Evaluation of Collision Alerting System Requirements for Paired Approach

by

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Abstract

Airports that have closely spaced parallel runways can have their arrival capacity cut in half due to inclement weather. The "Paired Approach" Concept would allow aircraft to perform dependent closely spaced parallel approaches to runways that are separated by as little as 750 ft during Instrument Meteorological Conditions. This would be achieved by enforcing longitudinal spacing constraints between the two aircraft by placing the trail aircraft inside a protection zone. This separation serves two purposes: to prevent a collision in the event that one of the aircraft deviates from the intended approach path, and also to guard against a wake vortex encounter. The size of this protection zone could possibly be increased with the use of a Collision Alerting System that would alert the trail aircraft to break out if a blunder occurs.

This paper describes an evaluation of the potential improvement in protection zone size that may be possible with the addition of an alerting system. A numerical simulation of paired approaches was performed in which several different approach conditions, breakout maneuvers and system delay times were considered. Missed approaches were also examined for each aircraft independently and for both aircraft simultaneously. All of these factors contributed to the determination of the design requirements for an effective collision alerting system.

In general a climbing-turn breakout maneuver was the most effective. In order to take advantage of this effectiveness however the total system delay should be limited to 10 seconds. No significant benefit was found for situations when the aircraft had a lateral separation of less than 1000 ft, because of the limited time to initiate a breakout. An alerting system may be necessary in order to maintain separation during missed approaches.

Thesis Supervisor: James K. Kuchar
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List of Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
CAS	Collision Alerting System
CDTI	Cockpit Display of Traffic Information
FAA	Federal Aviation Administration
FAF	Final Approach Fix
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
MLS	Minimum Longitudinal Spacing
PRM	Precision Runway Monitor
PZ	Protection Zone
SFO	San Francisco International Airport
VMC	Visual Meteorological Conditions

CHAPTER 1 Introduction

The capacity of airports that have closely-spaced parallel runways can be limited by a combination of the lateral spacing between their runway center lines and the meteorological conditions at the time of approach. During visual meteorological conditions (VMC), simultaneous visual approaches may be conducted to runways that are separated by as little as 750 ft. When aircraft are operating under instrument meteorological conditions (IMC), runways separated by less that 2500 ft are effectively treated as a single runway. This is because the runways are so close that there is not enough time for pilots to take action to avoid a collision should something go wrong. The result is a reduction in runway throughput and an increase in delays.

San Francisco International Airport (SFO) is an excellent example of an airport with closely-spaced parallel runways that suffers under instrument conditions. The runways 28L and 28R at SFO for example, are separated by 750 ft. Under VMC there is a typical arrival throughput of about 60 landings per hour, however under IMC the arrival throughput drops to about 30 landings per hour (Hammer, 1999).

During simultaneous visual approaches the pilots are responsible for maintaining adequate separation between the aircraft. When the aircraft are operating under IMC the air traffic controller (ATC) becomes responsible for maintaining adequate separation between the aircraft. IMC approaches to parallel runways can be conducted in two ways, independently or dependently.

Simultaneous independent approaches are allowed for runways separated by more than 4300 ft (FAA, 2000). During these independent approaches a final controller monitors the position of each aircraft for deviations from the flight path. The simultaneous independent approach can be extended to parallel runways with center lines as close as 3400 ft with the use of a precision runway monitor (PRM) radar (Shank & Hollister, 1994). When using the PRM, if either aircraft crosses a "no transgression zone" (an area 2000 ft wide located equidistant between the final approach courses), the controller issues instructions to the deviating aircraft to: return to the appropriate approach course, perform a missed approach, or execute a breakout maneuver. The controller could also issue a breakout command to the threatened aircraft.

Parallel dependent approaches must be used for runways with lateral spacing between 2500 and 4300 ft unless PRM is present. The dependent approach procedure utilizes specific radar separations to turn the aircraft on to the final parallel approach course and staggered separation between the aircraft while on the approach. It requires 1000 ft vertical separation or 3 nmi of radar separation as the aircraft turn on to the parallel approach course. Once on the approach the aircraft must maintain a minimum diagonal separation of 2 nmi and longitudinal separation of 2.5 nmi.

An alternate procedure has been proposed called "Paired Approach" that would enable dependent approaches into runways that are separated by as little as 750 ft under instrument conditions (Stone, 1998). Two compatible and eligible aircraft (a lead and a trail), are paired up on a final approach course by ATC, with some initial required altitude separation and a specified longitudinal separation. The trail aircraft must then achieve and maintain a specified longitudinal separation behind the lead until passing the final approach fix (FAF). The longitudinal spacing between the two aircraft is designed to serve a dual purpose of wake vortex and collision avoidance. The flight crew of the trail aircraft has the responsibility of maintaining the minimum longitudinal spacing between the aircraft, and if unable to do so, may be required to perform a breakout maneuver. The flight crew will maintain this spacing with the help of a yet to be determined cockpit-based tool set to conduct these tasks. One possible system may include a combination of an Automatic Dependent Surveillance-Broadcast (ADS-B), which is a datalink that supplies state information such as velocity, position, etc., and a Cockpit Display of Traffic Information (CDTI). Whatever tools are used it will be at least necessary for the trail aircraft of the pair to be equipped with a full set of "paired approach tools" and the lead to be equipped with the ADS-B datalink.

The trail must remain far enough behind the lead so that if the lead should blunder (deviate from the intended flight path) toward the trail, there is no danger of a collision. The wake vortices of the lead aircraft, however, tend to move laterally depending on factors such as

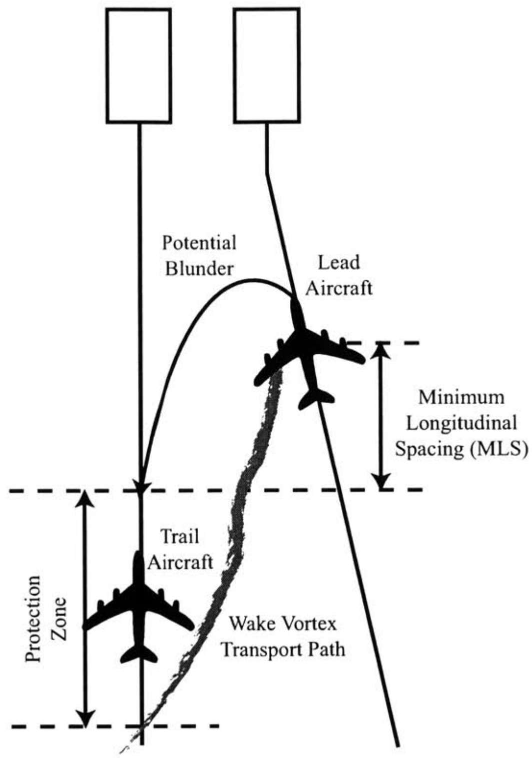

Figure 1-1: Illustration of Trail Aircraft within Protection Zone

crosswind. If the trail is too far behind the lead, it may encounter these wake vortices. Figure 1-1 is an illustration of the two separation requirements. The two limits of separation form the boundaries of the Protection Zone (PZ) which are also shown in Figure 1-1. When the trail aircraft is within this PZ it is protected from a wake vortex encounter (rear boundary), and also from a collision should either aircraft blunder (forward boundary). The forward or collision limit of the PZ is defined by the minimum longititudinal spacing (MLS) between the aircraft that essentially makes a collision impossible. This MLS is also shown in Figure 1-1.

