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EVALUATION OF COLLISION ALERTING SYSTEM REQUIREMENTS FOR PAIRED APPROACH

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Abstract

In the Paired Approach Concept, pilots are given responsibility to maintain spacing between aircraft on parallel approach. By placing the trail aircraft of an approach pair in a protection zone behind the lead aircraft, safety from collision and wake vortices can be managed. The size of the protection zone may be increased using a Collision Alerting System that commands the trail aircraft to break out should a blunder occur. This paper describes a study to evaluate the potential increase in protection zone size with the addition of an alerting system. A variety of approach conditions, blunder types, escape maneuvers, and system delay times were examined. Climbing-turn breakout maneuvers were found to be most effective in general, though the total system delay should not exceed 10 seconds. No significant alerting system benefits are possible when aircraft lateral separations are less than 1000 ft due to the limited time to take action. However, the need to separate aircraft during a missed approach suggests that collision alerting may be necessary.

Introduction

The Paired Approach Concept has been proposed as a potential means by which aircraft can perform dependent parallel approaches to runways as close as 750 ft apart in Instrument Meteorological Conditions [1,2]. The concept involves pilot responsibility for maintaining a certain longitudinal stagger spacing between aircraft through the use of Cockpit Display of Traffic Information (CDTI) with enhancements to aid the spacing task. As originally posed, the concept was that the approach be performed without a separate automated Collision Alerting System (CAS) to monitor traffic separation. Instead, safety would be ensured by locating the aircraft such that they could not collide given physical maneuvering limitations. The result, however, is a relatively restrictive window of safe relative positions between aircraft [3]. Rigorous spacing limitations could seriously reduce the flexibility and acceptability of the procedure. Additionally, the need to protect aircraft during a missed approach may require the addition of a CAS due to the reduced predictability of trajectories and the close proximity of the aircraft.

This paper discusses the potential benefits that the addition of a CAS could have in terms of both relaxing the separation accuracy required in the spacing task as well as improving safety by alerting pilots to a collision threat. CAS benefits are examined first assuming an ideal system in which evasive breakout maneuvers are performed immediately when a blunder begins, and then through the inclusion of time delays to simulate system latencies due to filtering, processing, human performance, and aircraft dynamics. Finally, CAS requirements are outlined for enhancing safety during missed approach procedures.

The Paired Approach Procedure

In the Paired Approach Concept, two compatible aircraft (a lead and a trail) are paired up on a final approach course by air traffic control (ATC), with initial altitude separation. The trail aircraft must then achieve and maintain a specified longitudinal separation behind the lead aircraft until passing the Final Approach Fix (FAF). CDTI tools with a datalink of aircraft position and final approach speed will be used to aid the trail pilot in controlling airspeed, while the lead aircraft flies a predefined deceleration profile. The flight crew of the trail aircraft has the responsibility of maintaining the necessary longitudinal separation between aircraft, and if unable to do so, may be required to perform a breakout maneuver. Once beyond the FAF, the flight crew is relieved of the spacing task, but may still be commanded to perform a breakout maneuver should the aircraft exit the PZ. Thus, an additional design consideration is to ensure that the PZ is large enough to absorb nominal variations in aircraft speed after the FAF so that unnecessary breakout maneuvers are minimized.

