Examining Assumptions about Pilot Behavior in Paired Approaches

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Abstract

The design of flight deck systems and air traffic control operations often focuses on one particular part of the overall system. In doing so, implicit assumptions are often made about pilot behavior. A recent flight simulator study investigated a proposed air traffic procedure called paired approaches. This study has indicated that a number of the assumptions made by previous studies may be invalid, with significant implications for the design of paired approaches and, more generally, human-centered design.

Introduction

This paper examines whether assumptions about pilot behavior implicit to proposed implementations of paired approaches are valid. Results of a piloted simulator experiment are discussed, highlighting the sometimes significant discrepancies between actual pilot behavior and pilot behavior assumed by previous studies of paired approaches. This paper then concludes with the broader implications for designing these systems and procedures, including the need for cognitive systems engineering methodologies for design.

Paired approaches is a proposed air traffic control operation that places two aircraft on instrument approaches to closely spaced parallel runways, with one aircraft initially offset behind the other (Stone, 1996) (Hammer, 2000)(Pritchett and Landry, 2001). The trail aircraft remains within a range of positions relative to the lead aircraft (called the "safe zone") 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 ("blunder"). If the trail aircraft remains within the safe zone it is also protected from the lead aircraft's wake vortex.

The safe zone consists of two limits – a front, which provides protection from loss of separation, and a back, which provides protection from wake vortex. The front of the safe zone is calculated from the possible trajectories of the two aircraft, which requires knowledge of aircraft speeds, lateral (i.e. across-track) separation, and the types of blunders for which protection is provided (typically change in heading and turn rate). The back of the safe zone is based on a prediction of wake vortex movement, conservatively modeled as traveling across the lateral distance between the two aircraft at crosswind speed. The back of the safe zone therefore requires knowledge of crosswind speed as well as aircraft position and speed. The values of these variables can either be obtained in real-time or can be predefined by worst-case assumptions.

In some implementations of paired approaches, the trail aircraft is intended to remain within the safe zone should the lead aircraft blunder. In others, an "Emergency Escape Maneuver", or EEM, is required in the event of a blunder. Either way, an EEM must be designed for the case in which the trail aircraft departs the safe zone.

Previous Studies

A number of previous studies have investigated paired approaches. These studies have examined how paired approaches might be implemented by examining flight deck displays, procedures, and alerting systems. These approaches have made a number of assumptions, both explicit and implicit, about pilot behavior as summarized in Table 1 and described in the following sections.

MITRE Studies

Researchers at MITRE have been investigating the practical implementation of paired approach operations. They have developed procedures and displays after analyzing possible blunders and performing a task analysis of operational requirements. They then investigated those procedures and displays in a simulator experiment.

Summary of method and results. Specifically, Hammer [3] used Monte-Carlo simulations to determine the front of the safe zone required to avoid different types of blunders by the lead aircraft. Both aircraft flew initially at 170 knots, and then slowed to a final approach speed of between 105 to 145 knots inside of 5 nautical miles (NM). The blunder extent (the heading change) of the lead aircraft was randomized from 5° to 30°, the blunder turn rate was varied to correspond with accelerations between 0.1G and 1.0G, and the blunder commenced randomly at any position along the entire approach path.

Hammer concluded that maintaining a position of 3000 feet in trail outside of 5 NM, then from 2000 to 1000 feet

