

CHAPTER XX

Comparison of Procedures for Dual and Triple Closely Spaced Parallel Runways

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ABSTRACT

A human-in-the-loop high fidelity flight simulation experiment was conducted, which investigated and compared breakout procedures for Very Closely Spaced Parallel Approaches (VCSPA) with two and three runways. To understand the feasibility, usability and human factors of two and three runway VCSPA, data were collected and analyzed on the dependent variables of breakout cross track error and pilot workload. Independent variables included number of runways, cause of breakout and location of breakout. Results indicated larger cross track error and higher workload using three runways as compared to 2-runway operations. Significant interaction effects involving breakout cause and breakout location were also observed. Across all conditions, cross track error values showed high levels of breakout trajectory accuracy and pilot workload remained manageable. Results suggest possible avenues of future adaptation for adopting these procedures (e.g., pilot training), while also showing potential promise of the concept.

1 INTRODUCTION

The Next Generation Air Transportation System (NextGen) is being designed with the expectation that the volume of the traffic will double by 2025 (Joint Development and Planning Office, 2004). In order to handle the expected traffic demand, airport capacity needs to expand dramatically. To gain such capacity at the airport, runways with centerline distances closer than 2500 ft need to be

explored, as they are a potential solution to meeting increased demand. Runways could be built in-between existing dual runways that have greater than 2500 ft separation between them. One of the main challenges of closely spaced runway operations is that capacity is greatly reduced in low visibility conditions. The FAA allows simultaneous instrument approaches on two and three runways spaced at least 4300 ft apart using the Instrument Landing System (ILS), and Precision Runway Monitor (PRM) approaches to runways 3000 ft apart for most domestic airports. Some airports, like San Francisco International (SFO) airport, land flights on parallel runways that are 750 ft apart using the Simultaneous Instrument Offset Approach (SOIA) procedures in lower visibility conditions (Magyrtatis, 2001). SOIA approaches require the trailing aircraft in the paired approach to obtain a visual sighting of the lead aircraft, which is possible under marginal weather conditions such as a 2100 ft cloud ceiling and 3nmi visibility.

Focusing on closely spaced runways that are 750 ft apart, the current investigation assumes technologies and procedures (described later in this paper) such that arrival capacity is maintained even when weather conditions degrade. While procedures under nominal conditions may not pose as much of a concern, one of the most serious concerns regarding simultaneous landings on runways closer than 2500 ft has been finding off-nominal breakout procedures that are acceptable to the pilots and maintain safe separation. The reduction of runway spacing for independent simultaneous operations increases the likelihood of wake vortex incursion and allows for less maneuvering area if the lead aircraft deviates from its course. Thus, there is a requirement for the calculation of safe and proper escape maneuvers.

The authors conducted a study to investigate off-nominal procedures for dual parallel runways in all-weather conditions (Verma et al., 2008). Further capacity on the airport could be achieved with triple runways 750 ft apart. This led the authors to design and conduct another experiment involving triple runways that were 750 ft apart and included off-nominal conditions (Verma et al., 2009).

This paper provides a comparative analysis of two experiments using runways spaced 750 ft apart when approaches include off-nominal conditions. One study used dual runways (the “2-runway” study) and the other used triple runways (the “3-runway” study). The off-nominal conditions investigated in these two studies included the lead aircraft deviating, or blundering off course, and wake intrusion. This paper will compare the breakout maneuvers of two and three closely-spaced parallel runways and their impact on workload and accuracy of flying the breakout trajectory.

2 BACKGROUND

Airports with parallel runways lose capacity under poor visibility conditions. Hence, there is a need for investigating parallel runway operations that will work under poor weather conditions. For runways 750 ft apart, the safety of simultaneous landings and breakout procedures that might be required due to off-nominal conditions is paramount. Such concepts currently in operation include SOIA and PRM approaches, while others have been developed and investigated in the research (Verma et al., 2008; Verma et al., 2009).