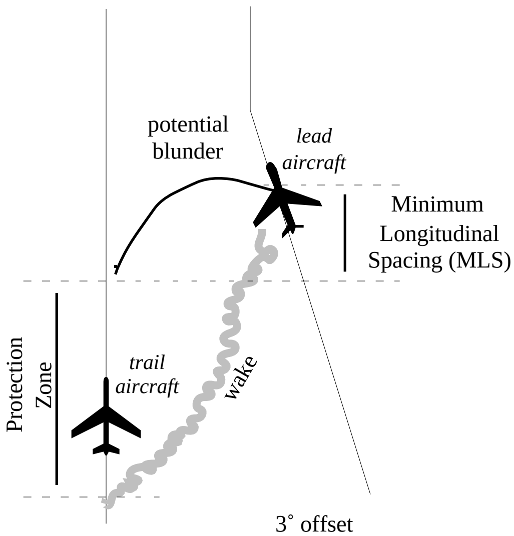

Figure 1: Paired Approach Concept

The longitudinal spacing requirement is designed to serve a dual purpose of wake and collision avoidance (Figure 1). Preventing a collision between aircraft requires that the trail aircraft be at least a certain distance (termed here the Minimum Longitudinal Separation, MLS) behind the lead aircraft. Additionally, the wake vortices from the lead aircraft could transport into the path of the trail aircraft due to crosswinds. This wake transport takes time, and thus the farther the trail aircraft is from the leading aircraft, the larger the potential for the wake to transport into the trail's path. The result is that the trail aircraft must remain within a certain safe window, or Protection Zone (PZ), behind the lead aircraft. When the trail aircraft is within the PZ, it is protected from a wake vortex encounter (defining the rear boundary of the PZ) and from a collision should the lead aircraft blunder (defining the forward boundary of the PZ). The forward limit of the PZ is of special interest in this paper, as it defines the MLS that is acceptable for the approach. MLS may vary during an approach due to changes in lateral separation and speed.

The baseline geometry of the procedure involves two parallel runways spaced 750 ft apart laterally. One runway has a straight-in Instrument Landing System (ILS) approach path, while the other runway has a 3˚ lateral offset ILS extending approximately 0.75 nmi from the threshold. The 3˚ offset allows for a significant expansion in the PZ size when the aircraft are far from the runway and also precludes overlap of the ILS courses.

There is a possibility that the forward boundary of the PZ could be extended with the addition of a CAS that would warn the flight crews of deviations or collision threats during the approach. The advance warning time and use of a breakout maneuver could allow the trail aircraft to be outside of the guaranteed PZ but still be protected by the CAS. This could also reduce the number of forced missed approaches due to PZ violations and enhance safety should one or both aircraft perform a missed approach. Although the Traffic Alert and Collision Avoidance System (TCAS) is on transport aircraft, its sensors and algorithms were not designed with closely-spaced parallel approaches in mind. TCAS could produce an unacceptable nuisance alarm rate due to the close proximity of aircraft [4]. Thus, a specialized CAS would need to be developed for this procedure.

It should be noted that conformance monitoring and feedback must be provided to the flight crews of each aircraft to warn them if they are deviating from their own approach path. This would serve as the primary line of defense against a collision, and would likely resolve most "blunders" before they developed into an actual collision threat. The CAS under consideration here is the final safety net in the system, should the nominal procedures and conformance monitoring warnings fail to return the deviating aircraft to its correct position.

Analytical Simulation

A fast-time simulation of the paired approach was used to determine MLS as a function of approach condition and blunder dynamics. MLS must be maintained to prevent a collision (defined as separation less than 500 ft) for a given type of blunder. The simulation was performed so that the dependence of MLS on variables such as blunder roll angle (turn rate), blunder heading, velocity, and distance from the runway (determining lateral separation due to the 3˚ offset) could be determined. Another function of the simulation was to examine the effectiveness of different breakout maneuvers that may be needed should the trail aircraft be unable to maintain its position in the PZ.

A point-mass model was used for each of the aircraft in the simulation. The simulation began with each aircraft at a given (but varied) distance from the runway, with a certain longitudinal separation, on the centerline of the approach path (either straight-in or with the 3˚ offset, depending on the runway), and at a given initial velocity. The initial altitudes of both aircraft were determined from their distances from the runways, assuming a 3˚ glideslope angle.

The aircraft velocities during the approach depended on their distances from the runway threshold. Outside the FAF (5 nmi from the runway), the velocity was held constant at an initial approach speed of 170 kt. Once each aircraft reached the FAF, it flew a deceleration profile (at a constant 1 kt/sec) to a predetermined final approach speed (which was generally different for each aircraft). Once the aircraft's final approach speed had been reached, that speed was maintained until touchdown. As a somewhat worst-case condition, the trail aircraft's final velocity in the cases reported here was faster than the lead aircraft (125 kt vs. 115 kt). The fact that the lead aircraft begins to decelerate before the trail, combined with the difference in final approach speeds, results in a continuous reduction in separation after the FAF.

