EXAMINING THE FEASIBILITY OF PAIRED CLOSELY-SPACED PARALLEL APPROACHES

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ABSTRACT
‘Paired’ closely-spaced parallel approaches may enable closely-spaced runways to operate at near-visual capacity in all weather conditions. This concept requires each trail aircraft in the pair to fly in a ‘safe zone’ in front of the lead aircraft’s wake vortex and in back of the lead aircraft’s potential blunder trajectories. This paper examines the position and length of this safe zone to understand the structure of this operating environment. The results highlight the need for an alerting system, and identify facets of procedures needed for this operation.

INTRODUCTION
Many airports have parallel runways, allowing for simultaneous operations without concern for crossing traffic flows. For aircraft to land simultaneously on these runways requires them to fly close together for several minutes on parallel approach paths to the runways. This demands a mechanism for ensuring safe separation between aircraft, and between aircraft and other aircraft’s wake vortices.

When weather conditions allow aircraft to visually acquire each other for all of the approach, the responsibility for separation is given to the pilots. However, weather conditions frequently do not allow visual approaches; in these cases, other mechanisms are required. Currently, air traffic controllers supervise the approaches and ensure separation. However, several factors – including concerns about wake vortex separation, the resolution of controllers’ radar systems, and the time required for controller intervention – limit parallel operations to runways with at least 4300 feet separation (for independent operations), 3000 feet (for independent operations with the specialized Precision Runway Monitor), or 2500 feet (for ‘dependent’ operations where the controller stagger the aircraft along the approaches to keep a large separation between them).

Several studies have examined airborne separation assurance, in which pilots and flight deck systems maintain safe separation, with the hope of allowing all weather use of closely spaced parallel approaches. One method of parallel approaches is reactive; i.e. it relies upon pilot monitoring and/or alerting systems to detect any possible loss of separation.

Another method 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. As shown schematically in Figure 1, this method is preventive in nature – this positioning guarantees 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 operation needs to be clearly understood before implementation, as the aircraft are closer together in reduced visibility than allowable in any other airborne civilian operation. Several preliminary studies have examined paired approaches, suggesting possible procedures, and assessing cockpit traffic displays. However, studies to date have typically examined specific implementations, such as tests of a specific traffic display or procedure.

The novelty and complexity of this operation merits a comprehensive examination of the underlying system dynamics; with such knowledge, we can more conclusively determine the pilots’ information, procedure, and technology needs, and potentially applied more-structured design methodologies to reduce the time required to design and test new technologies and procedures for this operation. In this case, the system dynamics are largely governed by the size and position of the safe zone, which is determined by several factors (including pilot actions to stay within the safe zone), procedures, aircraft dynamic behavior, and alerting system look-ahead time.

In this paper we first outline how the safe zone is calculated, and then we identify the impact of procedural assumptions and technologies on system dynamics. Finally we discuss the insights provided into the structure of the environment, and their implications for this air traffic control operation.

**CALCULATING SAFE ZONE LOCATION**

The location of the safe zone can be found analytically from examination of current positions and potential future trajectories of the two aircraft. Since vertical position can vary quickly and unpredictably, 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, which is limited by procedural restrictions on allowable behavior and on aircraft dynamic behavior – namely, transport aircraft can not fly sideways, and can not quickly turn to a new heading.

In calculating the safe zone, we use the worst case model of a potential loss of separation, i.e. a blunder by the lead aircraft where it changes heading. We assume the blunder heading change rate is achieved instantly, an assumption that was tested and found to have negligible consequences. The horizontal distance guarantee collision and wake avoidance at future times between the aircraft in a turn lasting for a duration $T_{\text{turn}}$ can then be found:

\[
D = \sqrt{(x_2(0) - K_1t)^2 + (K_3 - K_4t)^2}
\]

\[
K_1 = \frac{v_1}{\cos v} \sin v \cdot t_{\text{turn}} \cos v
\]

\[
K_2 = v_1 \cos v \cdot v_2
\]

\[
K_3 = \frac{v_1}{\cos v} (1 + \cos v) \cdot y_2(0)
\]

\[
K_4 = v_1 \sin v
\]

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 equation can be solved for the minimal value for $x_2$ guaranteeing separation in all allowable future conditions within the protection time.

The distance the trail aircraft can fly while the wake to crosses between the aircraft is the maximum allowable in-trail distance. We assume that the wake is transported at crosswind velocity, a reasonable approximation of recent research. The back of the safe zone is therefore determined by the lateral separation between aircraft, the crosswind, 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 statistical properties.

| $x_2(0)$ | Initial longitudinal separation |
| $y_2(0)$ | Initial lateral separation between aircraft |
| $v_1$, $v_2$ | Lead and trail aircraft speeds |
| ? | Blunder heading change |
| ? | Blunder heading change rate |
| $t_{\text{prot}}$ | Protection time cap of safe zone |
| $V_c$ | Crosswind |

Table 1. Front of safe zone variables

**RESULTS**
This study explores how the front and back of the
safe zone change with the variables listed in Table 1.
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. The following sections highlight some of
the most important results of this analysis.
Impact of Aircraft Ground Speed

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 additional insights should be noted beyond its overall sensitivity to speed. First, 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. Second, additional analysis identified conditions where the front of the safe zone needs to protect against blunders of the trail aircraft towards the lead – specifically, when the trail aircraft is faster.

