FEASIBILITY ANALYSES FOR PAIRED APPROACH PROCEDURES FOR CLOSELY SPACED PARALLEL RUNWAYS

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Abstract

In current air traffic operations in the U.S., closely spaced parallel runways (CSPRs) separated by less than 2500 feet (ft) can be used to conduct simultaneous parallel operations using visual separation. Once below visual approach minima, such dual runway operations are no longer possible. To address this loss of throughput, several concepts are currently under consideration. This paper discusses a “paired approach” concept which enables use of CSPRs down to Category I and II approach minima. The paper documents Monte Carlo analyses on the feasibility and trade-offs of paired approach procedure variants with and without an escape maneuver. It concludes that both procedure variations require echelon staggering for most airports with runway centerline (RCL) separations below 2500 ft and provides window parameters required for an acceptable Target Level of Safety (TLS). It shows that a value of up to 4000 ft for this echelon spacing is adequate for most CSPRs for an adverse wind threshold of 10 knots; the specific value depending on the concept variation and geometry. Other findings include the ability to achieve abeam positioning with an escape procedure for several runway configurations. Many procedural combinations examined are capable of pairing 95% to 100% of aircraft.

Additionally, this paper presents an analysis of wake encounter risk during blunders. The analysis results suggest the non-escape procedure variant has a high probability of wake vortex encounter during blunder. On the other hand, the escape procedure variant with a delay in breakout of 8 seconds or less appears to provide protection from wake encounters even during a blunder.

Preliminary considerations for surveillance requirements are presented, including optional 1090 MHz Extended SQuitter (1090ES) Automatic Dependent Surveillance-Broadcast (ADS-B) messages and fields that may support the escape procedure variation.

Introduction

The ability to use closely spaced parallel runways (CSPRs) for simultaneous operations is generally lost when visual approaches cannot be conducted. Federal Aviation Administration (FAA) Order 8260.49A enables Simultaneous Offset Instrument Approaches (SOIA) down to ceilings and visibilities of about 2100 feet (ft) and 4 statute miles (mi) respectively, depending on the runway geometry. FAA Order 7110.308 enables some airports to continue operating to Category I minima as long as a heavy or Boeing 757 aircraft is not leading. For other airports, however, going below visual approach minima reduces the two-runway CSPR arrival operation to essentially a single runway operation. Depending on the airport, this may imply nearly halving the capacity. Several concepts are currently under consideration to address this loss of throughput. Some of them, called Wake Turbulence Mitigation for Arrivals (WTMA) build on FAA Order 7110.308 to develop procedural and wind based concepts. This paper discusses a so called “paired approach” concept which extends the procedures considerably further to enable use of the CSPRs down to Category I and II minima under considerably more adverse wind conditions. Two broad variations are being considered for paired approaches:

• A procedure without an escape maneuver for non-blundering aircraft (also known as the United Paired Approach, or UPA, concept).
• A procedure with an escape maneuver for non-blundering aircraft (also known as the Simplified Aircraft-Based Paired Approach, or SAPA, concept).

Paired Approach Procedure without Escape

In the late 1990s, United Airlines proposed a procedure in which aircraft are paired in close longitudinal proximity [1]. Longitudinal separation between paired aircraft is provided by the use of
Automatic Dependent Surveillance-Broadcast (ADS-B) combined with a set of Cockpit Display of Traffic Information (CDTI) tools. This variation of the procedure consists of a trail aircraft maintaining spacing relative to a lead aircraft through an approach; this spacing must be within a specific window defined by front and rear gates. The front gate of the window is the minimum distance allowed between the trail and lead aircraft. The front gate is designed so that it is geometrically impossible for the aircraft to collide in the event of a blunder. The rear gate of the window is the maximum distance allowed between the trail and lead aircraft, constrained by wake vortex avoidance considerations. The trail aircraft needs to be sufficiently close to the lead aircraft in order to stay in front of wake vortices transported by atmospheric conditions. In the case of a blunder by either aircraft, the concept expects the other aircraft to continue on its approach; no breakout maneuver is envisioned, since collision protection is guaranteed by the geometry. Figure 1 depicts the paired approach procedure without escape.

This variation of the paired approach concept, with a 3 degree offset approach, accommodates existing navigation performance and enables approaches down to Category I minima. Area Navigation (RNAV) or Required Navigation Performance (RNP) is expected to facilitate minima of roughly 300 ft Above Ground Level (AGL). Alternatively, an Instrument Landing System (ILS) with 3 degree localizer offset is also expected to support this procedure variant. This procedure has been studied extensively through analyses and real time simulations\(^1\) [2-4]. Potential benefits of the procedure are reported in [5].