Blunder Model

Each simulation began with a blunder from the lead aircraft. Blunders were modeled as a constant-speed, constant-altitude turn to a pre-specified blunder heading, ψ, relative to the runway centerline. Throughout the turn, the turn rate was held constant, and was defined in terms of the roll angle. The roll-in and roll-out to the specified roll angle were assumed to be achieved instantaneously. While the lead aircraft was flying the blunder, the trail aircraft was either flying a straight-in approach or one of several possible breakout maneuvers, which are discussed later. Blunder cases included several combinations of blunder headings (15˚, 30˚, 45˚, 60˚) and roll angles (5˚, 15˚, 30˚, 45˚).

Additionally, a set of blunders were examined in which the lead aircraft sidestepped varying distances toward the trail aircraft. The case in which the lead aircraft sidesteps directly in front of the trail aircraft may actually be a relatively likely form of blunder due to the potential for pilots to line up on the wrong runway. This type of blunder may also fail to be resolved using on-board conformance checking systems if the automation on the aircraft has been programmed to use the incorrect runway.

A series of sinusoidal blunders were also simulated where the lead aircraft oscillated left and right at varying magnitudes and frequencies. Finally, simulation runs were performed with the lead and trail aircraft at varying lateral offsets from their approach paths. This represents nominal approach deviations due to guidance and flight technical errors. A maximum offset of 200 ft of each aircraft toward the other was used, resulting in a minimum lateral separation of 350 ft when within 0.75 nmi of the runway threshold.

For brevity, only cases with a blunder roll angle of 30˚ are reported here. Generally, performance was insensitive to blunder roll angle unless it was less than 5˚. Otherwise, varying the rate of turn had little effect on the required PZ size. A complete description of roll angle effects can be found in Ref. 5.

Trajectory Analysis

The simulation began using a relatively large longitudinal separation (6000 ft) between aircraft. Next, the resulting trajectories of the lead and trail aircraft were examined to determine whether a collision (less than 500 ft separation) had occurred at some point along their length. The initial longitudinal separation was then systematically reduced in successive simulation runs until a collision occurred. The value of the initial longitudinal separation that resulted in this collision then defined the MLS for that specific approach condition and blunder type. By repeating the simulation over varying conditions and blunder types, it is then possible to build a picture of the required MLS to ensure safety.

The trajectories that begin with the aircraft located at the MLS were saved and plotted to provide insight into the conditions leading to the loss of separation. Figure 2 shows an example plot of a 45˚ blunder heading case for a lead aircraft initial position of 3 nmi from the runway, which corresponds to an initial lateral separation of approximately 1400 ft. As shown, the blundering lead aircraft turns toward the trail aircraft, which continues to fly straight along its approach path. A collision (separation of 500 ft) occurs at the relative locations of the diamond symbols. The initial longitudinal separation between aircraft (when the blunder started) that resulted in this collision can be determined by examining the starting location of the trail aircraft, which in this case is located approximately 1200 ft behind the lead aircraft. Any spacing more than 1200 ft apart in this case would not lead to a collision. Thus, 1200 ft is the MLS for this blunder and approach condition.

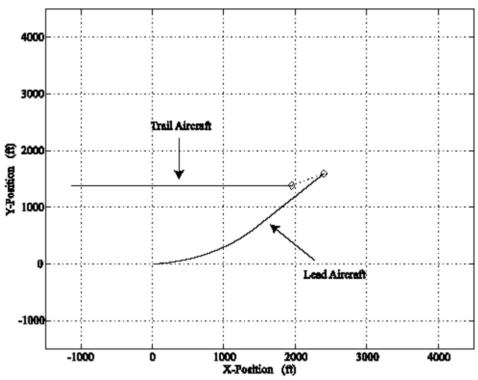

Figure 2: Example Collision Trajectories

Baseline Separation Requirements

By repeating the analysis presented above for varying initial positions from the runway (and therefore lateral separations), a composite view of the MLS can be developed. Figure 3 shows the MLS as a function of the distance from the runway when a blunder begins, for 4 different blunder headings (all at a 30˚ roll angle). The trail aircraft is required to have a separation from the lead aircraft greater than the value shown by the Collision Avoidance Limit curves. For example, if a 30˚ blunder occurs 3 nmi from the runway, the trail aircraft must be at least 1000 ft behind the lead to prevent a collision. If the blunder heading grows to 60˚, the trail would need to be at least 1200 ft behind to prevent a collision. Ultimately, the appropriate limit on MLS is determined by the assumptions regarding the types of blunders that could occur.

