic displays in other phases of flight,[for example, 9,10,11,12] or examined traffic displays providing only the low-level state information[2,8] or alerting information.[13] Two different underlying bases can be used to determine the safe zone. The first is based on procedural information; i.e. the 'predicted' safe zone is calculated assuming that the aircraft are following a pre-specified approach procedure, thereby presenting a spatial boundary which is predictable, small and un-changing throughout the approach, but which does not account for aircraft behavior outside the approach procedure. The second is based on real-time information; i.e. the 'actual' safe zone is re-calculated throughout the approach based on new information about both of the aircraft, thereby presenting a spatial boundary which is as large as possible for the immediate context, and constantly (sometimes rapidly) changing in size and location.

The objectives of this study are:

- To examine the feasibility of paired approach in general in terms of pilots of trail aircraft maintaining their position within the safe zone, and recognizing off-nominal conditions;
- To examine the utility of displaying the safe zone to the pilot as an aid in flying paired approaches; and
- To examine the relative merits of the different underlying conceptual bases of the safe zone, which each imply different control strategies and foster different types of monitoring for unusual situations.

Experiment Design

Participants

The participants in the experiment will be 12 airline pilots current on glass cockpit aircraft. At this time, only one airline pilot has fully completed the experiment.

Apparatus

Participating pilots are asked to fly approaches using Georgia Tech's Reconfigurable Flight Simulator (RFS).[14] The RFS is a multi-agent medium fidelity simulator running on Pentium III desktop computers. The simulator is configured with a dynamic model and cockpit systems representing a Boeing 747-400. Control inputs are implemented via a sidestick controller, a throttle quadrant, and virtual panels for gear, flaps and display controls accessed on the screen using a mouse. The flight deck displays are provided on a flat panel monitor in front of the pilot, including a primary flight display and a navigation display. The navigation display includes an overlay of traffic information about the other aircraft on the approach and the various safe zone presentations. This navigation display can be scaled; to account for the close separation between the aircraft, additional scale values of 2 and 5 miles are available to the pilot.

Procedure

The participants will be instructed that they are to fly an instrument landing system (ILS) approach, while remaining within the safe zone. The participant pilots will be flying the trail aircraft and other aircraft will always be the lead aircraft. In each run, they are started at approximately 20 miles from runway threshold. They and the other aircraft are established on their respective localizers, but at different altitudes. The lead aircraft's approach path is offset by three degrees to provide greater lateral separation at the start of the approach. The participant pilots are cleared for the approach, and are asked to capture their glide-slope intercept altitude and then track the glide-slope. Until 5 miles from runway threshold, they are asked to maintain 180 knots, plus or minus 10 knots, and to stay within the safe zone.

If the safe zone limits are exceeded, they are to execute a missed approach according to the procedures provided on modified approach plates, which indicate both a climb and a turn away from the other approach path. In their briefings on the safe zone, it is noted that if they stay within the safe zone and the other aircraft blunders towards their approach path, it is recommended to stay on the approach.

Experiment Design and Independent Factors

Each participant pilot flys 10 data collection runs. The first nine runs represent at 3 display X 3 scenario test matrix, with the following safe zone displays and scenarios: This experiment will have two independent variables: traffic display type and scenario type. The three traffic display variants refer to the calculations that determine the size and location of the safe zone, as follows:

Safe Zone Displays

- 'Predicted' Safe Zone Display: The safe zone is calculated using the procedural limits given to the pilot prior to commencement of the approach. The procedural safe zone limits are shown as a pair of green staple-shaped lines.
- 'Actual' Safe Zone Display: current information is taken from the two aircraft to determine the safe zone. The real-time safe zone limits are shown as a pair of yellow staple-shaped lines.
- 'Both' Safe Zone Display: Using the same formats as for the other two displays, both types of safe zone are explicitly shown to the pilot, allowing the pilot to directly compare the two types of information. The presentation is expected to be particularly useful in two situations: (1) when tracking the safe zone, this presentation provides both a static presentation of the smaller 'predicted' safe zone and the larger, less conservative 'actual' safe zone, providing both a stable representation of the safe zone but also a larger, more accommodating area should the smaller 'predicted' safe zone be temporarily existed; and (2) should the lead aircraft deviate from nominal approach procedures, the relative position of the two types of safe zone will reflect this deviation quite quickly. This display is shown in Figure 9.