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	MITRE	MIT	Stanford	Georgia Tech
Calculation of safe zone	Predefined speeds, deceleration profiles	Real-time aircraft states	Real-time states plus predicted EEM parameters	Both real-time and predefined
Variance in speed allowed	40 kts	40 kts	0	must be > 140 kts and <230 kts
Types of blunders	Lead aircraft lateral blunders only	Lead aircraft lateral blunders only	Lead aircraft lateral blunders only	Either or both aircraft, lateral or speed blunder
Part of safe zone considered	Both front and back	Front only	Front only	Both front and back
EEM turn rate	0.1 to 1.0 g	5° to 45° roll angle	2.7 - 4.5 deg/sec	None assumed
When does EEM commence?	When safe zone cannot be maintained but before departing	After departing safe zone, delay of up to 20 secs	After departing safe zone, reaction time approx. 3 secs	After departing safe zone
Position requirements at EEM	Both aircraft must be on nominal approach path	> runway separation	> runway separation	none
EEM Maneuver	Turn away and climb	Turn or Turn/Climb	Varying turn rate and acceleration	Turn away and climb
EEM safety guaranteed?	Only if remaining within the safe zone during EEM	Yes, if constraints met	If constraints met, for up to 13 seconds	Yes, for up to 30 seconds
Tracking behavior assumed	Track position within safe zone	Track position within safe zone	Track position within safe zone	Track position within safe zone
Monitoring required	Safe zone, lead compliance	Safe zone, alerting system	Safe zone	Safe zone, lead compliance

Table 1. Summary of assumptions of previous studies.

inside of 5 NM, would be acceptable. Hammer then examined how this "ideal" safe zone would vary with respect to total system error, differences in the final approach speeds, deceleration rates of the two aircraft, the initial separation of the two aircraft, and head winds.

Other researchers at MITRE (Bone, Olmos, and Mundra, 2001) performed a piloted simulator experiment to investigate procedures, cockpit display of traffic information (CDTI) tools, and pilot opinions. Pilots were given speed commands, indications of the front and back of the safe zone, and a target position arrow. The speed commands steered the trail aircraft to the proper position prior to or at the final approach fix. If the trail aircraft departed the safe zone, an indication was given (the safe zone was replaced by an "X"), and the procedure directed that an EEM be initiated. This EEM was a turn away from the lead aircraft's approach path, a climb, and acceleration. Pilots were generally positive about the operation and tools provided in the experiment. The researchers concluded that, although more work needed to be done (and indicated several particular concerns), the operation was generally feasible.

Assumptions on pilot behavior. These studies assumed that the pilot would track a position within a static, predefined safe zone. Therefore, pilots were provided with speed commands to maintain that position. They also implicitly assumed that the pilot would monitor lead aircraft compliance to the speeds dictated by the approach procedure, since the safe zone would be invalid were they not being followed.

If the lead aircraft did blunder, the pilot of the trail aircraft would, it was assumed, attempt to remain within the safe zone (regardless of the lead aircraft's actions). If they could not remain within the safe zone on the nominal approach path, an EEM would have to be performed, during which the pilot needs to continue to track the safe zone. These assumptions require monitoring and tracking of the safe zone throughout both the nominal approach and during an EEM.

Stanford Studies

Researchers at Stanford (Teo and Tomlin, 2000) utilized differential game theory to define the safe zone limits. This methodology treats the lead aircraft as a deliberate pursuer of the trail aircraft, thus calculating the safe zone in "worst-case" conditions.

Summary of method and results. Teo and Tomlin's method of analysis results in an analytical solution to the safe zone that can be computed in real-time. This safe zone is different than in the MITRE studies, however, as it is based on the position from which the trail aircraft can perform an EEM and be protected from collision danger. This means that the safe zone depends on the trail aircraft performing an EEM if the lead aircraft blunders, rather than continuing on the approach as in the MITRE studies. The analysis was later refined (Teo and Tomlin, 2001) by ensuring that protection was provided for up to 13 seconds (described as the amount of time it would take for the trail aircraft to turn 60 degrees at 4.5 degrees per second).

These studies only focused on the front of the safe zone, and disregarded the back of the safe zone (except for commanding an EEM due to wake vortex when lateral separation is less than 200 feet). In addition, the EEM was no longer a predefined maneuver. Instead, the trail aircraft would determine what maneuver was required from a number of alternatives. These maneuvers were complex, requiring turns with sudden shifts in turn rates, and speed changes with various accelerations.