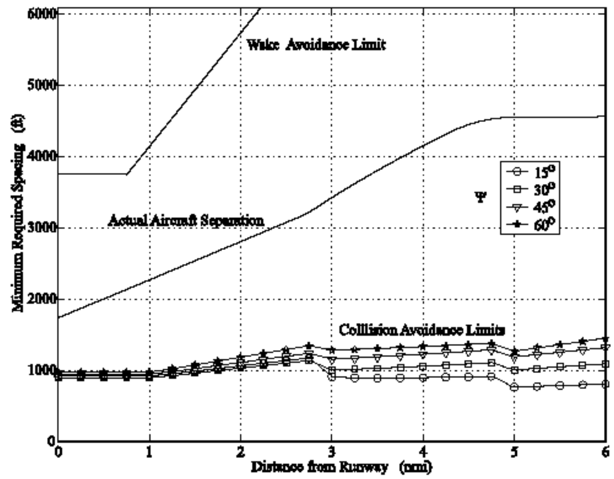

Figure 3: Protection Zone Dimensions
(varying blunder headings)

In general, the lower the Collision Avoidance Limit curves are in this plot, the larger the PZ can be because the trail aircraft is allowed to be closer to the lead aircraft. In the limit, the curves could drop down as far as the horizontal axis (longitudinal separation of 0 ft), corresponding to a situation where the lead and trail are side by side. The various bends and slopes in the curves are due to the velocity profiles of the two aircraft and changes in lateral separation as the aircraft near the runway.

The rear limit of the PZ due to wake vortex constraints is also shown in Figure 3, based on a worst-case 25 kt wake transport velocity. The aircraft must maintain a separation somewhere between the Wake Avoidance Limit curves and the Collision Avoidance Limits curves. An example aircraft separation curve is also shown, illustrating the reduction in separation that occurs due to differences in the timing of reaching the FAF and in the final approach speeds.

The sidestep and sinusoidal blunders could cause problems in the paired approach because the lead aircraft can become positioned directly in front of the trail at a similar heading. The trail may then encroach on the lead aircraft due to differences in approach speeds. This involves relatively small closure rates, however, and could be managed by enforcing a breakout maneuver once the trail aircraft violated restrictions on MLS. Wake vortex encounters could be a significant factor in these types of blunders as well, but were not considered in this analysis.

Offsetting the aircraft laterally from their approach path centerlines had only a modest effect on MLS (increasing approximately 200 ft). However, such an offset would have a significant impact on the wake vortex constraint defining the rear boundary of the PZ. As the aircraft are offset toward one another, the wake transport distance decreases in proportion, moving the rear limit of the PZ forward. Ensuring a PZ large enough to absorb normal lateral deviations and speed excursions then becomes a significant challenge, further supporting the motivation to expand the front limit of the PZ through the use of a CAS.

Ideal CAS Performance Benefits

The CAS benefit analysis consisted of determining (1) which breakout maneuvers are effective in the event a warning is issued, and (2) the maximum total system delays that are acceptable. The results are first presented for an ideal system in which evasive breakout maneuvers are initiated immediately when the lead aircraft blunders.

Three different breakout maneuvers were examined: climb, turn, and full breakouts. The climb breakout represents a missed approach with a climb to a given altitude but no turn involved. This offers a solution that involves the least incurred pilot workload. Prior research, however, has shown that a climbing-turn breakout can be significantly more effective than a climb-only maneuver [6]. The full breakout represents this climbing-turn maneuver. Finally, the turn breakout represents a case where either the trail aircraft turns at constant altitude, or where the blundering aircraft is gaining altitude at the same rate as the aircraft that is breaking out. Thus, the turn breakout allows for an examination of the potential loss of effectiveness of the full breakout should altitude separation not be achieved.

The simulation of breakout maneuvers was generally similar to that of the blunders, with the aircraft velocity for the breakout held constant. The climb breakout consisted of a pull-up at a load factor of 1.25 g to a climb rate of 2000 ft/min until an altitude gain of 500 ft had been achieved. The turn breakout consisted of an instantaneous roll to a 30˚ roll angle, a level constant-rate turn to a breakout heading of 45˚, and an instantaneous roll-out on that heading. The full breakout was simply a combination of the climb and turn breakouts performed simultaneously.