Figure 9. Navigation display with indication of parallel traffic, actual safe zone and predicted safe zone

Scenarios:

- No noncompliance: a baseline in which the lead aircraft complies with all procedural restrictions.
- Speed noncompliance: the lead aircraft slows substantially below the minimum allowed procedural speed, as if this aircraft is configuring and attaining final approach speed 5-10 miles before allowed by approach procedures. This will necessitate the participant pilot to slow as well, or to fly through the front of the safe zone.
- Lateral noncompliance: the lead aircraft will turn toward and cross the trail aircraft's approach path, in the form of turn to a new heading typically used as a blunder model. This will not require any action by the trail aircraft if the trail aircraft is in the safe zone at the beginning of the lead aircraft turn.

Once the participant pilot has completed these nine runs, he or she flies a tenth run with one of the three displays which, unknown to him or her, is a novel 'combined deviation' scenario: specifically, the lead aircraft will first slow below the minimum allowed procedural speed, and then the lead aircraft will also turn toward and cross the trail aircraft's approach path. If the participant pilot has not kept the trail aircraft within the safe zone during the speed change, the following blunder can cause loss of separation.

Measurements and Results to Date

At this time, only one pilot has participated in the experiment. Observations of this pilot and his or her subjective comments provide some anecedotal evidene of issues with paired approaches.

Generally, this pilot tried to match the lead aircraft's speed whenever a blunder was detected, otherwise this pilot tried to maintain a particular distance from the front of the safe zone. The pilot was confused by the actual safe zone, however. In two scenarios the pilot noticed the front of the safe zone approaching the lead aircraft (This occurs when the two aircraft's speeds are close or the trail aircraft is slower, and lateral separation is 750 feet or less.) The pilot felt concerned by having the lead aircraft within the bracket (although it was explained that this is not a dangerous situation), and therefore slowed; this change in speed exacerbated the situation by moving the front of the safe zone forward. Post-experiment debriefing failed to convince the pilot that the situation in question was not dangerous, and although he or she understood that speeding up would move the bracket back, he or she thought this was too counterintuitive to be a valid strategy.

When asked about procedural elements that would make paired approaches feasible, this pilot selected desired minimums of 500-1 for all scenarios. He or she indicated that this was because he or she wanted to visually acquire the lead aircraft before landing to ensure that it would not incur upon his runway either on landing or on rollout. He or she felt there was insufficient detail in the navigation display to satisfy the subject of the lead aircraft's intentions.

The following quantitative measurements are being taken throughout the experiment, and will be analyzed once sufficient data is collected for valid statistical inferences:

- Pilot ratings of task difficulty at the conclusion of each approach, using a modified Cooper-Harper structure.
- Pilot ratings of their understanding of the situation during each approach (collected at the conclusion of each approach), using a modified Cooper-Harper structure in which each possible rating is associated with a set of actions that the pilot feels comfortable with given their awareness of the situation.
- Pilot detection of non-procedural actions by the lead aircraft, and the ability of the pilot to describe what the lead aircraft did, its impact on their position within the safe zone, and the type of action best suited to resolving the situation. As an estimate of these results, for the one pilot tested to date, thecorrect detection rate was 73%, the missed detection rate was 18%, and the misidentification rate was 9%.
- Approach stability as indicated by the variation about mean in the throttle movements, elevator movements, and glideslope tracking.
- Ability to track the safe zone, as indicated by both discrete counts of safe zone violations, and in the variation about the mean in distance from the front of the safe zone.

SUMMARY AND CONCLUSIONS

In summary, paired approach operations, if they can be demonstrated to be safe, have the potential to dramatically reduce delays at airports with runways spaced too close for other mechanisms including dependent approaches, specialized ground systems (such as PRM) or specialized reactive airborne systems (such as AILS). This paper has outlined two studies which examine pressing issues with paired approaches, the first through numerical analysis, the second through a piloted simulation.

The first study highlighted the range of conditions in which paired approaches may be feasible, which includes all but the closest runway spacings and largest range of allowable aircraft speeds. These results also highlighted that a cockpit alerting system capable of detecting slow blunders (but leaving separation assurance for fast blunders to be within the protection time of the safe zone) can enlarge the safe zone, as indicated by the benefits of capping the protection time provided by the safe zone.

This numerical analysis indicates that one significant problem remains unresolved. During a blunder, wake protection disappears; in other words, while it can be best for the trail aircraft's pilot to stay on the approach for collision avoidance should the lead aircraft blunder whilst they are in the safe zone, in doing so they are leaving wake avoidance to chance. It may be possible to overcome this limitation with a vertical maneuver, with a better model of wake transport, and/or with wake position sensing or prediction tools.

The second study remains underway, with 1 pilot (of 12) having participated to date. This study is examining both basic display and procedural issues, as well as the issue of how the safe zone should be conceptualized and calculated – using a fixed procedural basis, or using real-time information.

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