Pilot Control Behavior in Paired Approaches

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Abstract

A piloted flight simulator study investigated pilot control behavior while self-separating from a proximate aircraft during an instrument landing system approach. This “paired approach” operational concept pairs two aircraft, with the trail aircraft of the pair remaining within a safe zone calculated to be free (for a specified period of time) from collision danger and wake turbulence interactions. Enabling this operation would reduce dependent spacing between aircraft landing on closely spaced parallel runways in poor weather conditions, which is a significant source of weather-related delays. Pilots in the study flew the trail aircraft and were given displays that either showed the current safe zone, a “worst-case” safe zone based on information contained in the approach procedure, or both. The lead aircraft’s compliance to the expected procedure was also varied so that it either complied fully, changed its speed unexpectedly, or blundered across the trail aircraft’s flight path. It was anticipated that the pilots would track the safe zone, resulting in significantly different behavior depending on the type(s) of safe zone displayed to them. However, the results suggest a strategy of matching speeds with the lead aircraft, rather than tracking the safe zone. Since the procedures and technologies for paired approaches had not considered this strategy, changes to support pilots in using this strategy, or training to overcome it, are necessary.

Introduction

In order to reduce air traffic controller workload, reduce communications requirements between controller and pilot, or to eliminate communications delays between controller and pilot, moving some aircraft to aircraft separation responsibility to the flight deck has been widely proposed. This is referred to as “self-separation”, and requires additional new monitoring and control behaviors from pilots. Pilots must monitor their position relative to other aircraft, and maneuver their aircraft to remain at the proper distance from those aircraft.

One example of self-spacing is found in a proposed operation called “paired approaches”, which places two aircraft on instrument approaches to closely spaced parallel runways with one aircraft offset behind the other. The trail aircraft maintains a position relative to the lead aircraft (Stone, 1996; Pritchett, 1999; Hammer, 1999) that guarantees that neither aircraft will be in danger of loss of separation within a certain time window should the other depart its approach path, and that neither aircraft will be affected by the other’s wake.

Two different underlying bases can be used to determine the safe zone (Pritchett and Landry, 2001). The first uses procedural information; i.e. a “predicted” safe zone can be calculated assuming that the aircraft are following a pre-specified approach procedure, thereby presenting a spatial boundary which is predictable, small and stable throughout the approach, but which does not account for either aircraft not complying with the approach procedure. The second is based on real-time information; i.e. the “actual” safe zone is recalculated throughout the approach based on the current states of both 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.

From an implementation viewpoint, these two bases for a safe zone are important considerations because each may have different equipment and procedure requirements. The actual safe zone requires a broadcast of the lead aircraft’s position and speed. The trail aircraft must have the capability to receive this information, and also have the means to rapidly calculate...
and display the safe zone. The predicted safe zone could be calculated in advance, and would not, in theory, require any special equipment except an indication of the longitudinal separation from the lead aircraft, displayed on the flight deck of the trail aircraft.

The approach procedures would also have to be different. The trail aircraft, if given only the actual safe zone, would have to remain within the safe zone regardless of the behavior of the lead aircraft, and follow a missed approach procedure if the safe zone were departed. This missed approach procedure would probably be a predetermined maneuver consisting of a turn away from the lead aircraft’s approach path, a climb, and acceleration. If given the predicted safe zone, the trail aircraft would also have to remain within the safe zone, and would have to perform a missed approach if those limits were exceeded. However, the trail aircraft would also have to execute a missed approach if either aircraft violated the assumptions of the predicted safe zone.

Both safe zones are defined as a range of positions relative to the lead aircraft. As the lead aircraft changes position, both safe zones move with it. Movement of the trail aircraft relative to the lead aircraft is therefore also movement relative to the safe zone. For example, if the trail aircraft is closing on the lead aircraft, then it would also be closing on the front of the safe zone (and moving away from the back of the safe zone).