Assumptions on pilot behavior. In addition to the explicit requirement that pilots react within a few seconds, there were implicit assumptions on pilot behavior as well. First, pilots must monitor and track the safe zone, commencing the EEM if it is departed. Since the safe zone in this case is calculated in real-time, the safe zone could potentially change position and size rapidly, complicating the task of tracking it. In addition, the method used to calculate the safe zone is highly dependent on several factors, particularly turn rate. If an evading pilot failed to achieve the predicted turn rate, the EEM would probably not be safe.

These requirements on the EEM could be achieved by automating them, as pilots may be able to perform them. However, it is also unlikely that the pilots could understand an EEM maneuver, and therefore would be "along for the ride" when performed automatically.

MIT Studies

Researchers at MIT (King and Kuchar, 2000) have focused on alerting system design, and how it might be used in conjunction with the safe zone. King and Kuchar examined potential designs for alerting systems to extend the safe zone. They performed Monte-Carlo simulations to determine the effectiveness of different EEM procedures, and the amount of system delay that could be tolerated by an alerting system.

Summary of method and results. The safe zone was determined by simulating paired approaches in which the trail aircraft flew the same speed and deceleration profile as in the MITRE studies. The lead aircraft would blunder laterally using a roll angle of from 5° to 45°, changing heading by 15° to 60°. The trail aircraft would begin an EEM once the lead aircraft began its blunder (presumably due to an alert), with the EEM consisting of either a constant velocity climb, a level constant-rate turn to a heading offset of 45°, or a combination of the two. Further simulations included from 5 to 20 seconds pilot reaction time.

The study concluded that the effectiveness of an alerting system would be highly dependent upon what types of blunders were assumed in determining the alerting algorithm, as well as the details of the EEM. It was determined that less than 10 seconds of delay was needed for an alerting system to be effective, and may not be effective in any case at very close lateral spacing.

Assumptions on pilot behavior. Since the safe zone was recalculated in real-time during the approach, as in the Stanford studies, tracking the safe zone would be required, with the same complications as mentioned before. In addition, an alerting system would have to be monitored and complied with. As indicated by the study, a pilot would have no more than 10 seconds to react to the alert and begin an EEM.

Georgia Tech Study

A deterministic analysis of the safe zone was conducted to determine the position and size of the safe zone over a wide range of lateral separations and aircraft speeds. This analysis presupposed no limits on blunders; instead, the safe zone was "safe" for a predetermined period of "protection time" (30 seconds was used for this experiment), determining the blunder that resulted in the most restrictive position of the safe zone.

Summary of method. Two different underlying bases can be used to calculate the safe zone. The first uses procedural information; i.e. the predefined safe zone is calculated assuming that the aircraft are following a pre-specified approach procedure (as in the MITRE studies), thereby presenting a spatial boundary which is predictable, small and stable throughout the approach, but which does not account for aircraft behavior outside the approach procedure. The second is based on real-time information; i.e. the real-time safe zone is recalculated throughout the approach (as in the Stanford and MIT studies) 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.

The blunders performed by the lead aircraft caused different types of departures from each of the safe zones. When the lead aircraft blundered laterally, the trail aircraft was able to remain within the real-time safe zone until the lead aircraft crossed in front of it, at which time the trail aircraft would depart the back of the safe zone. If given the predefined safe zone, then no departure would occur since the predefined safe zone calculations assumed that the lead aircraft was still on its approach path. If the lead aircraft slowed early, then the trail aircraft, if it could not slow to match the lead aircraft's speed, would depart the front of whichever safe zone was displayed.

Assumptions on pilot behavior. The assumptions made for this study are also shown in Table 1. It was anticipated that pilots would track the safe zone, attempting to remain within in a relatively stable position from the front (and/or back) of the safe zone. When given the predefined safe zone, control movements may be diminished to reflect the static nature of this safe zone, but monitoring of lead aircraft compliance to the procedure would be necessary, since the accuracy of the predefined safe zone was only guaranteed for 30 seconds following a lead aircraft blunder. Providing both safe zones was expected to provide the benefits of each safe zone.