**Paired Approach Procedure with Escape**

More recently the FAA has proposed a somewhat similar procedure with the difference that in the event of a potential blunder, the non-blundering aircraft on the parallel approach would breakout with a specified escape maneuver. This procedure variation is performance-based in that it takes advantage of implementation of new technology and avionics, including: ADS-B, Category III capable digital flight controls, lateral navigation (LNAV) guided missed approach algorithms, and navigation systems producing total system error (TSE) of 40 meters (m) or less (95%) \([6]-[9]\). Navigation systems that satisfy the TSE requirement include either Ground Based Augmentation System (GBAS) or Space Based Augmentation System (SBAS) Localizer Performance with Vertical guidance (LPV). This variation of the paired approach concept is expected to enable approaches down to Category II, and perhaps to Category III, minima.

This procedure expects to provide collision protection through an escape maneuver and provides wake protection by staying approximately abeam. It is hypothesized that the approximate abeam positioning would enable a more flexible geometry in that aircraft could pass each other which they cannot do in the non-escape version. Figure 2 depicts the paired approach procedure with escape (i.e., SAPA), based on information from [6-9].

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\(^1\) Simulations were conducted with full performance controllers and line pilots
Collision Risk Analysis

A quantitative safety analysis of the paired approach procedure has been conducted, consisting of Monte Carlo examination of collision probability. The analysis presented in this paper considers straight-in (i.e., parallel) and 3 degree offset procedures with and without escape, thus presenting four permutations in total.

In order to analyze the procedure requirements, relevant documentation and assumptions from similar parallel procedures were examined. A key result identified in the Precision Runway Monitor (PRM) demonstration report [10] is the acceptable Target Level of Safety (TLS) for collision on parallel approaches, which was stated as $4 \times 10^{-8}$ per approach. However, as safety risk management has progressed over the years, a more stringent standard of $10^{-9}$ per operation is typically applied today. This paper will document analysis with respect to the more stringent standard. In assessing the achieved level of safety for paired approaches, the risk of collision per approach is computed with two factors: the probability of blunder per approach, and the probability of collision given a blunder:

$$p(\text{collision per approach}) = p(\text{blunder per approach}) \times p(\text{collision | blunder})$$

Recent analyses [11-13] have yielded empirical values for $p(\text{blunder per approach})$. Monte Carlo techniques have been used to determine values for $p(\text{collision | blunder})$, window sizes that meet an acceptable TLS, and procedure feasibility.

Table 1 has been produced with data from [11]-[13]. The study examined deviations resulting in no transgression zone (NTZ) violations and examined a total of 785,203 instrument approaches from 12 airports from October 2007 through June 2009. Table 1 shows the principal results of the study; in total NTZ violations occurred at a rate of $4 \times 10^{-5}$ per approach. For the purposes of this paper, these NTZ violations are also considered to represent blunders for CSPR operations.

Table 1. Summary of NTZ Penetrations & Angles

<table>
<thead>
<tr>
<th>Deviation (degrees)</th>
<th>FY2008</th>
<th>FY2009</th>
<th>Total</th>
<th>Rate Per Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10°</td>
<td>12</td>
<td>8</td>
<td>20</td>
<td>2.55E-05</td>
</tr>
<tr>
<td>10-19°</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>1.02E-05</td>
</tr>
<tr>
<td>20-29°</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>5.09E-06</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>18</td>
<td>32</td>
<td>4.08E-05</td>
</tr>
</tbody>
</table>

Data from References [11-13]

In order to achieve a rate of $10^{-9}$ collisions per approach, based on the data presented in Table 1, the blunder to collision rate must be kept to a value of $10^{-4}$ or less. For the purposes of this study, the factor of 4 in the NTZ penetration rate is ignored as it is believed that there is uncertainty in the first significant digit. The analysis of $p(\text{collision | blunder})$ is presented by first listing assumptions, followed by an explanation of analysis techniques, and presentation of results.

Simulation Model Conditions and Assumptions

Lateral navigation path tracking accuracy for straight-in approaches was assumed to be 40 m (95%), per [8]; to assure landing on the runway, Instrument Landing System (ILS) accuracies (40 ft/nautical mile [nmi], 95%) were used at distances less than 2.25 nmi from the threshold. For 3 degree offset approach cases, the aforementioned ILS accuracy was applied to the entire approach path. A random traffic mix was selected from a distribution based on an analysis of Enhanced Traffic Management System (ETMS) data for San Francisco: heavy (13%), large (70%), small (17%). Each aircraft in the pair for each Monte Carlo iteration was selected independently, and at random, from this distribution.
A speed of 180 knots (airspeed) to the outer marker was followed by deceleration to final approach speed. Final approach speeds were selected at random from empirically derived distributions, stratified by aircraft type (shown in Figure 3). The final approach speed distribution was based on an (unpublished) empirical analysis of aircraft approaches using Terminal Radar Approach Control (TRACON) Automated Radar Terminal System (ARTS) data from Chicago O'Hare International Airport (ORD) in 2002.

A typical deceleration rate of 0.05 gravitational acceleration (G) was used with Gaussian uncertainties ($\mu = 0 \text{ G}, \sigma = 0.005 \text{ G}$). Uncertainty was added to the final approach deceleration point, uniformly distributed between $\pm 1 \text{ nmi}$ from a nominal 5 nmi final approach fix. All aircraft are fully configured at 1000 ft above ground level (AGL).