Climb Breakout

The best results for the climb-only breakout maneuver were for small blunder roll angles and headings — the less severe or slower blunder situations. There was effectively no benefit, in terms of reducing the MLS, for 30˚ or larger blunder headings when a climb-only breakout was flown. This is because the blundering aircraft can reach the parallel traffic's position before 500 ft altitude can be gained. In slow blunders (e.g., less than a 15˚ heading change) the trail aircraft can gain enough altitude to prevent a collision, but only in cases beyond approximately 2 nmi from the runway (corresponding to initial lateral separations of greater than 1100 ft). When closer than 2 nmi to the runway, there is little benefit from the climb-only maneuver due to the lack of time to climb 500 ft given the smaller lateral separation. Beyond 2 nmi, however, an instantaneous climb-only breakout is able to safely resolve any slow blunder (of less than approximately 15˚ heading change) regardless of longitudinal spacing. That is, there need not be any forward limit to the PZ when the aircraft are more than 2 nmi from the runway if only slow blunders are possible (and again assuming an ideal system without any delays).

The major drawback to the climb breakout is that altitude separation is the only means by which a collision is actively avoided. Should the blundering aircraft climb at the same rate as the trail aircraft, this altitude separation may be lost. By making the CAS logic adaptive (e.g., modifying the strength of the climb command), this problem can be mitigated somewhat, though there will still be relatively stringent limitations. For example, it is anticipated that a descend command (or even a do not climb command) would not be acceptable, given the low altitudes of the aircraft.

Turn Breakout

The turn breakout offered significantly more benefit than the climb breakout, but also had some disadvantages as shown in Figure 4. For a

15˚ blunder heading, for example, no forward limit on the PZ is required, as shown by the line along the horizontal axis in Figure 4. In these slow blunder cases, an ideal CAS could protect the trail aircraft from a lead aircraft spaced anywhere longitudinally, at any lateral separation down to the minimum of 750 ft.

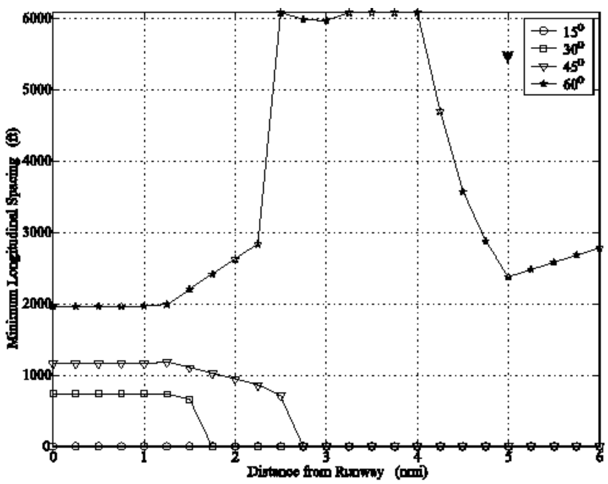

Figure 4. Turn Breakout Performance
(ideal CAS, no time delay)

A forward limit of the PZ is likewise not needed for the 30˚ and 45˚ blunder headings, but only at larger distances from the runway (corresponding to increasing lateral separations). For example, a 30˚ blunder can be completely protected by the CAS for distances from the runway greater than approximately 1.75 nmi. At distances less than 1.75 nmi, MLS requirements are needed and in fact are similar in size to that for the baseline case without a CAS (Figure 3).

When the blunder heading exceeds the heading of the breakout there is a large increase in the MLS (limited artificially here to 6000 ft). This is because the blunderer will continue to converge and cross the trail aircraft's path. Note, however, that the turn breakout reduces closure rate, and it would take more than 60 sec for the aircraft to collide. If the trail aircraft could be commanded to turn to a greater heading angle (or to climb) under these conditions, then the large increase in MLS would not occur.

Full Breakout

The full breakout behaves similarly to the turn breakout maneuver in that it offers a good amount of improvement outside 2 nmi from the runway threshold (Figure 5). A significant advantage to the full breakout is that because of the turn component, the aircraft performing the breakout maneuver has enough time to gain sufficient altitude and avoid the problem of a blunderer turning with the trail aircraft. Again, a CAS based on the assumption of altitude separation may fail should the blundering aircraft climb at a similar rate to the evading aircraft. This may necessitate adaptive alert guidance or other methods to ensure adequate vertical separation regardless of the blundering aircraft's behavior.