For the actual safe zone, the safe zone has a second source of movement relative to the trail aircraft. Since the safe zone is continuously updated based on the current speeds and positions of the two aircraft, its position relative to the lead aircraft can be changing. For example, as the trail aircraft increases (or the lead aircraft decreases) its airspeed, the safe zone needs to be further in trail of the lead aircraft. So, if the lead aircraft slows, not only will the trail aircraft begin closing on the lead aircraft (and the front of the safe zone), but the front of the safe zone would be moving away from the lead aircraft (and back towards the trail aircraft). The movement of the front of the safe zone may therefore be based on several factors, which could be difficult for the pilot to understand.

There are many different control strategies that could be used by the pilot for this operation, and these strategies differ by which safe zone is being displayed (as shown in Table 1). If given the actual safe zone, pilots may choose to remain at a particular position relative to the front of the safe zone, with control movements consistent with this tracking. Since the actual safe zone is dynamic, control movements may be frequent. Since the actual safe zone could potentially change faster than the pilot could react, control movements may be somewhat severe as well. If given the predicted safe zone, pilots may also try to remain at a given distance from the front of the safe zone. However, since the predicted safe zone is relatively stable, fewer control movements would have to be made. In addition, these control movements need not be severe due to the static nature of the predicted safe zone.

In addition to the control strategies, pilots would have additional monitoring tasks. When given the actual safe zone, pilots would have to frequently monitor their position within the safe zone. If given the predicted safe zone, pilots would not have to monitor their position within the safe zone as frequently (since the predicted safe zone is fairly static), but would also have to monitor the lead aircraft for conformance to the procedure (since the predicted safe zone would be invalid if the lead aircraft does not comply with the approach procedure).

If both safe zones are displayed, pilots may choose to utilize the better features of each. The pilots may be able to track the predicted safe zone, resulting in less monitoring of the safe zone and less control movements, while also monitoring their position relative to the actual safe zone to reduce the need to monitor the lead aircraft’s compliance.

The reaction of pilots to a lead aircraft that was not conforming to the approach procedure would also be different for each of the safe zones. If the actual safe zone is displayed, and the lead aircraft did not comply, the trail aircraft would not have to take any action except to try to remain within the safe zone, and perform a missed approach if they depart the safe zone. If the predicted safe zone is displayed, the trail aircraft would have to consider whether the safe zone was still valid, and perform a missed approach if it is not.
Table 1. Expected control and monitoring behavior for the display of the two safe zones.

<table>
<thead>
<tr>
<th></th>
<th>Predicted Only</th>
<th>Actual Only</th>
<th>Both</th>
</tr>
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<tbody>
<tr>
<td><strong>General control strategy</strong></td>
<td>Stay within safe zone (predicted safe zone is small but stable).</td>
<td>Stay within safe zone (actual safe zone is large but dynamic).</td>
<td>Generally stay within predicted safe zone, but can briefly depart if within actual safe zone.</td>
</tr>
<tr>
<td>Measures of control strategy</td>
<td>Position within safe zone, correspondence of throttle movements to deviations of position within safe zone</td>
<td>Position within safe zone, correspondence of throttle movements to deviations of position within safe zone.</td>
<td>Position within predicted safe zone (or actual if predicted departed). Correspondence of throttle movements.</td>
</tr>
<tr>
<td><strong>General monitoring strategy</strong></td>
<td>Occasional checks on position in safe zone. Conformance monitoring of lead aircraft.</td>
<td>Frequent checks on position within safe zone.</td>
<td>Occasional checks on position within predicted safe zone. More frequent if outside of predicted safe zone.</td>
</tr>
<tr>
<td>Measures of monitoring strategy</td>
<td>Stable position maintained within safe zone. Able to detect lead aircraft noncompliance.</td>
<td>Stable position maintained within safe zone.</td>
<td>Stable position maintained within predicted and/or actual safe zone. Able to detect lead aircraft noncompliance.</td>
</tr>
<tr>
<td>Reaction to noncompliance</td>
<td>Should recognize noncompliance that will invalidate the safe zone.</td>
<td>Should execute a missed approach only upon departing safe zone.</td>
<td>Should execute a missed approach upon departing actual safe zone.</td>
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</table>

This study examined whether pilots would be able to fly a stable instrument approach when given the additional task of acting as the trail aircraft and tracking the safe zone. In addition, the relative merits of the two different underlying conceptual bases of the safe zone were studied, since they may require different control strategies and foster different types of monitoring for unusual situations. Finally, the study may give general insight into both paired approaches and, more generally, self-separation tasks.