Piloted Simulation Study

A piloted simulation experiment was recently performed at Georgia Tech on paired approaches, with particular attention paid to how the safe zone was calculated (either predefined or in real-time) and reactions of the pilots to different types of lead aircraft blunders.

Method

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, 2001). 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). The safe zone presented was varied between real-time, predefined, and both. Below-minimum instrument conditions were simulated, resulting in no outside view; pilots flew the approach solely on instruments.

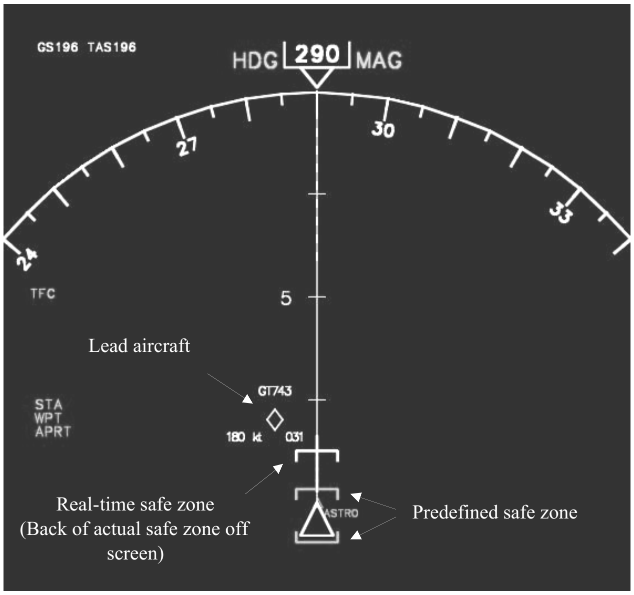

Figure 1. Navigation display with both safe zones.

The participants were instructed to fly an instrument landing system approach while remaining within the safe zone. The participant pilots flew the trail aircraft, with the lead aircraft being a scripted pseudo-aircraft. Pilots were trained on the operation of the simulator, on the safe zone, and allowed to practice until they felt proficient.

In order to measure the control movements of the pilots, control inputs were recorded every 2 seconds. Pilots were questioned concerning lead aircraft compliance following every simulation run to determine their ability to monitor the lead aircraft. Pilots were also asked a number of questions at the end of the experiment about their experience and attitudes towards the (currently performed) visual approaches to closely spaced parallel runways.

Results

To examine the pilot's strategy for controlling throttle, 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 differences between the lead and trail aircraft. This indicates that pilots were reacting to speed differences between themselves and the lead aircraft by moving their throttle so that this speed difference is decreased. Table 2 shows the probabilities that this relation does not exist for each subject and scenario.

Pilots had some difficulty in identifying blunders, not detecting 4% of the blunders and misidentifying 18% of the blunders. These errors were the same regardless of which safe zone was displayed.

The delay for pilots in commencing the EEM after departing the safe zone was an average of 15 seconds, with a standard deviation of 11 seconds. The minimum delay was 6 seconds, and the maximum delay was 35 seconds. The turn rate in an EEM was an average of 1.3 degrees/sec with a standard deviation of 0.6 degrees/sec. In lateral blunder cases, one pilot chose to remain on his approach path, and two other pilots elected to not fly the EEM as indicated in the procedure when the other aircraft had crossed in front of them (and therefore was flying in the same direction as the missed approach course).

In post-experiment questionnaires, pilots were asked how they currently maintain spacing when performing visual approaches to closely spaced parallel runways. Each pilot provided a different answer to this question, ranging from nose-tail separation to 5 miles. When asked whether they could maintain spacing within the safe zone while flying an EEM, 8 of the 12 pilots unambiguously indicated that they felt they could not.

Discussion and Implications for Previous Studies

These results shed some light on the assumptions of the previous studies. Shown in Table 3 is a summary of the findings of this study for comparison with the assumptions of previous studies.