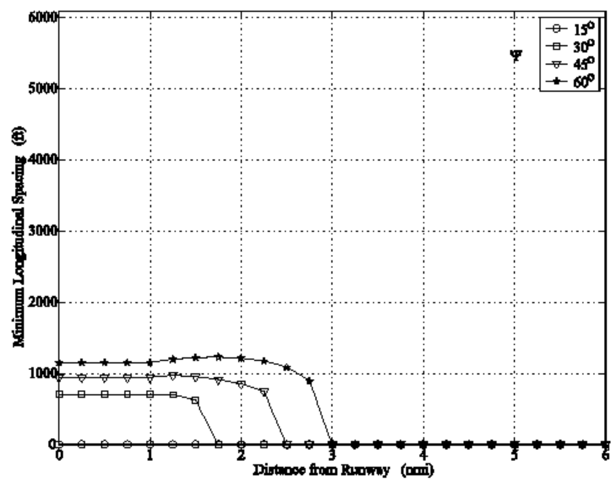

Figure 5. Full Breakout Performance
(ideal CAS, no time delay)

Figure 5 also shows, however, that the full breakout still fails to decrease MLS should a severe blunder occur (i.e., with a heading approaching or greater than the breakout heading) within 2 or 3 nmi from the runway. Thus, even an ideal CAS with a fairly aggressive breakout maneuver cannot improve the PZ size close to the runway if severe blunders are a felt to be a concern.

The results of the ideal CAS situations suggest that an alerting system could have benefit in less-severe blunder situations and cases farther from the runway (with larger lateral separation) if the breakout maneuvers include a turning component. Also, a CAS would be of benefit for sidestep-type blunders in which some evasive action is required but where closure rates may be relatively low. The key issue is determining how severe are blunders expected to be, as this then determines whether a collision can be avoided, and ultimately determines how large the PZ must be. In any case, no actual CAS would work ideally, without any delay from the onset of a blunder. This issue led to the second set of analyses, in which total system latency was included as a parameter.

Impact of Time Delays

The effect of system latency was introduced by delaying the breakout maneuver for a given amount of time after the blunder began. This delay time was representative of the time it took for the CAS to detect a blunder, the time it took to alert the pilot, and the time it took for the pilot and aircraft to initiate the breakout maneuver.

Figure 6 shows the MLS requirements for a 30˚ heading blunder using a full breakout CAS with varying system delay times from 5 to 20 sec. As the plot shows, any delay larger than approximately 15 sec makes little difference in the MLS curve. This indicates that such a delay is large enough to entirely offset the potential benefit of the CAS: a collision would occur before the breakout is successful. As the delay is reduced to 10 or 5 sec, the benefit of the CAS can be seen through the reduction in MLS at the larger distances from the runway.

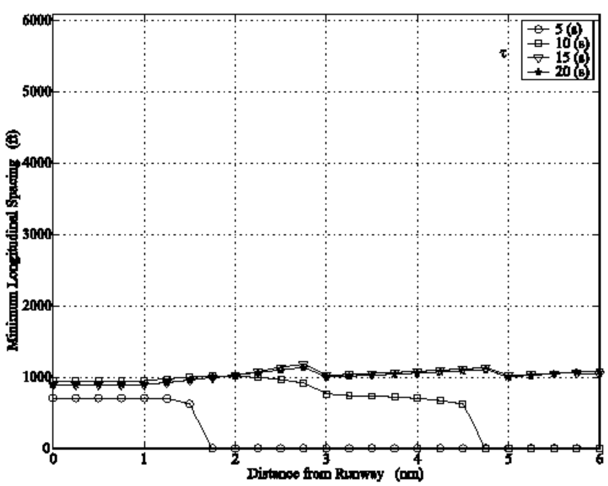

Figure 6. System Latency Effects
(full breakout maneuver, 30˚ blunder)

Comparing Figure 6 to Figure 5 shows that a similar MLS occurs with a delay of 5 sec as from an ideal CAS with no delay. Thus, for this blunder and breakout maneuver, the CAS should have no more than 5 sec total system delay for the best performance. Once delay reaches 10 sec, the benefit of the CAS is largely lost.