Stability of the approach was measured by both control movements (where smaller and generally fewer control movements would indicate stability), and approach error (as given by error about the desired glidepath). Control strategy was evaluated by examining whether there was a desired position within the safe zone that the pilot tried to maintain. Monitoring was studied by questioning the pilots concerning the compliance of the lead aircraft (which would be varied during the experiment) and evaluating their responses.

**Method**

**Apparatus**

Participating pilots (12 male airline pilots current or previously qualified in glass cockpit aircraft) were asked to fly approaches using Georgia Tech’s Reconfigurable Flight Simulator (RFS) (Ippolito and Pritchett, 2000). The RFS is a medium fidelity simulator running on a Pentium III desktop computer. The simulator was configured with a dynamic model and cockpit systems representing a Boeing 747-400. The navigation display (ND) included an overlay of traffic information about the aircraft on the other approach and the safe zone presentations, which were displayed as staple shaped brackets (Figure 1).
Procedure

Pilots were given detailed briefings on the simulator and the procedure, and given an opportunity to practice with each until they felt comfortable. In the briefing on the safe zone, it was stressed that a position within the actual safe zone was safe for the next 30 seconds from collision and wake turbulence regardless of the actions of either aircraft, while a position within the predicted safe zone was similarly safe, but only in the 30 seconds following noncompliance from the approach procedure by either aircraft. If the safe zone was departed, this protection was no longer guaranteed, and it was recommended that a missed approach be executed. The missed approach procedures were provided on the approach plate, and indicated both a climb and a turn away from the other approach path.

The pilots were instructed to fly an instrument landing system approach, while remaining within the safe zone. This type of approach relies on a broadcast signal indicating the extended runway centerline (localizer), and a separate signal indicating the proper vertical profile (glideslope). The pilot is given a display of his or her deviation from those ideal trajectories and must make corrections to return to the proper course and glideslope.

The pilots flew the trail aircraft, with the lead aircraft being a scripted pseudo-aircraft. Each run began at approximately 20 miles from runway threshold on the localizer and at approximately 200 knots true air speed (KTAS). The participants were instructed that ATC had told them (and the lead aircraft) to maintain 180 KTAS, plus or minus 10 knots, until 5 miles from runway threshold, where they could slow to their normal approach speed of 148 KTAS.

Experiment Design and Independent Factors

Each participant pilot flew 10 data collection runs. The first nine runs represented a two-factor design with three safe zone displays and three noncompliance types. The three displays refer to the conceptual basis of the safe zone, as follows:

- Predicted safe zone display: The predicted safe zone was shown on the ND.
- Actual safe zone display: The actual safe zone was shown on the ND.
Both safe zones display: Both safe zones were shown on the ND, allowing the pilot to directly compare the two types of information. In this case the pilots were briefed that they could depart the predicted safe zone as long as they remained within the actual safe zone. This display is shown in Figure 1.

The noncompliance type refers to the type of noncompliance committed by the lead aircraft:

- **No noncompliance**: a baseline in which the lead aircraft complied with all procedural restrictions.
- **Speed noncompliance**: The lead aircraft slowed substantially below the approach procedure’s minimum allowed speed, as if this aircraft were configuring and attaining final approach speed 5-10 miles before allowed by approach procedures.
- **Lateral noncompliance**: The lead aircraft turned toward and crossed the participant’s approach path, in the form of a turn to a new heading commonly used as a noncompliance model.