The MLS can become quite large if it is used to passively protect the trail aircraft from every possible blunder scenarios. The very large MLS becomes a problem when it begins to approach the wake vortex boundary of the PZ. This leaves a very tight window that the trail aircraft must remain inside and could make the procedure very difficult to fly successfully. There is a possibility that the MLS could be restricted in size so that it would protect against certain blunders while a collision alerting system (CAS) was added to warn the flight crews of deviations or collision threats exceeding the severity of those considered during the determination of the MLS.

The MLS and CAS requirements were examined using numerical simulations of paired approaches. There were four main goals of the research: determine the MLS required in order to perform a successful approach, determine what type of breakout maneuver the trail aircraft should perform when an alert is issued, determine the trade-off between CAS design and PZ size, and examine constraints due to missed approach issues. The impact that different types of blunders had on the MLS also needed to be determined.

The proposed paired approach procedure is explained in Chapter 2 of this paper. It includes a description of the approach procedure, necessary avionics and the geometry of the approach. The need for a CAS is also explored at the end of Chapter 2. Chapter 3 contains an explanation of the numerical simulation used. It includes an overview of the output of the simulation and any variations considered during the simulation. The baseline results for the case where the trail aircraft does not perform a breakout maneuver are covered in Chapter 4. The dependence of these results on blunder heading, blunder roll angle, aircraft velocities, and blunder maneuver are also covered in Chapter 4. Chapter 5 contains the results for the simulation where the trail aircraft performed a breakout maneuver. The results are categorized by the breakout maneuver performed, and then by blunder roll angle, blunder heading, and delay time to begin breakout maneuver. The results for one or both of the aircraft performing a missed approach procedure are in Chapter 6. Chapter 7 contains the summary of all of the results and conclusions.

CHAPTER 2

Paired Approach Concept

2.1 Air Traffic Control Overview

While an aircraft is en route, it receives instructions from an air route traffic control center (ARTCC). These centers are distributed throughout the U.S. and each center covers a different sector of the country. As an aircraft flies from one center's coverage area to the next it is issued a command to change to the receiving center's frequency. Prior to arriving to the destination airspace an aircraft will receive instructions to contact approach control for the destination airspace. Approach control is responsible for all instrument flights within its airspace. That airspace may include one or more airports and may have different coverage areas depending on the airports. After release to approach control aircraft are vectored to their final approach course. These vectoring instructions include any altitude and radar vectors that are necessary to maintain adequate aircraft separations. Approach control will then issue the aircraft an approach clearance and will include the final vectoring instruction that will allow the aircraft to intercept the final approach course. This final vector should allow the aircraft to establish itself on the final approach course before reaching the FAF. After passing the FAF the aircraft is expected to continue on the approach course and complete the approach or in the case of something going wrong, perform the appropriate missed approach procedure (FAA, 2000).

2.2 Paired Approach Procedure

2.2.1 Initial Approach

Prior to the aircraft entering the approach control airspace, the ARTCC will determine the number of potential aircraft pairs based on equipment declaration in the flight plan data, and their relative positions with respect to the arrival flow. Upon arrival in the terminal area, the aircraft are accepted by the feeder controller.

On initial contact the feeder controller will instruct the flight crews to expect the paired approach and request their planned final approach speeds. The procedure requires that the expected final approach speeds of the aircraft be within specified limits. The feeder controller will then enter the approach speeds in the scratch pad of the data block or on the flight strip, as appropriate. They may attempt to set up aircraft for pairing and will coordinate with the final controller, who will make the final decision on which aircraft are paired. The feeder controller will issue instructions to the flight crews as necessary and then hand off the aircraft to the final controller. The flight crews are not required to perform any actions for the procedure at this point other than follow routine ATC instructions and brief the paired approach procedure for their expected runway.

2.2.2 Final Approach

Once the aircraft are handed off, the flight crews will then check in with the final controller who will issue instructions to the flight crew of the aircraft to establish them on their final approach. The paired approach procedure will require that the final controller establish the two aircraft in the pair on their final approach courses within a predetermined longitudinal spacing window on long final. A 1000 ft altitude difference is also provided during the final approach course intercept. Airspace will be designed such that the feeder controllers will be able to deliver aircraft to the final controllers with adequate room for the final controllers to be able to meet this spacing requirement. The length of the final approach will be sufficient to ensure that adequate distance is available for the pilot of the trailing aircraft to make the final required adjustments to achieve the correct position relative to the lead.

As soon as possible, but no later than the intercept to the final approach course, the final controller will identify and communicate to both flight crews which aircraft they will be paired with, and which will be the trail aircraft as well as the other aircraft's final approach speed. This pairing may be determined by the aircraft types, positions, and reported final approach speeds.

The final controller will continue to issue vector and speed instructions such that the two aircraft are established on their approach courses and are within the required longitudinal spacing tolerances before the required Controller Decision Point. This is the point where

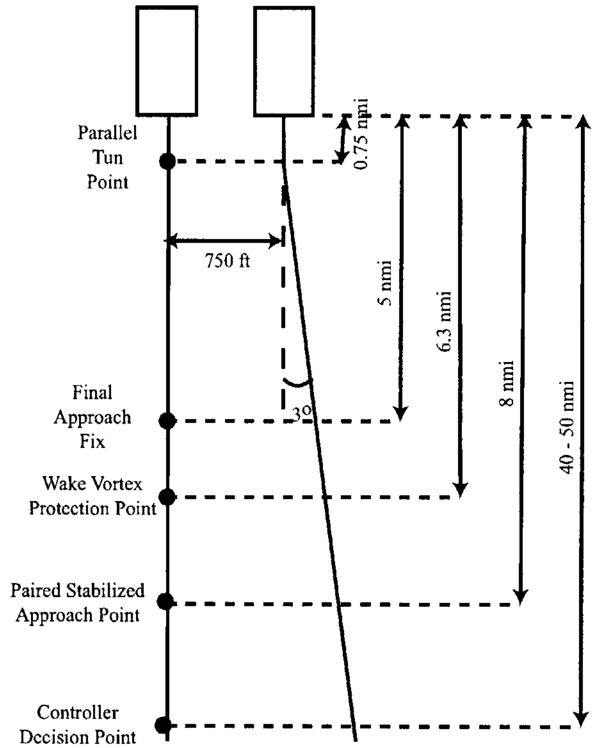

Figure 2-1: Paired Approach Geometry

the final controller must determine whether the aircraft are in a position to conduct the paired approach and is shown in Figure 2-1. If the aircraft are not in position, the controller must either issue a breakout command to an aircraft or establish another required separation (e.g., standard in trail radar separation).

2.2.3 Approach Clearance

Once the aircraft are established on final and the final controller has decided to continue the procedure, the controller will issue speed assignments up to the paired stabilized approach point, also shown in Figure 2-1, for both aircraft. The speeds assigned by the final controller will allow the trail aircraft to achieve adequate separation to continue the procedure. The final controller will clear the lead aircraft flight crew for the paired approach instrument landing system (ILS) for their runway. The lead aircraft flight crew will intercept their localizer and fly the paired approach ILS to their runway. This will include maintaining the localizer and intercepting and maintaining the glideslope.

Once the trail aircraft is established on the final approach course, the flight crew will use a set of specialized paired approach tools to maintain adequate separation until the FAF, also shown in Figure 2-1. These tools are expected to appear on the trail aircraft's CDTI. Once the tools have appeared the trail aircraft flight crew reports "able paired approach." At some point between the paired stabilized approach point and the final approach fix, wake vortex becomes a threat, so adequate spacing is required.