MITRE used a static, predefined safe zone, while MIT and Stanford used a real-time safe zone. Although these two safe zones should have different implications for pilot behavior, the monitoring of both types of safe zones was 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 the EEM.

		Subject											
Scenario type	Overall	1	2	3	4	5	6	7	8	9	10	11	12
No Noncompliance	**0.000**	**0.004**	**0.014**	**0.020**	**0.000**	**0.001**	**0.000**	**0.005**	**0.040**	0.289	**0.000**	**0.000**	**0.025**
Pre Speed Noncompliance	**0.001**	0.890	**0.002**	**0.083**	0.148	**0.016**	0.112	0.917	0.119	0.524	**0.068**	**0.013**	0.403
Post Speed Noncompliance	**0.000**	0.485	**0.060**	0.526	**0.002**	**0.055**	**0.000**	**0.002**	**0.012**	0.331	**0.000**	**0.001**	**0.019**
Pre Lateral Noncompliance	**0.010**	**0.002**	**0.062**	**0.079**	**0.001**	**0.000**	0.438	**0.000**	**0.025**	0.544	**0.000**	**0.000**	0.239
Post Lateral Noncompliance	0.142	**0.086**	**0.012**	0.936	**0.037**	**0.000**	0.622	**0.000**	**0.025**	0.538	**0.028**	**0.001**	0.717

Table 2. P-values for regressions of throttle movements against speed changes.

	Results
Definition of safe zone	Pilots indifferent to how safe zone is defined, they treat it as a "red-line"
Range of speeds	Pilot speeds varied outside of plus or minus 10 kt range
Types of blunders	Speed blunders generally cause departures from front of safe zone, lateral blunders generally cause departures from back of safe zone.
Part of safe zone considered	Pilots don't react to departures from the front and back the same way because they are caused by different conditions
EEM turn rate	Slow turns - 1.26 deg/sec average (0.6 deg/sec std dev)
When does EEM commence?	Average delay of 17 Secs after departing safe zone
Position requirements at EEM	Departures from the front of the safe zone generally occur at close to nominal lateral separation, while departures from the back of the safe zone generally occur at near zero lateral separation.
EEM Maneuver	Inconsistent - some pilots chose to remain on approach profile or turn in opposite direction to that assumed by the EEM.
EEM safety guaranteed?	No separation violations occurred in 120 runs
Tracking behavior assumed	Lead aircraft speed was tracked, position within safe zone was not.
Monitoring required	Lead aircraft speed and departures from the safe zone were monitored, but the lateral position of the lead aircraft was not; implications of lead aircraft noncompliance were not detected.

Table 3. Summary of flight simulator experiment findings contrasted to previous assumptions.

The predefined safe zone requires monitoring of the compliance of both aircraft to the assumptions of the safe zone calculations. If these assumptions are violated, the safe zone becomes invalid. However, pilots did not appear to follow the expected monitoring behavior. They did not consistently identify blunders, and were even less able to apply the consequences of these blunders. They did not react properly to lead aircraft blunders when they were given the predefined safe zone. This suggests that they did not (or could not) interpret the consequences of the lead aircraft blunders. They could potentially follow the predefined safe zone into an unsafe position when the lead aircraft's actions invalidated it. Moreover, blunder detection performance was the same regardless of safe zone type, even though monitoring should have been increased when given only the predefined safe zone.

The real-time safe zone presumes a strategy of maintaining a position within the safe zone, which could require significant control inputs on the part of the trail aircraft pilot. However, the pilots did not appear to follow the anticipated control strategies. The pilots did not maintain a particular position behind whichever safe zone was displayed, nor were the throttle movements correlated with position within the safe zone. Instead, these throttle movements corresponded with a difference in speed between the lead and trail aircraft, suggesting that the pilots instead chose to track lead aircraft speed, allowing their position within the safe zone to vary.