Once the participant completed these nine runs, he flew a tenth run with one of the three safe zone displays in a combined noncompliance scenario: specifically, the lead aircraft first slowed below the minimum allowed procedural speed, and then the lead aircraft also turned toward and crossed the trail aircraft’s approach path.

Basic aircraft parameters (position, speed, heading) were recorded throughout the data runs. In addition, pilot control movements (elevator and throttle) were recorded, as was glideslope deviation. Because the aircraft was laterally stable (no disturbances were introduced into the simulator scenarios) and most pilots were able to remain on the localizer without any aileron or rudder movements, measures of lateral-directional control, although recorded, were not used in the data analysis.

**Results**

For each subject and each experimental run, the control movement and glideslope deviation data were aggregated, providing a mean and standard deviation. For each of the measures, data collected after the pilot initiated a missed approach were removed. Since large changes in throttle and elevator, and large deviations from the glideslope, are undesirable and indicative of an unstable approach, the standard deviation of these measures was used to examine the stability of the approaches. In addition, the number of throttle movements was examined to compare the number of discrete control changes, both by display and noncompliance type, and before and after noncompliance occurred.

An ANOVA was then performed on the standard deviations for the three responses (throttle setting, elevator position, and deviation from glideslope) and on the number of throttle movements using a general linear model with three main factors: subject, display type, and noncompliance type.

For elevator position and glideslope error standard deviation, there were significant differences across subjects, but no significant differences across display or noncompliance type.

The ANOVA for throttle standard deviation is shown in Table 1, with the main effects shown in Figure 2. Significant main effects were found for subject and noncompliance type, but not for display type. Pairwise comparisons showed that, except for between lateral and speed noncompliance, all pairwise differences between noncompliance conditions were either significant or marginally significant (Both-Lateral, None-Speed).

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject</td>
<td>11</td>
<td>6884.1</td>
<td>6871.2</td>
<td>624.7</td>
<td>4.50</td>
<td>0.000</td>
</tr>
<tr>
<td>Noncompliance</td>
<td>3</td>
<td>6281.9</td>
<td>6014.3</td>
<td>2004.8</td>
<td>14.44</td>
<td>0.000</td>
</tr>
<tr>
<td>Display</td>
<td>2</td>
<td>223.6</td>
<td>223.6</td>
<td>111.8</td>
<td>0.81</td>
<td>0.450</td>
</tr>
<tr>
<td>Error</td>
<td>103</td>
<td>14295.3</td>
<td>14295.3</td>
<td>138.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>119</td>
<td>27684.9</td>
<td></td>
<td></td>
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</table>
A chi-squared test on the number of discrete throttle movements indicated no significant difference before and after noncompliance occurred.

Regressions examined whether throttle changes could be predicted by either changes to position within the safe zone, changes to the trail aircraft’s relative position with respect to the lead aircraft, or to changes in the speed difference between lead and trail aircraft. There was no linear relation of throttle changes to changes in safe zone position or lead aircraft relative position. However, in many cases there was an inverse linear relation of throttle changes to speed difference between the lead and trail aircraft. Table 2 shows the probabilities that this relation does not exist for each subject, with the highlighted cells being significant to $\alpha<0.10$. These results are shown in five conditions: the non-compliance scenarios; the speed non-compliance scenarios separated by behavior before and after the lead aircraft’s change in speed; and the lateral non-compliance scenarios separated by behavior before and after the lead aircraft’s change in lateral direction. Four pilots were found to have throttle control behavior correlated with speed differences in all conditions; all other pilots except Pilot 9 were found to have this correlation in behavior in at least two conditions. These results suggest that many of the pilots were using speed differences between themselves and the lead aircraft as a primary determinant of their throttle movements, except perhaps following lateral noncompliance from the lead aircraft.