However, prior to the controller clearing the trail aircraft for paired approach, the controller must determine that the lead aircraft is established on the approach. If the lead is established and the trail aircraft has been cleared, the flight crew of the trail aircraft may start its descent. The trail aircraft flight crew now uses the CDTI paired approach tools to maintain a safe longitudinal spacing from the lead aircraft. At this point the final controller has cleared both aircraft for their approaches and has advised them to contact the tower at the required position.

Once the aircraft reaches the FAF, the lead aircraft will follow a predefined deceleration profile and then maintain its final approach speed inside to a normal landing. The trail aircraft is required to have a certain target separation by the FAF. This separation is a predetermined longitudinal separation that will allow the aircraft to fly their deceleration profiles starting at the FAF to their final approach speeds while not concerning themselves with spacing for collision avoidance. Once the trail aircraft attains the target position and reaches the FAF, the spacing task by is discontinued, and the trail aircraft flies a defined deceleration profile to their final approach speed to a normal landing. If the trail aircraft is unable to attain the target position at the FAF, or if the separation is outside an acceptable limit after the FAF, one or both aircraft must execute a breakout maneuver. The breakout maneuver will be defined as either straight out or turning away from the other approach path and climbing.

2.2.4 Geometry

The aircraft will be paired for an approach by ATC with an initial separation of 1000 ft vertically and at least 1 nmi horizontally. The basic approach geometry is shown in Figure 2-1. One of the aircraft will fly an approach that is offset 3° from the runway center line and turns parallel to the runway at approximately 0.75 nmi from the threshold. The 3° offset allows an improvement in lateral separation far from the runways. The other aircraft flies a straight-in approach.

The first notable point on the approach path is the controller decision point. This is the point where the final controller has to decide whether or not the aircraft are in a position to perform a paired approach, have the proper equipage, and compatible final approach speeds. The next point is the stabilized approach point, where the aircraft should have matched ground speeds and, ideally, the trail aircraft will be at the target position.

The 3^o offset approach offers an improvement in protection against a wake vortex encounter over a straight-in approach. Based on FAA regulations, wake vortex encounters are no longer a concern once the aircraft are separated laterally by 2500 ft. This separation or more is possible with the angled approach outside approximately 6 nmi denoted by the wake vortex protection point shown in Figure 2-1. The FAF is the last significant point in the figure. At this location the trail aircraft must be at the target position, if not it must execute a breakout maneuver.

2.3 Necessary Avionics

The aircraft involved in the paired approach procedure will be required to have specific avionics capabilities. One possible system was used by MITRE in initial simulations of the paired approach procedure (Mundra, 1999). The equipment included an ADS-B system which enabled the aircraft to periodically broadcast its aircraft identifier, horizontal and vertical position, velocity, and its final approach speed. Also included in the avionics was a modified CDTI that displayed certain symbols and speed commands in order to help the flight crew maintain the minimum longitudinal spacing. Once the paired approach tools were armed the text, "PAIR" was displayed in white on the CDTI.

The proposed set of CDTI display symbols included brackets that represented the forward and rear bounds of the PZ and an arrow that depicted the target position that the trail aircraft needed to achieve. The target position was determined by a spacing algorithm that used the lead aircraft's final approach speed and the distance to the FAF. The PAIR text turned from white to green once the spacing algorithm was engaged. This signified that the aircraft was engaged in a paired approach. The spacing algorithm also provided speed recommendations that were used to achieve the required target position by the trail aircraft.

A sample of the CDTI paired approach tools is shown in Figure 2-2. The lead aircraft is shown by a small diamond surrounded by a larger diamond, and the trail is shown by the large triangle. The brackets that resemble staples represent the PZ. The one closest to the lead aircraft is the collision boundary and the one overlapping the trail aircraft is the wake vortex boundary. The trail aircraft must use its position in the PZ and the speed cues in order to attain the target position which is shown by a horizontal arrow midway between the brackets. The brackets change shape and color depending on the position of the trail aircraft with respect to the PZ boundaries. The brackets and arrow are displayed in green when the aircraft is in the correct position. The brackets change to a staple shape and are

Figure 2-2: Example of the proposed CDTI for paired approach (Mundra, 1999)

displayed in amber along with the arrow when the aircraft is in the incorrect position. The figure shows an example where the trail aircraft is not in the target position, but is too far away from the lead aircraft. Once the lead aircraft crosses the FAF, the speed commands and target position arrow are removed for the remainder of the approach.

Should the trail aircraft exceed the forward or rear boundaries of the PZ, the bracket closes and turns red to indicate a missed approach should be executed. The speed guidance is removed once this occurs. If the algorithm fails, the PAIR text appears in red and is outlined by a red box. The brackets and speed command are also removed in this case.

2.4 Collision Alerting System

The size of the PZ is dependent on how the collision and wake avoidance calculations are carried out. Ideally the PZ is sized so that the aircraft are protected from a collision regardless of what the other is doing. In reality however, the aircraft are only protected against the magnitude of blunders that are considered in defining the size of the PZ. The inclusion of a CAS could possibly protect against any blunders that exceed the magnitudes of those considered.

There is another potential benefit to the size of the PZ if a CAS is added. Instead of passively protecting against all blunders, a CAS could offer an advanced warning of a blunder at which time a breakout maneuver could then be executed. The advanced warning and use of a breakout maneuver could possibly expand the PZ. It would allow the trail aircraft to be outside of the guaranteed PZ and still be protected by the CAS. This could also

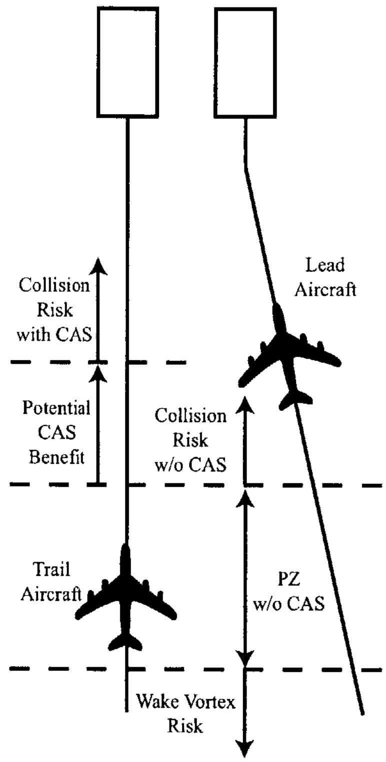

Figure 2-3: Possible Expansion of Protection Zone due to CAS

reduce the number of missed approaches due to PZ violations. A schematic of the possible expansion of the PZ from the addition of a CAS is shown in Figure 2-3.

When designing the CAS some of the functional components that need to be considered include, sensors, processing, displays, and system response time. The sensors are used to determine the relative and available aircraft states while the processing segment uses these states and some predefined alerting thresholds in order to determine if an alert should be issued. The displays are used to convey the alert and any other pertinent information to the pilot when necessary. The system response time includes latencies due to filtering, processing, human performance and aircraft dynamics. All of these components have some amount of time that is required to carry out each operation. These individual times combine and produce a delay time that characterizes the system's performance.

CHAPTER 3

Simulation of Paired Approach

3.1 Overview of Simulation

A fast-time simulation of the paired approach landing procedure was used to determine the forward limit of the PZ. The forward limit in effect is represented by the MLS that must be maintained between the aircraft. This required separation was the final output of the simulation. The simulation was performed in such a manner that the dependence of the required separation on variables such as roll angle (turn rate), aircraft velocity, blunder heading, and distance from the runway 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.