The dual and triple studies analyzed in this paper use a concept developed by NASA in collaboration with the Raytheon Corporation called the Terminal Area Capacity Enhancing Concept (TACEC), which allows paired approaches on runways that are 750 apart in instrument meteorological conditions (Miller et al., 2005). The TACEC concept includes a ground-based processor, which identifies aircraft that could be paired approximately 30 minutes from the terminal airspace boundary. The aircraft are selected for pairing based on several parameters such as relative aircraft performance, arrival direction, and the size of the aircraft's wake. The ground based processor then assigns 4-dimensional (4-D) trajectories to the aircraft in the pair. It is assumed that all aircraft will use differential GPS-enabled, high-precision 4-D flight management system capabilities for the execution of these trajectories. Enhanced cockpit displays provide the trailing pilot with detailed position and some intent information about the lead aircraft, and show a predicted wake for the lead aircraft.

The concept uses breakout trajectories that require a less extreme turn than the maneuvers used in other concepts. This concept that was originally developed for dual runways and then extended to triple runways considers wake prediction data to determine when a breakout is required, and provides for a dynamically generated breakout trajectory that changes as the aircraft flies the approach. Most of the previous concepts did not consider wake data in their concepts or displays.

This paper provides a comparative analysis of the 2-runway and 3-runway experiments by comparing results of the pairs of aircraft in the triple formation (left and center aircraft or center and right aircraft) with the 2-runway pair (left and right aircraft). Procedures for dual runways involving a leading and trailing aircraft pair are compared to procedures from the 3-runway study, when the piloted aircraft was either the center or the right aircraft in the echelon formation (Figure 1). The comparison between the dual and triple runways is meant to evaluate the dual-runway procedures that were implemented to create new procedures for triple runways. The dual and triple runway procedures are compared on level of accuracy for flying breakouts and differences in workload experienced by the pilots. Results on these factors will provide insight into the human factors issues associated with the different positions of the aircraft in the dual and triple formation.

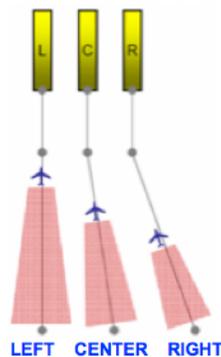


Figure 1: Echelon formation for triples (shaded area below aircraft shows predicted wake turbulence zone)

3 METHODS

3.1 Airport and Airspace Design

Both the 2-runway and 3-runway studies used a common fictitious airport (KSRT) based on the current Dallas/Fort Worth International Airport (DFW) layout and operations, with the exception of the runways which were set 750 feet apart. The west side of the airport was simulated in its south configuration only (18L and 18R for 2-runways, and 18L, 18C and 18R for 3-runways). Equipage to a CAT-IIIB level was assumed.

3.2 Operational Procedures

Flights in the simulation were initiated at about 25 nmi from the airport, with the assumption that they were already placed into aircraft pairs or triples. Approach and departure routes and procedures were similar to those used at DFW. The aircraft flew 4D arrival trajectories and were paired or ‘tripled’ with aircraft arriving from any of the four meter fixes (NE, NW, SE, SW) located near the edge of the terminal airspace, about 40-60 nmi from the airport. The concept allows for pairing based on aircraft type, performance characteristics and estimated time of arrival. In the study, the pairing was scripted in the traffic scenarios.

The aircraft fly 4D trajectories up to a point in the airspace, referred to as the coupling point, designated at 12 nmi from the runway threshold. From the coupling point onwards, the aircraft fly in a formation such that they were coupled for speed. In the 2-runway study, the trailing aircraft precisely maintained temporal spacing of 15 sec with +/- 10 sec tolerance for error (a window of 5-25sec), behind the lead aircraft to avoid wake of the lead aircraft (Rossow et al., 2005). The path flown by the trailing aircraft in the 2-runway study involved a slew angle of six degrees to the landing runway. The aircraft became parallel at about two nmi from the runway, as shown in Figure 2.