Speed errors in the final approach speed, empirically derived per [14], were applied to the aircraft. The speed errors were applied against the planned final approach speed that the (simulated) pilot would report to the paired approach system. A large aircraft speed error distribution was also applied to small aircraft since no specific data for small aircraft speed errors were available. The aircraft represented in [14] included Airbus aircraft as well as Boeing aircraft. Although not presented here, the uncertainty in actual speed achieved from planned is very similar between the Boeing and Airbus aircraft. Therefore, the effect of the differences in Airbus and Boeing aircraft in final approach are also represented by distributions from [14].

**Collision Risk Analysis Techniques**

Empirical methods were used to determine the front gate for collision avoidance. The front gate was determined for aircraft on long final (outside the outer marker), and short final (inside the outer marker). The front gate was determined separately for the escape and non-escape versions of the procedure. The results of the front gate analysis are presented in the next subsection. The rear gate for wake avoidance was determined analytically based on aircraft wingspan, assumed maximum unfavorable crosswind velocity of 10 knots, and rear aircraft velocity.

The Monte Carlo analysis was conducted by running many paired approaches that were randomized. The final approach speeds of each aircraft were chosen at random as previously shown. For each aircraft pair, it was determined whether it was feasible, based on the aircraft speeds and deceleration profiles, for the trailing aircraft to stay between the required front and rear gate through the approach. If it was possible for the trail aircraft to stay within the required window, the aircraft pair was run and a blunder was simulated. Data on the minimum separation were then collected for that pair, and statistics were accumulated on the probability of collision over the ensemble of Monte Carlo experiments.

Each Monte Carlo run involved a setup phase, in which the aircraft is delivered on final approach and the initial spacing is established, and the execution phase, in which the lead aircraft blunders. During the setup phase, a controller model delivered the aircraft to the required initial spacing. Controller accuracy in delivery was modeled with a 9 second standard deviation. Once the aircraft was delivered, the trail aircraft attempted to make up for the delivery error and achieve the initial desired spacing through a simulated speed control law. On average, desired longitudinal separation was achieved within 150 seconds. The execution phase involved having the lead aircraft in each modeled pair execute a blunder, randomized between 5 and 30 degrees (uniformly distributed). Simulated blunders did not contain speed changes.
There may be a reduced likelihood of blunder as an aircraft gets closer to the runway threshold. A separate, unpublished, analysis of data from 2009, otherwise reported in [11,12], shows that for the 305,217 approaches to independent parallel runways observed in that study, no lateral deviation occurred closer than 3.7 nmi from the threshold\(^2\). Two cases were therefore examined in this study: first, that blunders might occur anywhere along the final approach path, and second, that blunders would not occur inside the final approach fix. The required front gate distance was analyzed for these two cases.

The escape and non-escape versions of the procedure were modeled separately; in the case of the escape version, 3, 5, and 8 second delays were modeled between the beginning of the lead aircraft blunder and the trail aircraft initiating the breakout maneuver. The breakout maneuver consisted of a 35 degree turn. Figures 4 and 5 depict synthesized trajectories for the escape and non-escape versions of the procedure, respectively.

**Figure 4. A Simulated Trajectory for the Escape Version**

This deviation by a large aircraft started 3.7 nmi from threshold and ended 2.7 nmi from threshold

**Figure 5. A Simulated Trajectory for the Non-Escape Version**

Statistics were collected on: the number of rejected pairings (due to incompatible approach speeds), the number of near midair collisions (less than 500 ft horizontal separation with no credit taken for altitude differences), and distribution of minimum separation.

**Collision Risk Analysis Results**

The aforementioned Monte Carlo techniques were used to determine minimum front gate distances for paired approaches to runways with centerlines separated by 700 ft. Visual approaches today are authorized to runways separated by at least 700 ft. A preliminary analysis for greater runway separations is presented later in this document.

Table 2 contains results for the case of straight-in approaches with blunders occurring anywhere along the approach path; front gate distance versus collision rate results, \(p(\text{collision} \mid \text{blunder})\), are presented for the procedure with an escape maneuver (3, 5, and 8 second delays in breakout initiation) and without an escape maneuver. As indicated earlier in this paper, based on estimated blunder rates, the required probability of a collision given a blunder needs to remain at or below \(10^{-4}\). Procedural combinations that resulted in acceptable performance are indicated by shaded cells in Table 2. Results were insensitive to front gate distances of more than 750 ft inside of the outer marker; therefore, front gate

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\(^2\) This deviation by a large aircraft started 3.7 nmi from threshold and ended 2.7 nmi from threshold.
distances were only varied outside of the outer marker.