The geometry of the paired approach simulation is shown in Figure 3-1. The origin for the simulation was set at the threshold of the lead aircraft's runway. The simulation began with each aircraft at some initial position and traveling at some initial velocity, which was dependent on the distance the aircraft were from the runway. The initial longitudinal position of the lead aircraft was specified in the form of a distance from the runway. The lateral position was then found by using the 3^{o} offset approach angle and the specified distance from the runway, assuming the aircraft was centered on its approach path. The initial position of the trail aircraft was then found from a specified longitudinal separation behind the lead aircraft and the lateral spacing between the two runways (750 ft), again assuming no lateral position error. The initial altitudes of both aircraft were determined from their distance from the runway and the assumption of a 3^{o} glideslope angle.

The simulation began with the lead aircraft beginning its blunder maneuver. The starting positions of each aircraft were calculated from the variables stated above, which are also shown in Figure 3-1. The position of each aircraft was updated using an Euler integration with a timestep of 0.1 seconds.

The blunder consisted of a constant altitude, constant velocity, instantaneous roll-in turn to a pre-specified blunder heading, ψ, relative to the runway centerline. Throughout the turn, the turn rate was held constant, and was determined by the roll angle, ϕ. The lead aircraft was already assumed to be at the appropriate roll angle when the simulation began. While the lead aircraft was flying the blunder trajectory, the trail was either flying a straight-in approach or a breakout maneuver, which will be discussed later. At each timestep throughout the trajectories, the distance between the aircraft was calculated to determine whether a collision had occurred. A collision was defined to occur any time the absolute separation between the two aircraft was less than 500 ft.

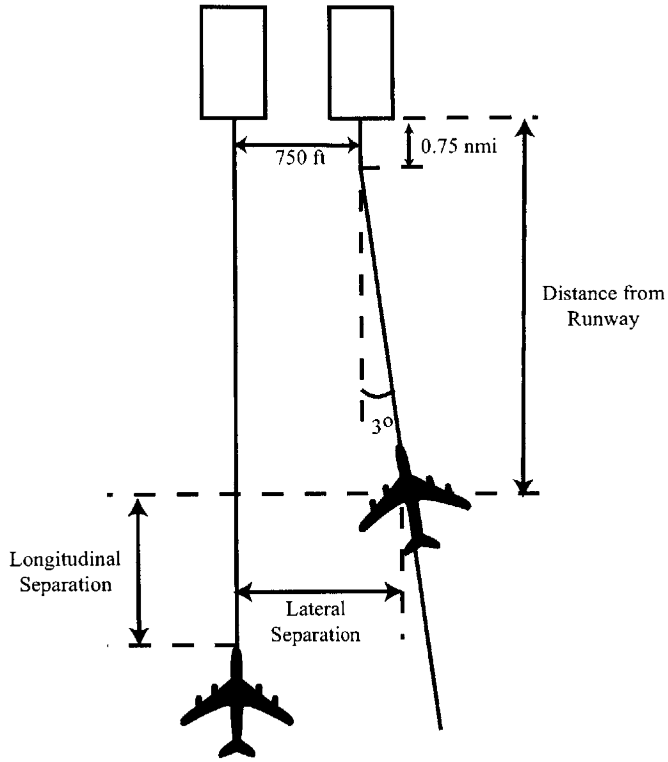

Figure 3-1: Initial Approach Geometry

The values of the aircraft velocities depended on the distance each aircraft was from the runway threshold. Outside the FAF (5 nmi) the velocity of each aircraft was held constant at the initial approach speed (170 kt). Once the aircraft reached the FAF, they flew a deceleration profile to a predetermined final approach speed which was different for each aircraft. The trail aircraft's final velocity was generally faster than that of the lead aircraft. As a worst case, the trail's final velocity was 125 kt and the lead's was 115 kt. A nominal deceleration of 1 kt/sec was used to determine the velocity of each aircraft as they decelerated from their initial velocities to their final approach speeds. These numerical values were used in order to remain consistent with a previous study performed by MITRE

(Hammer, 1999). When each aircraft reached its final approach velocity, that velocity was held constant for the remainder of the approach.

The lead aircraft reached the FAF first and therefore began to decelerate before the trail aircraft. This caused a compression effect between the aircraft, whereby the longitudinal spacing between the two aircraft decreased. This compression occurred because the aircraft started their decelerations at different times and had different final approach speeds. The compression is shown in Figure 3-2. For example, with an initial separation of 5000 ft at 6 nmi from the runway, the aircraft will be separated by only 1000 ft at the runway threshold. The figure also shows that if the lead aircraft's final velocity is faster than the trail an expansion in longitudinal separation occurs. This expansion increases the risk of a wake vortex encounter when the aircraft are close to the runway threshold.

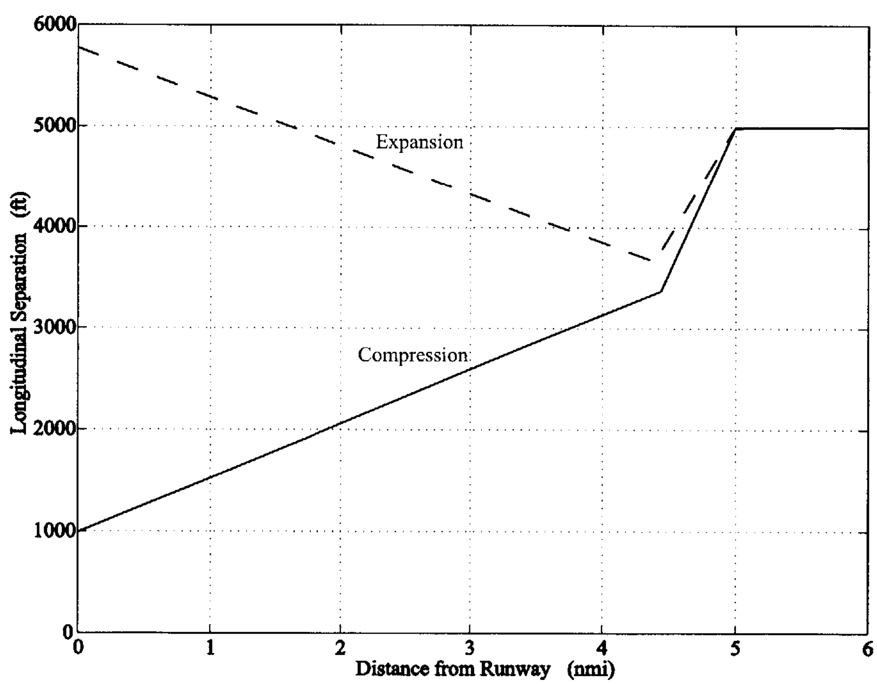

Figure 3-2: Illustration of Compression and Expansion Due to Aircraft Decelerations

Each time a collision occurred, the trajectories of each aircraft were saved so that they could be examined later. A sample trajectory for each aircraft is shown in Figure 3-3. The figure shows a case where the lead aircraft is 3 nmi from the runway, this corresponds to a lateral separation of approximately 1400 ft. The lead aircraft blunders with a roll angle of 30°, and a blunder heading of 45°, toward the trail aircraft which, in this situation simply continued on its original flight path. The diamond shapes indicate the position of each of the aircraft when the collision occurred: the aircraft were separated by less than 500 ft. The initial longitudinal separation that resulted in the collision can be determined from the initial position of the trail aircraft which in this case was approximately 1200 ft behind the lead aircraft. The trajectories that were saved represent a limiting case where the collision just occurs. At a larger initial longitudinal separation, a collision would not occur. Thus, 1200 ft represents the MLS for this approach condition and blunder type.