In addition, since the real-time safe zone presents the current limit of safety, departures from it would likely require a rapidly executed EEM. However, pilots did not perform this maneuver rapidly or aggressively. Pilots had a significant delay in performing the EEM, and failed to achieve a high turn rate. Significant delays were also seen in an earlier study on parallel approaches (Pritchett, 1999).

Additional time delays and less aggressive maneuvering may have to be considered. It is likely, however, that the addition of such factors may cause the safe zone to be so far in trail of the lead aircraft as to negate the benefits of paired approaches.

The previous studies either only considered the lateral blunder cases (Stanford and MIT), or they did not consider how an EEM could be performed (MITRE). In addition, none of the previous studies accounted for the possibility that the lead aircraft may not comply in some other way (such as by slowing early). However, there appears to be an interdependency of blunder type to safe zone departures. Lateral blunders, since they cause the lateral separation between the two aircraft to shrink, generally result in departures from the back of the safe zone. In addition, these departures occur at near-zero lateral separation between the two aircraft. Speed blunders can cause departures from either the front or the back. Since the trail aircraft will probably be closer to the front than the back, the cases in which the lead aircraft slows too soon is of greater concern (and more likely). In this case the trail aircraft will depart the front of the safe zone, with nominal lateral separation between the two aircraft.

Pilot reaction to blunders was at least partly unanticipated. Although pilots did execute an EEM if they departed the safe zone, they sometimes turned opposite the direction indicated by the pre-specified EEM procedure. In addition, not all pilots followed the recommended EEM procedure. Although these could potentially be addressed in training, the infrequency with which pilots will encounter the need to perform an EEM would likely make reliance on rapid reaction times and high turn rates inadvisable. The pilots seemed less inclined to follow the EEM procedure when the lead aircraft was in front of them and flying in the same direction indicated by the EEM procedure. Therefore, their reaction to lateral and speed blunders may not be the same.

Regardless of the how the EEM would be performed, the pilots would probably have some tendency to remain within the safe zone as long as possible, since they treated the safe zone indication as a red line. For departures from the front of the safe zone, this decreases the likelihood that they will have much room in which to maneuver to remain within the safe zone when commencing the EEM. In addition to the fact that pilots did not believe they could track the safe zone during an EEM, this makes it extremely unlikely that the pilots could remain within the safe zone throughout the EEM as required by the MITRE procedure.

Instead, the EEM would have to be treated as part of the operation as in the MIT and Stanford studies. However, both assumed very tight limits on control inputs and speeds for the EEM. Unless the EEMs are to be automated (which could incur delays and situational awareness problems in addition to significant technical hurdles), the EEM would be hand flown, and deviations from the specified EEM excessive. This is particularly true since these EEMs require rather extreme maneuvering by the trail aircraft pilot, including a hard turn and climb.

It is possible, however, that the predefined safe zone could be used to reduce the requirement of rapid reactions to departures from the safe zone, since departures from the predefined safe zone do not immediately confer an unsafe condition, but rather a potential one. Once departing the predefined safe zone, pilots would have up until they depart the real-time safe zone to commence an EEM. Additional analysis is being performed to determine the potential of such a solution.

Conclusions

The previous studies of paired approaches included a number of assumptions that had implicit requirements on pilot behavior. The technologies, procedures, and dynamics of an operation are often coupled with operator behavior, and designs that rely on assumptions about one of the former aspects often implicitly require particular operator behaviors that may or may not be realizable.

In this study these implicit assumptions were not confirmed. It is probably true that with additional training pilots could be compelled to exhibit the behaviors expected of them. However, there is no evidence that the expected behaviors are better than the more compelling strategy that the pilots chose to use. Further examination of the alternative strategies should be conducted.

This problem is undoubtedly not unique to paired approaches. Design of many complex human-integrated systems are likely to have similar problems, incurring implicit assumptions about operator behavior as parts of the system are designed separately. Designers must try to understand not only the implicit behaviors expected by the system, but also attempt to determine the strategies that operators naturally bring to the system.

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