Table 2. Collision Risk: Blunders Anywhere on Approach

<table>
<thead>
<tr>
<th>Front Gate Distance outside marker (ft)</th>
<th>Escape with 3 Second Delay In Breakout</th>
<th>Escape with 5 Second Delay In Breakout</th>
<th>Escape with 8 Second Delay In Breakout</th>
<th>Non-Escape</th>
<th>Acceptable Pairings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>1E-3</td>
<td>78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>2E-4</td>
<td>1E-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>&lt;1E-4</td>
<td>7E-4</td>
<td>1E-3</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>2E-5</td>
<td>3E-4</td>
<td></td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>3500</td>
<td>1E-4</td>
<td></td>
<td></td>
<td>67</td>
<td></td>
</tr>
</tbody>
</table>

Echelon (i.e., stagger) spacing is required for both variations of the procedure (with or without an escape maneuver) for 700 ft runway centerline spacing (RCL); an abeam position (i.e., no stagger) cannot be achieved due to collision risk. For the procedure involving an escape maneuver, the necessary front gate distance decreases with decreasing delay in breakout initiation. $P(\text{collision} \mid \text{blunder})$ of $10^{-4}$ (indicating acceptable TLS) is achieved with a front gate distance of 2500 ft for a 3-5 second delay. With a 3000 ft front gate distance, acceptable performance is easily achieved with an 8 second delay. For the non-escape procedure, performance is acceptable with a front gate distance of 3500 ft. These results indicate that, depending on the reaction time, the escape maneuver provides some advantage in terms of the flexibility of the procedure relative to collision risk.

Additionally, the escape maneuver variation of the procedure provides for over 75% of acceptable pairings. The non-escape procedure provides a lower acceptance of aircraft pairs (67%).

Table 3 contains results for the case of straight-in approaches with blunders occurring only outside of the final approach fix (FAF). As before, results were insensitive to front gate distances of more than 750 ft inside of the outer marker; front gate distances were only varied outside of the outer marker.

Table 3. Collision Risk for No Blunders Inside FAF

<table>
<thead>
<tr>
<th>Front Gate Distance outside marker (ft)</th>
<th>Escape with 3 Second Delay In Breakout</th>
<th>Escape with 5 Second Delay In Breakout</th>
<th>Escape with 8 Second Delay In Breakout</th>
<th>Non-Escape</th>
<th>Acceptable Pairings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>3E-4</td>
<td>1E-3</td>
<td>1E-3</td>
<td>1E-3</td>
<td>79</td>
</tr>
<tr>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2E-4</td>
<td>78</td>
</tr>
<tr>
<td>2000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>78</td>
</tr>
</tbody>
</table>

As with the previous case, use of an escape maneuver provides some advantage in terms of the required front gate distance to meet the maximum collision risk. Minimum front gate distances of 1500 ft and 2000 ft outside of the outer marker result in acceptable performance for the escape and non-escape procedures, respectively. With blunders only occurring outside of the FAF, the lead aircraft crosses more quickly due to greater speeds which allows for tighter longitudinal spacing. These conditions also cause results to be insensitive to delay in the escape maneuver initiation for the delay values examined.

Table 4 demonstrates potential advantages of a procedure using a 3 degree offset approach. An additional column has been added for the required front gate spacing inside of the outer marker, as results were found to be sensitive to this parameter in this case. Blunders were considered anywhere along the approach path.

Table 4. Collision Risk: 3 Deg. Offset Approach

<table>
<thead>
<tr>
<th>Front Gate Distance outside marker (ft)</th>
<th>Front Gate Distance Inside marker (ft)</th>
<th>Escape with 3 Second Delay In Breakout</th>
<th>Escape with 5 Second Delay In Breakout</th>
<th>Escape with 8 Second Delay In Breakout</th>
<th>Non-Escape</th>
<th>Acceptable Pairings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>3E-4</td>
<td>99.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>250</td>
<td>2E-4</td>
<td>99.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>750</td>
<td>3E-5</td>
<td>99.99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>750</td>
<td>2E-4</td>
<td>3E-4</td>
<td>99.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>750</td>
<td>&lt;1E-4</td>
<td>3E-4</td>
<td>99.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>750</td>
<td>3E-5</td>
<td>99.99</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With a 3 degree offset, abeam positioning for the escape procedure is achievable with a 3 second delay in breakout initiation, indicating that the echelon requirement for this case is eliminated. The required front gate distance of 1000 ft for the 5 second delay
case is significantly lower than the 2500 ft front gate required for the same case with a straight-in approach. The required front gate distances for the 8 second delay and non-escape cases (3000 ft and 4000 ft respectively) were similar to straight-in approach cases.

Because of the 3 degree offset, the lateral spacing is greater than 2500 ft over a large portion of the approach, eliminating the rear gate requirement until the aircraft are approximately 6.5 nmi from the threshold. This significantly increases the likelihood of an acceptable pairing as compared to the straight-in case. As the last column in Table 4 indicates, nearly all aircraft pairs provided acceptable combinations of final approach speeds. The trade-off is that implementation of the 3 degree offset procedure may be difficult due to topography or environmental constraints.