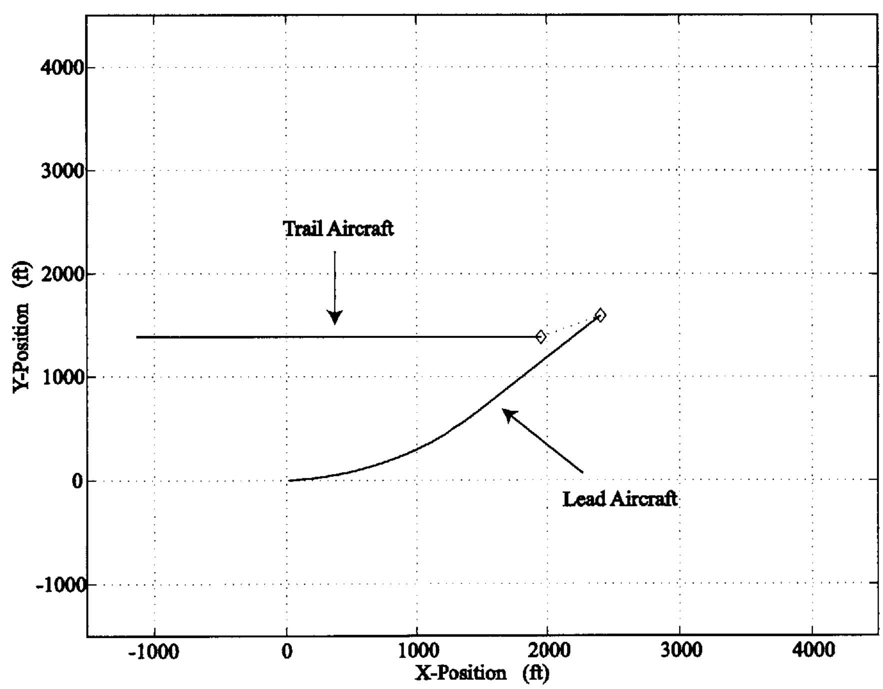

Figure 3-3: Sample Plot of Simulated Trajectory

Figure 3-4 shows a composite of the collision trajectories at several distances from the runway for the same blunder conditions. The coordinates of each trajectory are shifted in order to display the trajectories for several distances from the runway on one plot. The shift was done in such a way that all of the blunder trajectories begin at the same point on the final plot. In the figure there are several different curves that represent the lead aircraft blunder trajectories. There is more than one blunder curve because the lead aircraft has a different velocity at each distance from the runway and therefore for each blunder. This change in velocity results in slightly different turn rates for each blunder. The trail aircraft trajectories are spread out along the y-axis because as the aircraft get farther from the runway the lateral spacing between them increases. In this way, the MLS over a variety of conditions can be examined.

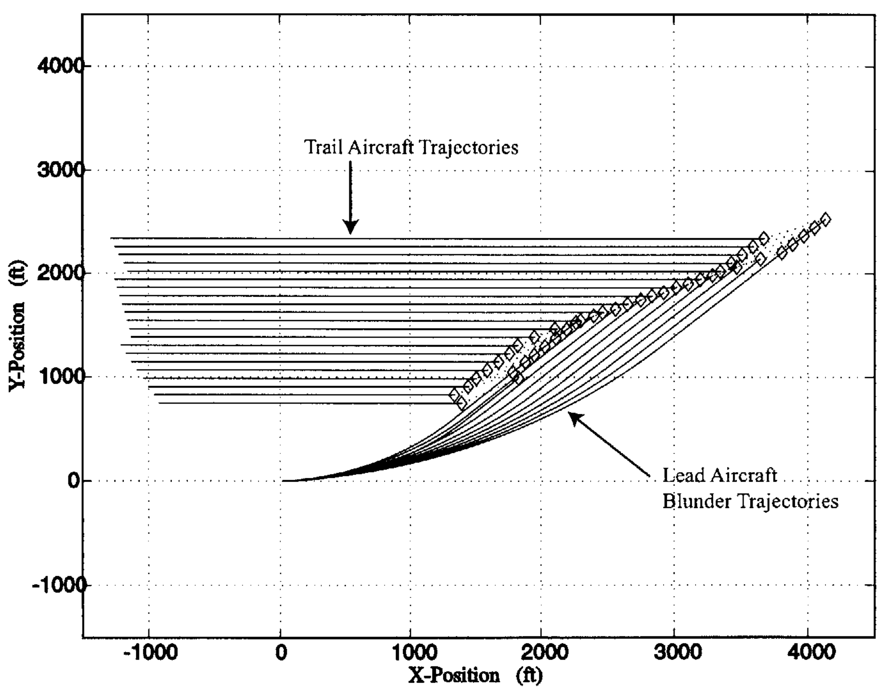

Figure 3-4: Sample Plot of Multiple Simulated Trajectories

3.2 Minimum Longitudinal Spacing

The simulation was started with a longitudinal separation between the aircraft that was 1 nmi, large enough so that a collision could not occur. The longitudinal separation was decreased in increments of 0.1 nmi and the simulation rerun, until a collision occurred at some point in the trajectories. If no collision occurred even with a longitudinal separation of zero, the PZ limit was defined as a MLS of zero. If a collision occurred, a "bisection" code was used in order to pinpoint the exact longitudinal separation that induced a collision. The bisection algorithm used the separation for which the collision occurred and the previous separation for which no collision occurred as its input. It continually cut the interval between the two endpoints in half, always reassigning the point for which a collision occurred and the one for which it did not occur as the new endpoints. This reduction process for the longitudinal separation is shown in Figure 3-5.

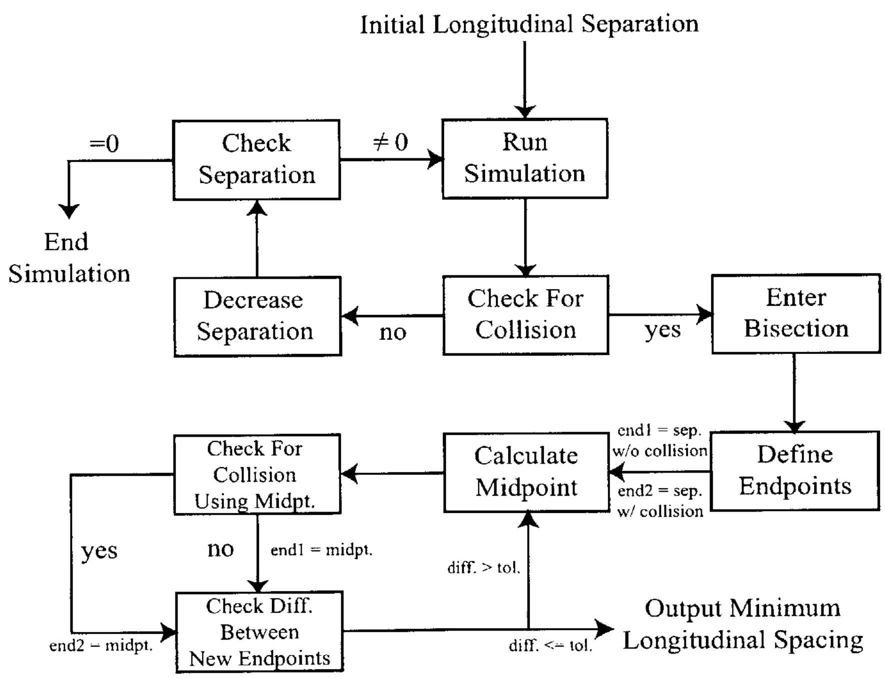

Figure 3-5: Flowchart for Reduction in Longitudinal Separation

Once the bisection code had reached a specified tolerance, 1 ft, the simulation ended and the MLS was recorded. This data represented the forward limit of the PZ and can be graphed as a function of distance of the lead aircraft from the runway, along with other variables. A sample plot is shown in Figure 3-6. The figure shows the MLS for various blunder headings, a roll angle of 30°, a lead aircraft final velocity of 115 kt, and a trail aircraft final velocity of 125 kt. Each curve represents the forward limit of the PZ for the accompanying variables. For example, at 3 nmi from the runway, and a blunder heading of 30°, the trail aircraft must be at least 1000 ft behind the lead aircraft.