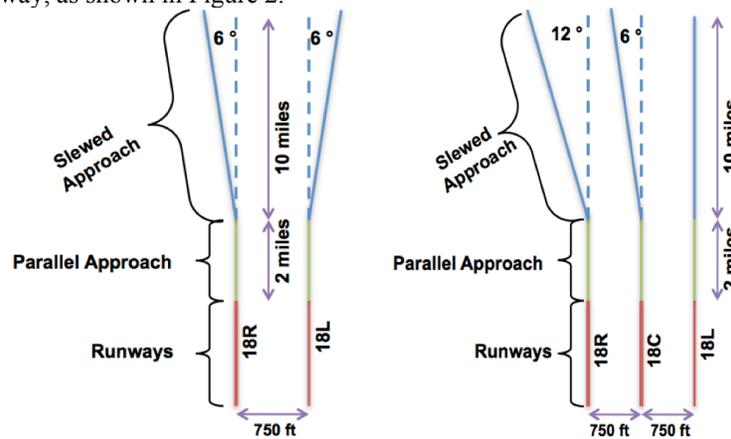


Figure 2: Final approach geometry for operational procedures for dual and triple runways

In the 3-runway study, the center aircraft precisely maintained 12 s spacing behind the lead aircraft, and the right aircraft maintained 24 s behind the lead aircraft beyond the coupling point. As shown in Figure 2, the approach paths of the two trailing aircraft were at designated slew angles from the center of the runway -

6-deg for the center runway aircraft and 12-deg for the right runway aircraft. All three aircraft turned straight-in for the final approach during the last two nmi from the runway.

For both the 2- and 3-runway procedures, onboard automation monitored the paired runway for potential conflicts. Automation also displayed the predicted safe zone from the wake generated by the lead aircraft (and center aircraft for 3-runway procedures). Visual and aural alerts were used to alert pilots to the lead (or center) aircraft blunders or the wake of the lead (or center) aircraft drifting towards the aircraft behind it. The navigation displays (Figure 3) depicted the breakout trajectory as a white line, after the aircraft crossed the coupling point. For the 3-runways study, the breakout trajectory was shown for both the center and the right aircraft. In both studies, the breakout trajectory was dynamically generated considering wake, traffic, structures, and terrain of airport surroundings.

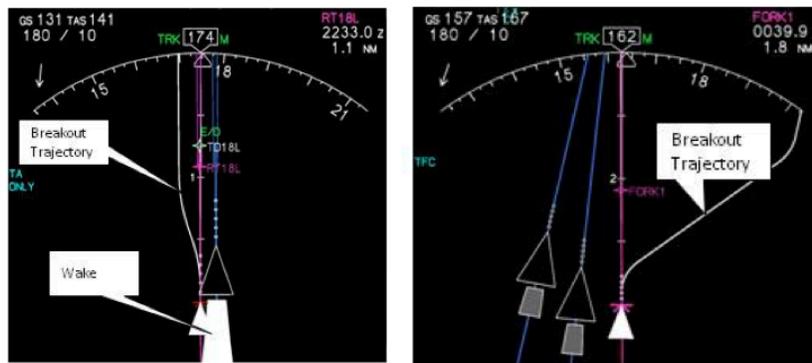


Figure 3: Navigation Displays for final approach for 2 and 3 parallel runways

Breakouts were caused by an intentional lead-aircraft blundering towards the following aircraft, or the wake of the lead aircraft drifting towards the following aircraft. Different locations of the breakout on the arrival path required different breakout maneuvers, which change the angle of the escape trajectory on the navigation displays. When the breakout was required at different altitudes on the arrival path, different bank angles for the breakout maneuvers were used and the curvature of the breakout trajectory changed on the navigation displays. The pilots were required to fly the breakout trajectory manually using the flight director when they received an aural and red visual alert.

For both the 2-runway and 3-runway studies, the breakout performed above 500 ft altitude required an initial bank angle of 30 deg, and the breakout at an altitude between 200-500 ft required an initial bank angle of 10 deg (Tables 1 and 2). The pilots at this stage were instructed to follow the “S” shaped breakout trajectory displayed on the navigation display as accurately as possible (Figure 3). The trajectory was “S” shaped so the final leg of the trajectory became parallel to the runways.

The 3-runway study used similar bank angles to those used in the 2-runway study. In addition, the pilot participants flew different headings based on the position in the echelon. The center aircraft (18C) changed its heading to 20-deg and

the right aircraft (18R) changed its heading to 40-deg, giving more space to the center aircraft. The aircraft performing the breakout maneuver also climbed to 3000 ft as part of the breakout trajectory. The final leg of the breakout trajectory parallel to the runways was 1.5 nmi abeam for aircraft flying to 18C and 3.0 nmi for aircraft flying to 18R.