**Pairability Analysis**

The Monte Carlo simulation used for collision risk analysis was modified for additional analyses. The first analysis presented is an examination of the escape procedure aircraft “pairability”. Pairability, or acceptable pairings, is defined as the number of feasible aircraft pairings divided by total attempted pairings. The goal of this analysis was identification of RCL separations that support acceptable pairings of 95% or greater and provide a collision risk, or \( p(\text{collision} \mid \text{blunder}) \), of \( 10^{-4} \) or less (implying a TLS of \( 10^{-9} \)). Additionally, this analysis sought identification of a relationship between RCL spacing and procedure pairability.

For this analysis, a straight-in escape procedure was modeled with a 5 second delay in breakout. This delay, assumed to be the nominal case, represents the time between initiation of the acceleration for the blunder of the lead aircraft and the initiation of the acceleration of the trail aircraft breakout. Blunder angles were randomly selected from a uniform distribution ranging from 5 to 30 degrees. As with the collision risk analysis, the lateral navigation path tracking accuracy was assumed to be 40 m (95%), per [8]. A random traffic mix was selected from a distribution based on analysis of ETMS data for San Francisco. Each aircraft in a pair for each Monte Carlo iteration was selected independently, and at random, from this distribution. Final approach speeds were selected at random from empirically derived distributions, stratified by aircraft type.

The Monte Carlo analysis was conducted by simulating many randomized paired approaches for various RCL separations and echelon sizes. For each aircraft pair, it was determined whether it was feasible, based on the aircraft speeds and deceleration profiles, for the trailing aircraft to stay between the required front and rear gate through the approach. If it was possible for the trail aircraft to stay within the required window, the aircraft pair was run and a blunder was simulated. Statistics were accumulated on aircraft pairability and probability of collision over the ensemble of Monte Carlo experiments.

Table 5 contains pairability values for various RCL separations and front gate sizes that yielded acceptable collision risk. Procedural combinations that resulted in pairability of 95% or greater are indicated by shaded cells. Pairability was fairly sensitive to RCL separation, and less so to front gate size.

**Table 5. Pairability: Straight-in Escape Procedure**

<table>
<thead>
<tr>
<th>Runway Centerline Spacing (feet)</th>
<th>Front Gate Distance Outside Marker (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>2500</td>
</tr>
<tr>
<td>900</td>
<td>94.51%</td>
</tr>
<tr>
<td>950</td>
<td>96.99%</td>
</tr>
<tr>
<td>1000</td>
<td>98.34%</td>
</tr>
</tbody>
</table>

Figure 6 depicts the relationship between RCL separation and escape procedure pairability with front gate size held constant. Acceptable pairings show significant sensitivity to RCL spacing.

**Figure 6. RCL & Pairability: Escape Procedure**

This analysis suggests that for the straight-in escape procedure, pairability of 95% or greater is achievable with acceptable collision risk for runways

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separated by as little as 900 ft. For the permutations analyzed, variation in front gate size does not appear to significantly impact acceptable pairings, implying some degree of flexibility in the procedure. There appears to be a significant increase in pairability between RCL separations of 700 ft to 900 ft.

**Escape Procedure Abeam Positioning Analysis**

Abeam positioning may allow for more flexibility in a paired approach procedure as the trail aircraft may pass the lead aircraft with acceptable collision risk. This possibility may allow for more variation in speed differential; the approximation in the abeam positioning itself, is limited by wake considerations.

The Monte Carlo simulation described in previous sections was used to identify RCL separations that support an escape procedure with no echelon spacing required and provide a collision risk of $10^{-4}$ or less (TLS of $10^{-9}$ or less). For this analysis, the escape version of the procedure was modeled with 3, 5, and 8 second delays for initiation of the breakout maneuver. Blunder angles were randomly selected from a uniform distribution ranging from 5 to 30 degrees. The Monte Carlo simulation used for collision risk analysis requires specification of nonzero echelon sizes. To represent zero longitudinal spacing between aircraft, front gate size was set to 10 ft (both inside and outside of the outer marker). The lateral navigation path tracking accuracy was assumed to be 40 m (95%), per [8]; aircraft type and final approach speeds were selected at random from previously described distributions.

The Monte Carlo analysis was conducted by running many randomized paired approaches for various RCL separations, RCL spacing was manipulated until collision risk goals were achieved, under the constraint that smaller RCL separations are desirable. As previously described, feasible aircraft pairs were run and blunders were simulated. Statistics were accumulated on the probability of collision over the ensemble of Monte Carlo experiments.

Table 6 contains results for the analysis of escape procedure abeam positioning. Procedural combinations that resulted in acceptable collision risk are indicated by shaded cells. With no longitudinal