An increase in MLS means that the trail must remain farther behind the lead in order to remain in the PZ. The slope changes that can be seen in the figure for each curve around 5 nmi. and 3 nmi. are due to the beginning and end of the aircraft decelerations. Generally,

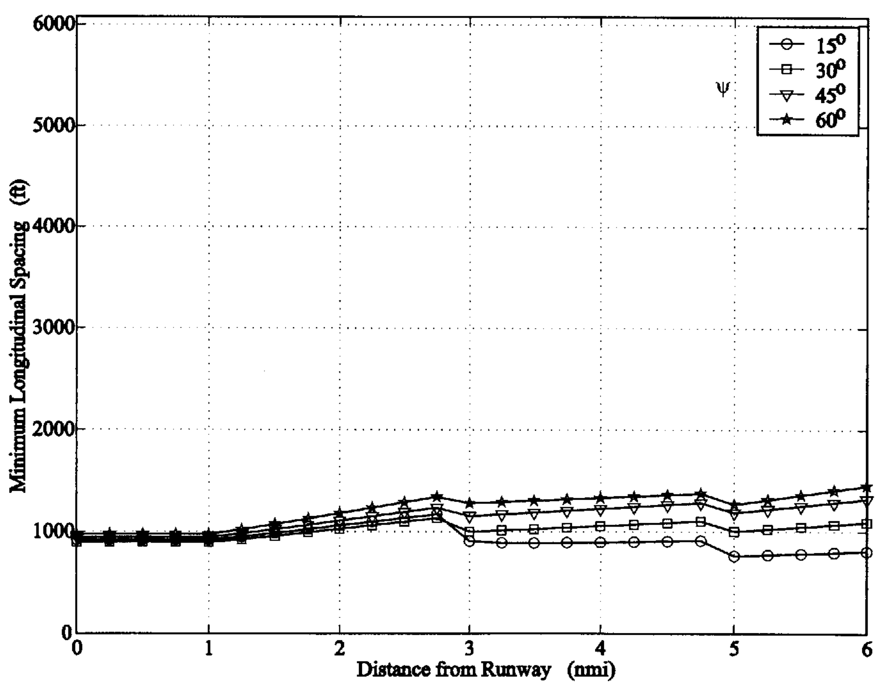

Figure 3-6: Sample Plot of MLS

the more extreme the blunder and the faster the trail velocity relative to the lead velocity, the larger the MLS.

3.3 Variation of Blunders

Several different blunder types were considered during the simulation of the paired approach procedure. The first blunder type was where the lead aircraft performed a turn at some roll angle to a specified heading, where it would then continue straight on that heading. Several different combinations of roll angles (5^o, 15^o, 30^o, 45^o) and blunder headings (15^o, 30^o, 45^o, 60^o) were considered for this blunder type in order to determine the dependence of the PZ size on each of these variables. The aircraft velocity was determined from the distance from the runway and held constant throughout the blunder maneuver. During the blunder maneuvers, an instantaneous roll in and roll out was used when starting and ending the turns.

Previous research has shown that a sudden severe blunder may not be the worst case blunder, but instead it may be a slow drifting blunder that causes the most problems with some alerting system algorithms (Winder & Kuchar, 1999). Therefore it was desirable to look at a couple of other blunder types to determine if the turn blunder was an accurate representation of a "worst case" blunder. The first alternate blunder considered was a "sidestep" blunder. It consisted of a turn and straighten maneuver in which the aircraft turned at some roll angle to a heading, then after some preset time the aircraft turned back to its original heading parallel to the runway centerline. The second alternate blunder was an "oscillation" blunder in which the aircraft turned for some preset time and then turned back for the same time interval, essentially flying a sinusoidal path. A plot of all three blunder types are shown in Figure 3-7.

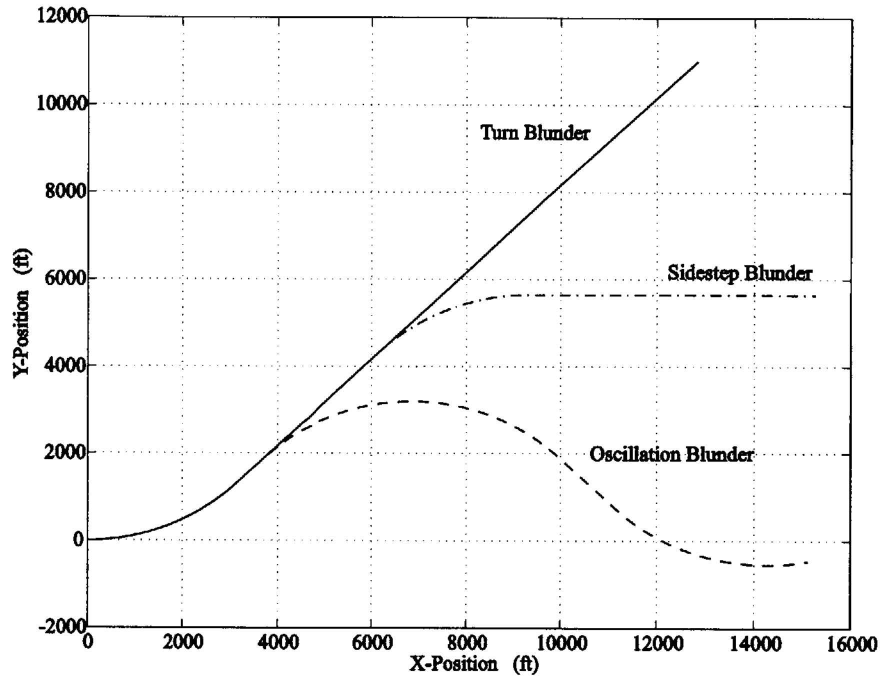

Figure 3-7: Sample Trajectories for Different Blunder Maneuvers

CHAPTER 4

Baseline Separation Requirements

4.1 No Breakout Maneuver

In its simplest form the PZ would be designed so that no breakout maneuver is required for protection. The trail therefore continues to fly a straight-in approach without any breakout which is representative of the case where no CAS is present. These results establish a baseline MLS that was used as a standard of comparison for all of the other cases that involved a CAS. Any improvement that resulted from the inclusion of a CAS was measured against this standard. The results from the study were also used to determine the dependence of the baseline PZ size on different variables such as roll angle, blunder heading, and distance from runway.

The standard scenario consisted of the lead aircraft blundering, while the trail performed a normal approach. The variables used were a roll angle of 30^{o}, a blunder heading of 30^{o}, a trail aircraft final approach speed of 125 kt, and a lead final approach speed of 115 kt. To determine the dependence on roll angle and blunder heading, the values of these variables were then varied independently from each other. The dependence of MLS on these variables is summarized in the following sections.