Pilots successfully identified 79% of all noncompliance cases. Pilots did not detect 4% (or a total of 4) of the noncompliance conditions and misidentified 18%. Misidentifications included cases where:

- no noncompliance occurred but pilots indicated it had occurred,
• speed noncompliance occurred and the pilot indicated either no noncompliance or lateral noncompliance had occurred, or
• lateral noncompliance occurred and the pilot indicated either no noncompliance or speed noncompliance had occurred.
An ANOVA found no significant differences for the missed detections and misidentifications by display or noncompliance type.

Discussion
The pilots did not appear to follow the anticipated control or monitoring strategies. The pilots did not maintain a particular position within whichever safe zone was displayed, nor were the throttle movements consistent with deviations of position with respect to the safe zone. Instead, these throttle movements corresponded with a difference in speed between the lead and trail aircraft, suggesting that the pilots were attempting to match the lead aircraft’s speed, regardless of which safe zone was displayed.

The pilots also did not appear to follow the expected monitoring behavior. Pilots made frequent mistakes about whether noncompliance had occurred, and of what type it was. Moreover, noncompliance detection performance was the same regardless of display type, even though monitoring needs to increase when given only the predicted safe zone. Pilots did, however, appear to be monitoring the speed of the other aircraft quite closely, making frequent mention of when the text display of the lead aircraft’s speed was obscured by other symbology, regardless of display type. This latter finding further supports the idea that the pilots’ control strategy was to null differences in speed between themselves and the lead aircraft.

In addition, pilots’ monitoring of the safe zone appeared to be similar to the monitoring of a “red line” on an engine instrument. Pilots did not want to exceed this limit, but otherwise made little attempt to track it. When the pilots exceeded the safe zone, they performed a missed approach.

Pilot reaction to noncompliance of the lead aircraft also was partly unanticipated. Although pilots did execute a missed approach as specified by the procedure if they departed the safe zone, they did not react properly to lead aircraft noncompliance when they were given the predicted safe zone. This suggests that they did not (or could not) interpret the consequences of the lead aircraft noncompliance.

Conclusions
The pilots in this study did not follow the position-keeping strategy that is implicitly expected in studies of paired approaches. In fact, they appeared to make little attempt to maintain a static position within the safe zone. Instead, they appeared to favor a strategy of matching speed with the lead aircraft. This strategy would keep them in a static position with respect to the safe zone only if the safe zone were static with respect to the lead aircraft. However, this is not the case for the actual safe zone, which is updated using real-time information, as the position of the safe zone behind the lead aircraft changes as speeds and lateral separation change.

The design of procedures and displays for paired approaches has not considered the possibility of this strategy. If this behavior is to be supported, then future analysis of the system must incorporate it into the modeling of the pilot and into the design of procedures and displays. For example, in addition to providing a text indication of lead aircraft speed, presenting relative speed and/or command information to the trail aircraft may provide direct support to matching the lead aircraft’s speed. Similarly, procedures could be adapted to allow the trail aircraft to match the lead aircraft’s speed, treating them much like a formation flight for the purposes of speed restrictions, rather than as individual aircraft.

If the strategy were deemed inadequate, then, in addition to training designed to adapt the pilot’s behavior, changes to displays and procedures would be required. The display changes may need to hinder the ability of the pilot to track the lead aircraft’s speed. An extreme example of this would be to remove the display of the lead aircraft entirely, showing only the safe zone.
Another possibility is to display a speed cue (most likely a range of speeds) that is calculated to ensure the trail aircraft will remain within the safe zone for a specified period of time, thereby encouraging tracking the safe zone. Alternatively, a “desired position” cue could be added to the display to indicate to the pilot where in the safe zone he or she should be.

In a general sense it is difficult to know a priori what strategies operators will bring to a novel operation. Assumptions about these strategies are often adopted from similar systems, and may be incomplete or inaccurate. These assumptions often have significant implications for how procedures and technologies are designed, and mismatches between these and operator strategy can cause poor overall performance. Careful up-front analysis and ecological experimentation can catch these assumptions before too much time and effort are expended on a poor design.

References