<table>
<thead>
<tr>
<th>Runway Separation (ft)</th>
<th>Echelon Spacing = 0, Breakout Delay = 3 s</th>
<th>Echelon Spacing = 0, Breakout Delay = 5 s</th>
<th>Echelon Spacing = 0, Breakout Delay = 8 s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Collision Probability</td>
<td>Pairability</td>
<td>Collision Probability</td>
</tr>
<tr>
<td>1000</td>
<td>0.0179</td>
<td>99.55%</td>
<td>0.1447</td>
</tr>
<tr>
<td>1100</td>
<td>0.0029</td>
<td>99.87%</td>
<td>0.0908</td>
</tr>
<tr>
<td>1200</td>
<td>0.0006</td>
<td>99.93%</td>
<td>0.0360</td>
</tr>
<tr>
<td>1300</td>
<td>0</td>
<td>99.89%</td>
<td>0.0110</td>
</tr>
<tr>
<td>1400</td>
<td>0</td>
<td>100.00%</td>
<td>0.0011</td>
</tr>
<tr>
<td>1500</td>
<td>0</td>
<td>100.00%</td>
<td>0.0002</td>
</tr>
<tr>
<td>1600</td>
<td>0</td>
<td>100.00%</td>
<td>0</td>
</tr>
<tr>
<td>1700</td>
<td>0</td>
<td>100.00%</td>
<td>0</td>
</tr>
<tr>
<td>1800</td>
<td>0</td>
<td>100.00%</td>
<td>0</td>
</tr>
<tr>
<td>1900</td>
<td>0</td>
<td>100.00%</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>0</td>
<td>100.00%</td>
<td>0</td>
</tr>
</tbody>
</table>

This analysis shows that abeam positioning of aircraft with an escape procedure for a straight-in geometry is achievable with respect to collision protection. However, feasible runway separations are heavily dependent on the trail aircraft breakout delay (in response to blunder). RCL separations of 2000 ft or more appear to support an escape procedure with breakout delays varying from 3 to 8 seconds. An RCL spacing of 1600 ft is required for a 5 second response time. An RCL spacing of 1300 ft is required for a 3 second response time. It is important to note that only 5 of the 49 CSPR pairs in the U.S. are separated by 1600 ft or more, and 11 of the 49 pairs have runway spacing of 1300 ft or more.

**Analysis of Wake Encounter Risk during Blunders**

Monte Carlo examination of wake vortex encounter probability during blunders has been conducted with an add-on tool coupled to the simulation used for collision risk analysis (described previously). Trajectories for feasible aircraft pairs were fed into the add-on tool and used to compute probability of a wake encounter given a blunder, encounter duration in seconds, and encounter strength (percentage of maximum strength) estimated via NASA’s AVOSS Prediction Algorithm (APA) [15].

**Simulation Model Conditions and Assumptions**

For this analysis, straight-in escape and non-escape versions of the procedure were examined with a runway centerline separation of 700 ft. The escape version of the procedure was modeled with 5 and 8
second delays representing nominal and worst cases, respectively for trail aircraft breakout maneuver initiation. Blunder angles were randomly selected from a uniform distribution ranging from 5 to 30 degrees. Lateral navigation path tracking accuracy was assumed to be 40 m (95%), per [8]. Differing from other analyses presented earlier, only heavy aircraft were modeled as the lead blundering aircraft. For each feasible aircraft pair, eight wind fields (graphically depicted in Figure 7) were modeled in an effort to represent a near worst case.

Figure 7. Simulated Wind Fields

The wind vector set is represented by rays pointing toward the origin defined by an angle (θ) and assumed maximum unfavorable crosswind component (vₓ) of 10 or -10 knots. The initial wind vector is roughly orthogonal to simulated blunders, measured 20 degrees clockwise from the negative x axis. Subsequent vectors were produced by incrementing the angle 45 degrees clockwise. Under the constraints of constant crosswind components and direction pointing toward the origin, significant variation was produced in y components of the wind vectors, defined as follows:

\[ v_y = v_x \tan(\pi - \theta) \]

For the purpose of comparing procedure variations, it is assumed that wake sink is negligible due to close proximity of aircraft in time and space. The wake encounter probability is only examined in the horizontal plane. Consideration of the vertical plane is expected to reduce wake encounter probability. It is also assumed that wake transport is linear and out of ground effect (OGE).

Wake Risk Analysis Techniques

The collision risk analysis tool (Monte Carlo simulation) was used to produce trajectories for feasible aircraft pairs. The add-on tool developed for this analysis used these trajectories as input. Aircraft state vectors were upscaled from 1 to 4 Hz. For each lead aircraft position, four initial wake boundary points were calculated (two per vortex). Initial wake boundary positions were linearly transported and time stamped at 4 Hz for 60 seconds beyond time of generation for the specified wind vector (analytically determined to provide sufficient time overlap with trail aircraft state in sample space). Trail aircraft positions were compared to transported wake boundaries. For equal time stamps, if the distance from the trail aircraft position (center of mass) to the transported wake boundary was less than 100 ft, an encounter occurred [16]. If this distance was greater than 100 ft but less than or equal to 200 ft, a near encounter occurred. Statistics were computed by repeating the wake transport and encounter detection process for all wind vectors applied to multiple aircraft pairs. Figure 8 depicts the process and formulas used for wake vortex synthesis and transport. For each wake encounter, duration and strength were computed. For this analysis, encounter strength is defined as a percentage of maximum strength: e.g., 90% after some transport time t. Encounter strength for each case (specific aircraft pair and wind vector) was calculated by inputting minimum transport time into a NASA Langley Research Center APA [15] lookup table pertaining to a heavy aircraft, medium turbulent atmosphere (Eddy Dissipation Rate = 0.001175 m²/s³), crosswind of 10 knots, and altitude of 1500 ft (descending).
Wake Risk Analysis Results

Table 7 contains results for the preliminary analysis of wake encounter probability during blunder. A wake vortex encounter occurred for all non-escape cases analyzed. The escape procedure (with 5 or 8 second delays in breakout initiation) provided significant protection; however, there were a small number of encounters.