4.2 Dependence on Blunder Roll Angle

The dependence of the MLS on blunder roll angle was examined using a blunder heading of 30°, and roll angles of 5°, 15°, 30°, and 45°. The results are shown in Figure 4-1. The figure shows that far from the runway, outside 3 nmi, the size of the MLS increases moderately with increasing roll angle. For a roll angle of 5° it is approximately 900 ft and for a roll angle of 45° increases to approximately 1100 ft. After the aircraft have reached their final approach velocities, the trail is traveling faster than the lead and the MLS actually decreases with increasing roll angle. This is because the lead aircraft is moving in front of

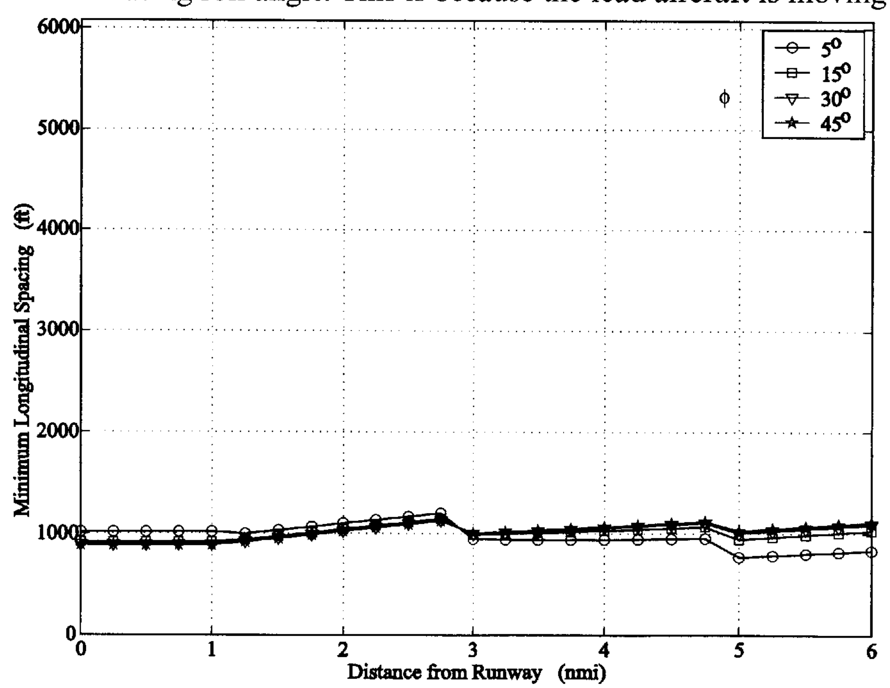

Figure 4-1: Separation Curves for Different Blunder Roll Angles (Baseline Conditions)

the trail aircraft faster with higher roll angle. It should be noted that the variations in roll angle that were considered only resulted in changes in MLS of approximately 200 ft.

4.3 Dependence on Blunder Heading

The dependence of the MLS on blunder heading was examined using a blunder roll angle of 30°, and blunder headings of 15°, 30°, 45°, and 60°. Figure 4-2 shows the results of this case. The figure shows that the MLS decreases as the blunder heading increases. The MLS is fairly constant over all distances from the runway, however it docs become more sensitive to blunder heading with increased distance from the runway. At 6 nmi there is a change of approximately 600 ft in MLS from the highest blunder heading to the lowest blunder heading, whereas at 2 nmi the change in MLS is less than 200 ft.

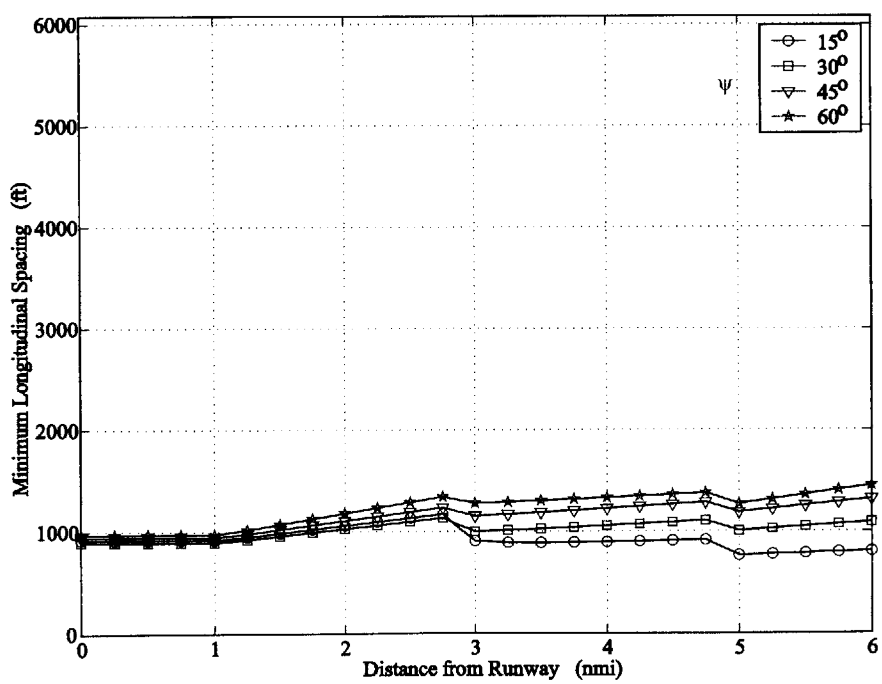

Figure 4-2: Separation Curves for Different Blunder Headings (Baseline Conditions)

4.4 Dependence on Speed and Lateral Offset

The figures for different roll angles and blunder headings show that the trail aircraft must be between 1000 and 1500 ft behind the lead, depending on how extreme the blunder is and the distance from the runway. There were two other variables that were varied in order to determine their effects on the MLS. They were the final approach speeds of the aircraft and the lateral spacing between the aircraft.

The simulation was run for lead and trail aircraft final approach speed pairs of 115 and 125 kt respectively, 135 and 145 kt respectively and it was also run with both aircraft having a final approach speed of 145 kt. The results of the three different velocity simulations are shown in Figure 4-3. The figure shows that the results did not change drastically for the two cases where each aircraft's final approach speeds were different. In the region where the aircraft are flying at their final approach speeds, inside 3 nmi, the MLS is slightly less for the higher final approach speeds. Another noticeable difference between the two cases was the distance from the runway at which the second "bump" in the curves took place, and the height of this second bump. It occurred farther from the runway for the higher final approach velocities because it did not take the aircraft as long to reach their final approach speeds, and was higher for the faster final approach speeds. The final approach velocities were set equal at 145 kt in order to determine what effect the difference in the final approach speeds had on the results. The 145 and 145 line in the figure shows that as the difference in the final approach speeds decreases so does the MLS.