Table 1: Breakout trajectory for dual runways

Runway	Breakout Location	Initial Bank Angle
18 R (2-runway)	> 500 feet	30 °
	200-500 feet	10 °

Table 2: Breakout trajectory for triple runways

Runway	Breakout Location (altitude)	Initial Bank Angle	Initial Heading Change
18 C [3- Runway (Center Ownship)]	> 500 feet	30 °	20 °
	200-500 feet	10 °	20 °
18 R [3- Runway-Right Ownship]]	> 500 feet	30 °	40 °
	200-500 feet	10 °	40 °

3.3 Simulation Platform

For both studies, the human-in-the-loop experiments of breakout maneuvers for paired and triple runways were performed approaches in the Advanced Concepts Flight Simulator (ACFS) located at the NASA Ames Research Center. The ACFS is a motion-based simulator that can be configured to represent current and future cockpits. At the time of this experiment, the simulator had performance characteristics similar to a Boeing 757, but its displays were modified to study advanced flight operational concepts.

3.4 Participants

The study participants were recently retired pilots from commercial airlines. All of them were male and all had experience with glass cockpits. Their average pilot experience was about 38 years, and their average number of years since retirement was less than two.

3.5 Traffic Scenario

For the 2-runway study, the traffic scenario involved two aircraft: (1) The ACFS flight simulator as the trailing aircraft (i.e., the ownship) and (2) A scripted Boeing 747-400 as the leading aircraft.

For the 3-runway study, the traffic scenario involved three aircraft, where the flight simulator (i.e., the ownship) was either the center or right aircraft. The other two aircraft were scripted. When the ownship was in the center position, the aircraft causing the off-nominal situation was the left-most aircraft. When the ownship was in the right-most position, the aircraft causing the off-nominal maneuver was the center aircraft. The off-nominal event was introduced in the

scenarios through lead aircraft intentionally deviating off its trajectory or adverse winds causing its wake to drift towards the following aircraft.

4 RESULTS AND DISCUSSION

Statistical results on two dependent variables are reported in the analysis of data generated from the experimental runs: (1) Ownship cross track error, collected digitally during the breakout phase of the simulation flight and (2) The pilots' subjective assessments of workload. Data were analyzed using 3-way Factorial Analysis of Variance with three independent variables, with each independent variable having 2 levels: (1) Number of runways (2 vs. 3), (2) Cause of breakout (aircraft deviation and wake) and (3) Location of breakout (high and low altitude).

4.1 Cross Track Error

Cross track error, collected by the simulator's digital data collection system, is one measure of trajectory accuracy particularly sensitive to breakout maneuvers. Cross track error was measured by the distance between the actual ownship position and the system-generated breakout trajectory position (i.e., the off-course distance), with both positions shown on the Navigation Display. Hence, less cross track error correlates to higher breakout trajectory conformance. For each simulation run, cross track error was averaged across time from the breakout point to the end of the flight.

A statistically significant ANOVA main effect of the number of runways on the ownship's breakout cross track error was found, in comparing the 2-runway and the 3-runway (right ownship) conditions ($F=21.92$, $df=1,15$, $p<0.001$) (Table 3).

Table 3: Breakout Cross Track Error (2-runway vs. 3-runway)

Runway	Mean (ft)	SE	MIN	MAX
2-runway	56.25	3.67	0.65	106.12
3-runway (center ownship)	73.44	11.45	5.83	542.42
3-runway (right ownship)	104.37	11.46	16.26	513.29

The directionality of means for this main effect indicates more cross track error under the 3-runway (right ownship) condition as compared to the 2-runway condition. This could be attributed to having 2 aircraft to the left of the ownship during breakout (3-runway, right ownship), creating an increased sense of urgency on the part of the pilot to escape the cause of the off-nominal situation, i.e., the possible additive effect of wake and/or blunder of both aircraft to the left of the ownship might prompt the pilot to overshoot the breakout trajectory further to the right as a safety measure. Some increased cross track error was also observed under the 3-runway (center ownship) condition as compared to the 2-runway condition, but this difference did not reach statistical significance. This lack of statistical significance might reflect the center position of the ownship, which requires that the pilot maintain safe separation with 2 other aircraft – one to the right, and one to the left of the ownship, thereby posing constraints on aircraft movement to either the right or the left, to maintain adequate separation. The pilot-participants pointed out that this prompted them to exercise a larger degree of vigilance in flying the breakout trajectory, which would explain less cross track error, as compared to the

3-runway (right ownship) condition, even though the right ownship is not much safer than the center aircraft. Mean cross track error values generally indicate reasonable levels of accuracy in flying the breakout trajectory. However, maximum values at the end of the distribution for the triple-runway operations (Table 3) might indicate a need for improved training to prevent the occasional overshoot of the breakout trajectory.