Impact of Blunder Severity

The safe zone is defined as preventing a blunder from causing loss of separation. Therefore, we examined the impact of requiring it to protect against blunders of greater and lower severity, as established by worst-case blunder heading changes and change rates. As shown in Figure 3, the most restrictive safe zone (i.e. one requiring a greater minimum in-trail distance) is determined by the lowest blunder heading change, and must be applied in situations where the trail aircraft is (or may be) faster than the lead aircraft, a situation corresponding to situations where the lead aircraft may slowly drift over-and-back into the trail aircraft. Large heading changes, conversely, do not have a significant impact on safe zone location as the lead aircraft may not have the time and space to enact a large turn before crossing over the trail aircraft’s approach path. A similar effect was found for blunder heading change rate.

Impact of Protection Time

The previous section’s results suggest that the front of the safe zone, if required to protect against all possible intrusions, is positioned conservatively by the lowest possible blunder heading changes and change rates. However, such blunders require a long time to cause a separation hazard. Therefore, we analyzed the impact of establishing a ‘protection time’ which the safe zone needs to provide; i.e. the safe zone will guarantee separation against blunders taking less than the protection time to evolve, whilst another mechanism – such as an alerting system – is required for blunders taking longer. As shown in Figure 4, laxer protection time limits move the safe zone forward substantially from the worst-case locations shown in Figure 3.
Figure 2. Impact of trail and lead aircraft ground speed on location of the front of the safe zone

- lateral separation = 1000 ft, trail speed = 150 kts
- heading change rate = 6 deg per sec

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

- lead speed = 150 kts, trail speed = 170 kts
- No blunders can cause separation violations within 20 secs at greater than 1800' lateral separation

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

- Protection Time (sec): 20, 30, 40
Is There Always a Safe Zone?

The previous sections discussed the location of the front of the safe zone. As noted earlier, the back of the safe zone is a simple linear function of lateral separation, crosswind speed, and trail aircraft speed. The safe zone may be said to exist when the ‘back’ is behind the ‘front’. There are some cases where this is not true; however, these combinations are confined to low lateral separations, large protection times, low lead aircraft speeds, and high trail aircraft speeds, as shown in Figure 5. The safe zone lengthens rapidly away from these combinations.

CONCLUSIONS

This study provides a comprehensive examination of the safe zone during paired approaches. These results show that the safe zone exists for all but the worst combinations of high protection times, low runway spacings, high crosswinds, and low aircraft speeds.

These results also highlight the important factors in calculating the safe zone location and size – aircraft speeds, protection time, lateral separation, and crosswind speed. Additionally, these results highlight the complexity of calculating the safe zone – their require computations can potentially be performed in near-real-time by a computerized cockpit display given knowledge of the immediate situation, but are likely too complex and intricate to require of a pilot during the high-tempo operation of final approach. (In addition, other studies of reaction methods of closely spaced parallel approaches suggest pilots may not be accustomed to, and not very good at, the task of spacing and collision detection in this phase of flight.6)

The results also highlight that the safe zone can only reasonably provide a limited protection time, capable of guarding against rapid losses of separation but not against very slow maneuvers of one aircraft towards another. This suggests that supplemental mechanisms of detecting slow intrusions will be beneficial in lengthening the safe zone. Reliance solely on controller intervention is unlikely due to the specialized ground based systems this would require and due to the extra time needed for a controller to effectively intervene through voice
commands. Likewise, relying solely on pilot monitoring of cockpit displays may reasonably be hypothesized to be problematic given their workload and competing tasks during approach. Therefore, these results suggest the need for a cockpit alerting system; design of such a system does not need to be overly complex, however, as it only to detect slow intrusions.

Procedural concerns are raised by these results. For example, the concept of paired approaches has typically assumed that the ‘trail’ aircraft both should be behind the ‘lead’ aircraft, and that the trail aircraft would be requiring protection from the lead aircraft’s actions. Instead, these results identified situations where the trail aircraft may safely be in front of the lead aircraft (when the trail aircraft is slower), and situations where the trail aircraft could potentially be the instigator of loss of separation (when it is faster). As such, the distinction between ‘trail’ and ‘lead’ aircraft may instead be viewed as a procedural matter where each aircraft in a pair are assigned a role – one to fly independently, and the other to fly within the safe zone they jointly define.

Of course, while providing guidance into procedural and technical needs, this numerical analysis can not completely specify the best implementation. However, the knowledge gained here may also help subsequent design processes by enabling more structured design methods. For example, Ecological Interface Design (EID) serves to create displays clearly portraying information about all levels of abstraction relevant to the task at hand, including functional relationships and physical properties. EID is has been widely studied in situations where the requisite means-end relationships are clearly defined by physical properties; the analysis here may serve as an example of identifying means-end relationships based on complex interplay between physical systems (in this case, aircraft dynamics), intelligent computerized systems (in this case, alerting systems), and procedural definitions of normative behavior.

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