Table 7. Wake Risk Analysis Results

<table>
<thead>
<tr>
<th></th>
<th>Non-Escape</th>
<th>Escape with 5 second Delay in Breakout</th>
<th>Escape with 8 second Delay in Breakout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Size</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>P(encounter</td>
<td>blunder)</td>
<td>1</td>
<td>0.0014</td>
</tr>
<tr>
<td>P(near encounter</td>
<td>blunder)</td>
<td>NA</td>
<td>0.0128</td>
</tr>
<tr>
<td>Mean Encounter Duration (s)</td>
<td>6.3</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Mean Encounter Strength (percentage of max. via APA)</td>
<td>89.6</td>
<td>91.3</td>
<td>89.5</td>
</tr>
</tbody>
</table>

This analysis indicates that the non-escape procedure has a high probability of a wake vortex encounter in the event of a blunder, averaging 6.3 seconds in duration and a strength of 89.6%, with no credit for altitude differences or wake descent and assumed near worst case wind fields. It should be noted that for non-escape cases, the trail aircraft is level when it strikes transported wake vortices generated by the lead aircraft.

An escape procedure with a 5 or 8 second delay in breakout has a low probability of wake vortex encounter during blunder (0.0014 and 0.0021 respectively), with encounters averaging 4.8 seconds in duration and strengths of 91.3% and 89.5%, respectively. Wake encounter probability is expected to increase for breakout delays beyond 8 seconds, as probability of near encounter for that permutation is not insignificant (0.0260). This analysis indicates that the escape procedure provides significant protection in comparison to the non-escape procedure, however, several encounter cases provide some cause for concern. One of these cases has been examined in detail and is graphically depicted by Figure 9.

Figure 9. Escape Procedure Wake Encounter

Figure 9 depicts a simulated escape procedure approach in which several factors contributed to a wake vortex encounter. Prior to blunder, the lead aircraft is 86.9 m off course laterally, deviating toward the trail aircraft trajectory. This is an outlier case where total system error (TSE) grossly exceeds expected performance (40 m). At the same time, TSE for the trail aircraft is laterally biased toward the lead aircraft trajectory. During this period of lateral convergence, the lead aircraft blunders toward the trail aircraft; 2 seconds after blunder initiation, the trail aircraft encounters wake vortices. This encounter lasts 4.5 seconds with a strength of 93.0%. Initiation of the escape maneuver (modeled with a 5 second delay in breakout) occurs during the wake vortex encounter. This is of concern because a 35 degree escape requires a significant bank. A catastrophic roll is a possibility that should be considered. These observations may warrant further study.
Considerations for Surveillance Requirements

Surveillance requirement considerations have been formulated for different variations of the paired approach procedure, differentiated and presented as follows:

- An escape procedure involving ADS-B equipped aircraft and a high level of automation.
- A non-escape procedure involving ADS-B equipped aircraft and a low level of automation.
- A procedure involving mixed equipage (e.g., ADS-B equipped ownship and Traffic Information Services-Broadcast, or TIS-B, coverage for traffic).

Escape Procedure with ADS-B Equipped Aircraft and High Level of Automation

The paired approach procedure with escape is envisioned to provide a higher performance capability [17] and involve ADS-B participants with a high level of automation. Autopiloted approach and autoland (e.g., via GNSS Landing System, GLS) are expected. The preliminary operational concept calls for a missed approach or breakout maneuver when either aircraft indicates loss of autopilot or navigation accuracy, or turns toward the other aircraft, creating a collision risk. These conditions are envisioned to be detected via the ADS-B messages.

If auto-throttles are coupled for an aircraft pair, implications for surveillance requirements include: high accuracy, high integrity, low data age, and high system design assurance (SDA, low potential for misleading information) for ADS-B state data. Detection of autopilot loss may be achievable with the optional/periodic “target state and status” ADS-B message specified by RTCA DO-260B [18]. These messages contain an “Autopilot Engaged” field that, if populated by an appropriate data source, may be used to detect target autopilot loss/decoupling. Navigation Accuracy Category for position (NACp) provided by target state and status (in addition to required) messages may be used to determine loss of navigation accuracy. However, NACp is only an indicator of target navigation system status when surveillance and navigation systems are using the same position sensor. FAA Advisory Circular 20-165 (ADS-B out airworthiness) [19] states that ADS-B position source is not required to be the same position source used for navigation. Target state and status messages are not minimum requirements; the paired approach procedure with escape will likely mandate inclusion of these messages. Additionally, the procedure may require a surveillance mechanism that indicates navigation system status.