A statistically significant Number of Runways by Breakout Location (altitude) interaction effect on cross track error was also observed. A larger mean cross track error difference between high and low altitude locations was observed under the 3-runway (right ownship) condition, as compared to the 2-runway condition ($F=16.12$, $df=1,15$, $p<0.005$) (Figure 4).

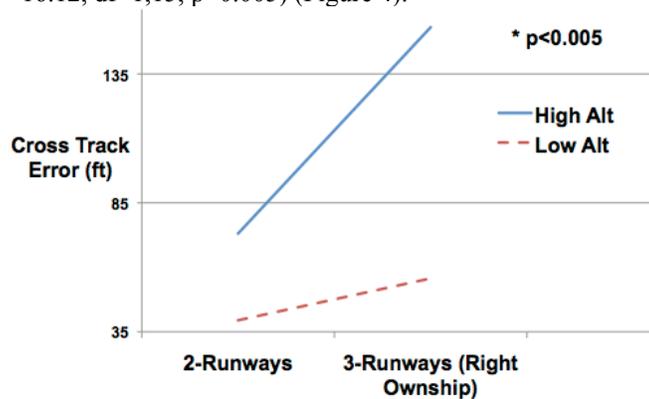


Figure 4: Number of Runways X Breakout Location Interaction Effect: Cross Track Error (* $p<0.005$)

This interaction effect is best understood when one considers that breakout procedures for the higher altitudes are more difficult and that procedures are more complex for the 3-runway operations. As postulated above, the 3-runway center-ownship pilot may have exercised special vigilance in flying the breakout trajectory more accurately, due to the aircraft's central location in the triplet echelon, which would account for less cross track error. Since the pilot in the 3-runway (right ownship) condition is mostly concerned about loss of separation with the center aircraft and the possible additive effect of having two aircraft to the left in the breakout formation (wake turbulence and/or track deviation of both aircraft), the pilot may be less concerned about exercising special vigilance in flying the breakout trajectory accurately, but rather, escaping the track deviation or wake turbulence of both aircraft by moving as quickly as possible towards the right, and possibly overshooting the breakout trajectory. Also, since the higher altitude breakout procedures require a more aggressive maneuver (as compared to the lower altitude procedures), the possible tendency for the pilot to overshoot the breakout trajectory further to the right at the higher altitude might reflect a continuation of the already aggressive nature of the required maneuver.

4.2 Workload

Participants completed the NASA TLX workload questionnaire (Hart and Staveland, 1988) after every run. Data were collected on each of the six TLX workload measures, which were combined to derive a composite workload measure, which ranged from 1 (very low workload) through 7 (very high workload).

Table 4 presents statistics on average composite workload, broken down by the number of runways and position of the ownship. Overall, workload can be characterized as moderate. While trends should be viewed with some caution, due to lack of statistical significance, the directionality of means shows increased workload under the 3-runway conditions as compared to the 2-runway condition. This would make sense, due to the increased geometric complexity of the 3-runway procedures and pilots needing to maintain safe separation with 2 other aircraft (as compared to only 1 other aircraft under the 2-runway condition), thereby increasing pilot workload.

A statistically significant Number of Runways by Breakout Cause interaction effect was observed, in comparing workload for 2-runways and 3-runways (Right Ownship) by Aircraft Deviation and Wake (Figure 5).