In the case of a sidestep or oscillatory blunder, however, the CAS may still provide significant benefit even with larger delay times. This is because closure rates in these situations is relatively low, leading to a substantial time budget in which to take action to resolve the problem.

Missed Approach Maneuvers

There is always the possibility that aircraft could perform a missed approach procedure due to equipment failure or poor visibility. It was therefore necessary to determine the effects on collision risk should either aircraft perform a missed approach at any point in the procedure.

As modeled, a missed approach had either a straight flight path or a 15˚ turn left or right to reflect the reduced level of directional guidance expected during a missed approach (i.e., the pilots revert to flying runway heading rather than following ILS guidance). No climb component was included, to model the worst-case where altitude separation is not achieved. Varying time delays were used between when either or both the lead and trail aircraft began a missed approach. Baseline missed approach MLS data are presented here, assuming no CAS is present.

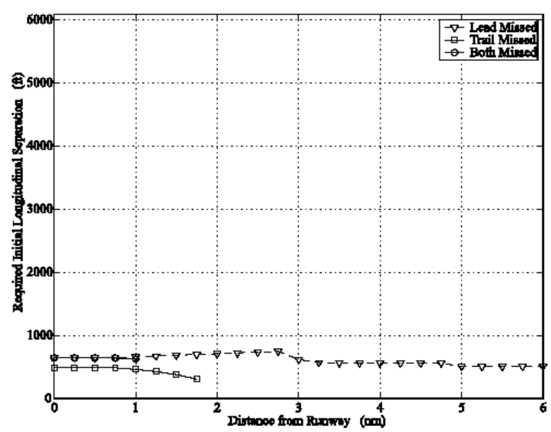

Figure 7. Missed Approach Situations

The impact on MLS of three different missed approach scenarios can be seen in Figure 7, with the missed approach being flown either by the lead aircraft only, the trail aircraft only, or both aircraft. The figure shows that MLS at worst is similar to the 15˚ blunder case shown in Figure 3. Missed approach can require an increase in MLS, however, if the maneuver is modeled as a sidestep rather than a single heading change (not shown here). Again, however, these sidestep maneuvers generally have a low closure rate, implying that a CAS could be effective in advising the aircraft to perform a breakout maneuver.

Conclusions

The results of the simulations provide insight into several issues regarding the required minimum longitudinal separation (MLS) between aircraft. First, the effectiveness of a collision alerting system (CAS) depends strongly on the underlying assumptions regarding the type of blunder to be protected from, the type of breakout maneuver to be performed, the degree of accuracy with which this maneuver can be flown, and the overall system delays. For blunders turning a shallower angle than the breakout, a climbing-turn maneuver was found to be effective as long as total system delay was less than approximately 10 sec. This imposes a rigorous constraint on system design, given that delays due to filtering and human response time could easily reach this limit. Close to the runway, the benefits of a CAS for any turn-type blunder are relatively limited, providing a decrease in MLS of only on the order of 200 ft.

The most effective breakout maneuver is to turn farther than the blundering aircraft and to achieve altitude separation. Both of these outcomes are difficult, however, with an alert that only provides open-loop commands to turn and climb. An adaptive, closed-loop alerting system that modified turn and climb commands could enhance separation performance, but at the expense of increased pilot workload, training, and the potential to increase response time.

Unfortunately, at the most critical point in the approach where the protection zone is smallest (within 0.75 nmi from the runway) a CAS cannot provide much relief in the MLS. Rather, aircraft will need to remain within the guaranteed safe zone assuming no CAS is available, or else will have to complete the approach visually. A relatively simple CAS may be beneficial in other types of blunders, however, such as a sidestep maneuver by the lead aircraft. Such a blunder could be reasonably expected to occur, for example if the flight crew lines up on the wrong parallel runway. In these sidestep blunders, closure rates are low, providing ample time for a CAS to alert and guide the pilots in performing breakout maneuvers. Similarly, during a missed approach, flight crews will not be performing the spacing task and so may benefit from a CAS.

The first line of defense against collision risk in the paired approach is to provide approach conformance feedback to aircraft. This would involve alerting the aircraft to a lateral or speed deviation so that corrective action can be taken.

Acknowledgment

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