The required “airborne position” and “airborne velocity” messages, also specified by [18], should provide data necessary for detection of a significant lateral deviation (blunder) through changes in geometric position or velocity. However, blunder detection algorithms may be fairly complex, potentially requiring a measurement that significantly deviates from multiple tracked (smoothed) measurements to quickly calculate dangerous changes in track angle and minimize false alerts. Analyses in this document expect an escape maneuver to occur within 8 seconds of blunder initiation to provide sufficient collision and wake protection for most cases.

Non-Escape Procedure with ADS-B Equipped Aircraft and Low Level of Automation

The non-escape paired approach procedure is envisioned to involve ADS-B participants with a lower level of automation. A preliminary operational concept potentially accommodates a manual approach and landing with guidance from navigation (e.g., ILS) and surveillance (e.g., Aircraft Surveillance Applications, ASA) systems. Collision protection is provided through maintenance of echelons, achieved with speed commands carried out by the flight crew.

Monitoring of parameters provided by ASA (e.g., range, differential ground speed) imply fairly high accuracy, integrity, and SDA requirements (likely more stringent than the enhanced Visual Separation on Approach, or VSA, application). Manual responses to speed commands imply potential relaxation of requirements for data age due to pilot workload limitations. Requirements are expected to be similar to those for the Interval Management with Delegated Separation (IM-DS) application; however, alerting for window conformance during approach may imply more stringent requirements.
Mixed Equipage Procedure

A version of the non-escape procedure in which surveillance for one aircraft in a pair is provided by TIS-B may be feasible. However, there are several considerations. TIS-B for such a procedure may only meet stringent requirements if the surveillance source is a multilateration (MLAT) system with a high update rate (e.g., 1 Hz) and service volume boundary sufficient for long final (e.g., 25 nmi from threshold). Current ground system specifications [20] state that MLAT based surface service volumes will end 5 nmi beyond the runway threshold, at which point terminal service volumes (based on monopulse secondary surveillance radar, or MSSR) will provide TIS-B coverage. Generation of multiple TIS-B tracks for individual targets may occur at this boundary; this phenomenon may preclude TIS-B traffic from participation in paired approach procedures. Additionally, MSSR error characteristics [21] may be unacceptably poor for paired approaches.

RTCA Special Committee 186 Working Group 4 (SC-186 WG4) is currently working to minimize TIS-B track shadowing across service volume boundaries. It is unclear if a solution will materialize as a ground system or airborne processor requirement.

Summary and Conclusions

Four variations for paired approaches to closely spaced parallel runways (CSPRs) have been studied: rectilinear and 3 degree offset procedures with and without escape\(^3\). Collision protection analysis has been conducted that incorporates several realistic uncertainties that can be expected in actual operations. These uncertainties include variations in deceleration rates and points at variation in achieved final approach speed compared to planned speed.

Collision avoidance and wake constraints in normal operation can be met for both escape and non-escape versions of the procedure by the provision of a “window” within which the trail aircraft must stay once standard separation has been lost. An echelon spacing value of up to 4000 ft provides adequate collision protection for an adverse wind threshold of 10 knots for most CSPRs. The precise value of the required echelon spacing depends on the concept variation and geometry. The longitudinal echelon spacing required for collision protection may be reduced if it is assumed that no blunders occur inside the outer marker.

The escape maneuver procedure requires echelon spacing to provide protection from collisions for most runway separations under consideration. The rectilinear escape maneuver procedure cannot tolerate an abeam position due to collision risk for runway spacing less than 1300 ft (1600 ft or greater if delay in breakout is 5 seconds or greater). Only 5 of the 49 CSPR pairs in the U.S. have runway spacing of 1600 ft or more. A 1300 ft limit adds 6 additional CSPR pairs.

A preliminary analysis of wake vortex encounter risk during blunder indicates that the non-escape procedure has a high probability of wake encounter during blunders with a significant duration and strength. The escape procedure provides significant wake protection during blunders; however, a small number of wake vortex encounters observed for this geometry may warrant further study.

ADS-B messages from the leading aircraft as required by the rule are expected to be adequate for performing at least the non-escape version of the procedure. Optional ADS-B messages are expected to be needed to support the escape procedure variant.

A procedure variation that accommodates current navigation performance could be deployed at airports with runways separated by 700 ft or more; this procedure would require a 3 degree offset approach to one of the runways and would facilitate minima of roughly 300 ft AGL.

A procedure variation may be deployed to enable approaches down to Category II (and potentially Category III) minima, pending further study and certification of navigation systems. This variant would likely require augmented Global Navigation Satellite System (GNSS) approaches provided by GBAS or SBAS LPV, and an ADS-B message indicating autopilot and navigation system status of each aircraft. Analyses presented in this paper indicate that such a procedure will support aircraft pairability of 95% or greater for runway separations of 900 ft or more and pairability of roughly 75% for runway separations of 700 ft.

\(^3\) The rectilinear procedure with escape is generally known as SAPA
References


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