Table 4: Average Composite Workload Statistics by Number of Runways

Runway	Mean	SE
2-runway	2.78	0.15
3-runway (Center Ownship)	3.69	0.12
3-runway (Right Ownship)	3.64	0.12

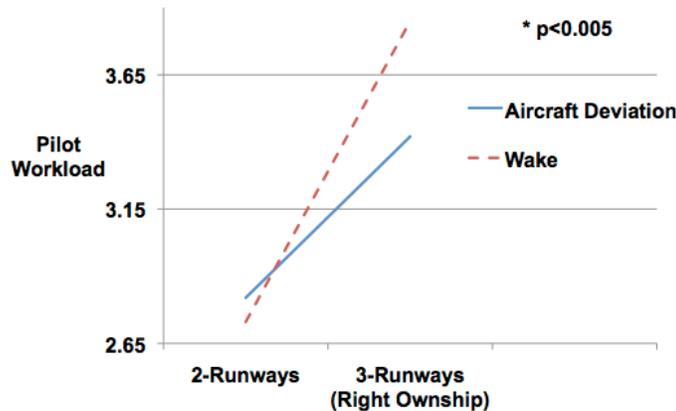


Figure 5: Comparison of Composite Workload for Wake versus Aircraft Deviation Under 2-runway and 3-runway Conditions (Right Ownship) * $p < 0.005$

Figure 5 shows a larger workload difference between Aircraft Deviation and Wake causes under the 3-runway (Right Ownship) condition, as compared to the 2-runway condition ($F=12.43$, $df=1,15$, $p < 0.005$). This effect can be explained by the relative complexity of the 3-runway operations and the unstable nature of wake turbulence from possibly two other aircraft to the left of the ownship. Since having two aircraft to the left of the ownship during breakout (3-runway, right ownship) could create an increased sense of urgency on the part of the pilot to escape the cause of the off-nominal situation, i.e., the possible additive effect of wake of both aircraft to the left

of the ownship, this increased sense of urgency might cause increased workload. Still, workload remained at manageable levels across all four interaction conditions (i.e., reasonably low, yet high enough to prevent tedium and vigilance decrement), which was further substantiated by pilot-participant feedback during open-ended discussion.

5 SUMMARY AND CONCLUSIONS

A high-fidelity human-in-the-loop flight simulation experiment investigated breakout procedures for Very Closely Spaced Parallel Approaches (VCSPA) with 2 and 3 runways. Results indicate larger cross track error under the 3-runway condition, where the ownship is approaching the rightmost runway, as compared to the 2-runway condition. However, breakout trajectories under both two and three runway conditions were flown with high accuracy, which degraded only slightly in the three runway procedures. Also, pilot workload levels, while higher under the 3-runway condition and the highest for the center-ownship, remained at manageable levels overall. The similarity in off-nominal procedures for dual and triple runways allows for pilots to fly either of the procedures with minimal adaptation. However, the positions of the aircraft in the 3-runway formation will impact procedures. This might suggest the need for further exploration of procedures for switching between 2- and 3-runway operations and future adaptation in pilot training.

6 REFERENCES

- Hart, S., & Staveland, L. (1988). Development of a Multi-Dimensional Workload Rating Scale: Results of Empirical and Theoretical Research, In P. Hancock & N. Meshkati (Eds.), *Human Mental Workload*, Amsterdam, The Netherlands, Elsevier, 139-183.
- Joint Development and Planning Office (2004). *The Next Generation Air Transport System Integration National Plan*. December 12, 2004.
- Magyratis, S., Kopardekar, P., Sacco, N. & Carmen, K. (2001). *Simultaneous Offset Instrument Approaches – Newark International Airport: An Airport Feasibility Study*. DOT/FAA/CT-TN02/01.
- Miller, M.E., Dougherty, S., Stella, J. & Reddy, P. (2005). CNS Requirements for Precision Flight in Advanced Terminal Airspace. *Aerospace, 2005 IEEE Conference*, 1-10.
- Rossov, V. J., Hardy, G. H., and Meyn, L. A. (2005). *Models of Wake-Vortex Spreading Mechanisms and Their Estimated Uncertainties*, AIAA-2005-7353, ATIO Forum, Arlington, VA, September 26-28, 2005.
- Verma, S., Lozito, S., Ballinger, D., Kozon, T., Panda, R., Carpenter, D., Wooten, D., Hardy, G., and Resnick, H. (2009). *Evaluation of Triple Closely Spaced Parallel Runway Procedures for Off-nominal Cases*, Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009).
- Verma, S., Lozito, S., Kozon, T., Ballinger, D., and Resnick, H. (2008) *Procedures for Off-Nominal Cases: Very Closely Spaced Parallel Runways Approaches*, Digital Avionics System Conference, St. Paul, MN.