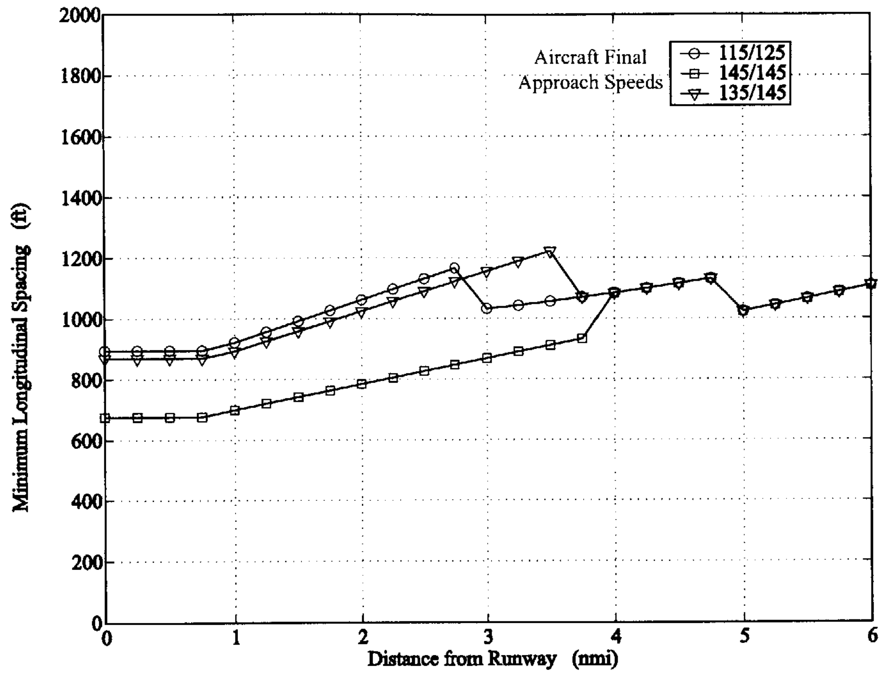

Figure 4-3: Separation Curves for Different Final Approach Speeds (Baseline Conditions)

The aircraft were also laterally shifted off their approach paths in order to simulate flight technical error. A decrease in the lateral spacing between the aircraft resulted in an increase in the MLS between the aircraft. The increase in MLS was not very significant, less than 100 ft usually, for every 100 ft that the aircraft were shifted off their approach paths. When the aircraft are offset toward one another the wake has less distance to travel and the wake vortex boundary of the PZ could move forward. This combined with the increase in MLS could decrease the size of the PZ considerably. This is one of the more compelling reasons to design a CAS that would expand the front of the PZ.

Figure 4-4 shows the approximate size of the PZ with the Wake Avoidance Boundary and the Collision Avoidance Boundary displayed. The Wake Avoidance Boundary was taken from previous work at MITRE (Hammer, 1999), and represents the maximum allowable separation between the aircraft (Hammer, 1999). The wake vortex is assumed to travel laterally at a 10 knot transport velocity, using the aircraft velocities and their separation it is possible to make a crude estimate of the boundary. An example of actual aircraft separation is shown in order to demonstrate how the separation must be much larger than the forward limit far from the runway in order to have adequate separation closer to the runway.

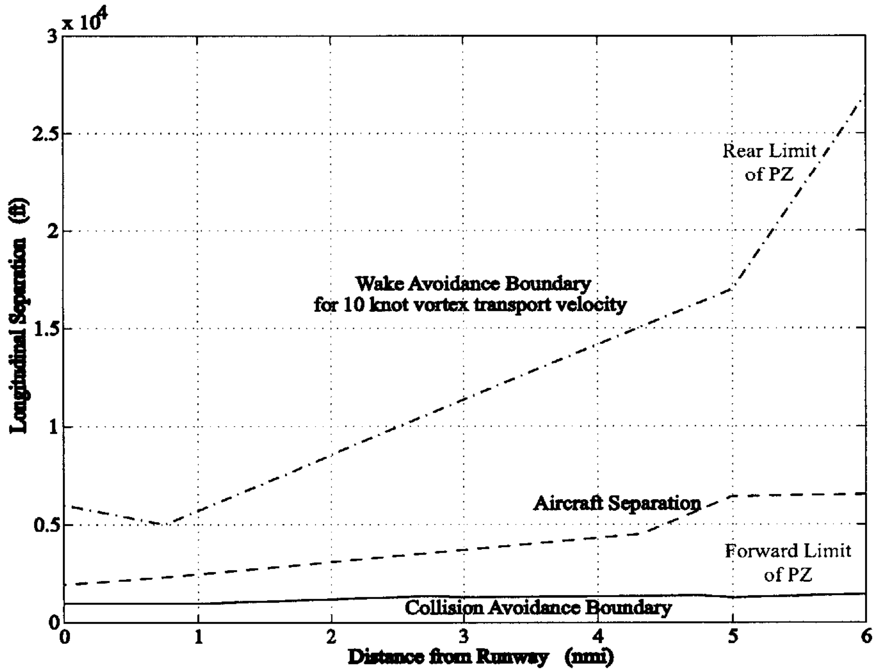

Figure 4-4: Illustration of PZ Size (Baseline Conditions)

4.5 Dependence on Blunder Maneuver

The turn blunder resulted in the largest MLS for all of the variables considered in this simulation. The variable that defined the trajectory for the sidestep and oscillation blunders was a time constant that determined the trajectory of the lead aircraft. As this time constant increased the MLS for these two blunders approached that of the turn blunder. This is because as the time constant increases the blunder trajectories approach that of the turn blunder.

CHAPTER 5

Minimum Longitudinal Spacing With The Addition of a Collision Avoidance System

5.1 Breakout Maneuver Analysis

The CAS analysis consisted of determining which breakout maneuver should be used in the event a warning is issued, and the total system delay that was acceptable. Initially, an analysis of three different breakout maneuvers was conducted. This analysis served a dual purpose. First it could determine the design requirements necessary in order for the addition of a CAS to be beneficial. Second, if there was a benefit to be realized, it could determine which maneuver should be performed in order to maximize that benefit. The three different representative breakout maneuvers that were considered were: 1) Climb Breakout, 2) Turn Breakout, 3) Full Breakout.

The climb breakout was examined because it is representative of a missed approach where the aircraft continue straight on their heading while performing a climb maneuver. This could offer a breakout maneuver that would involve the least amount of incurred pilot work load, since it is only a climb maneuver. Prior research showed that a climbing turn breakout was much more effective than a climb-only maneuver because the addition of the turn can reduce the closure rate between the aircraft (Winder & Kuchar, 1999). In this paper the climbing turn is referred to as a full breakout. The turn breakout is representative of the case where the blundering aircraft is gaining or losing altitude at the same rate as the aircraft that is breaking out, in effect cancelling out any altitude difference that might be gained by the climb component of the full breakout.

The simulation of the breakout maneuver was similar to that of the blunder. The aircraft velocity for the breakout was held constant throughout the breakout. The climb breakout consisted of a pull-up at a specific climb load factor of 1.25 g, to a specified climb rate of 2000 ft/min, until an altitude change of 500 ft had been achieved. The altitude change of 500 ft was chosen because it ensures enough separation between the aircraft to avoid a collision. The turn breakout consisted of an instantaneous roll to an angle of 30^{o}, which resulted in a constant rate turn to a breakout heading 45^{o}, after which the aircraft continued on that heading, all at constant altitude. The full breakout was simply a combination of the climb and turn breakouts performed simultaneously. The parameters of each breakout considered are shown in Table 5-1.

An additional variable was considered while examining the different breakout maneuvers. The time delay between the beginning of the blunder and the beginning of the breakout had to be specified. This time delay represented the total system latency in a CAS and the human operator. In all of the following analyses, blunders involved a 30^{o} bank angle to a heading of 30^{o} from the runway centerline unless otherwise noted.

Table 5-1: Breakout Maneuver Parameters.

	load factor (g)	*climb rate* (ft/min)	ϕ (deg)	ψ (deg)
Climb Breakout	1.25	2000	0	0
Turn Breakout	N/A	0	30	45
Full Breakout	1.25	2000	30	45

5.2 Climb Breakout

5.2.1 Blunder Roll Angles

Figure 5-1 shows the results of the climb breakout for different blunder roll angles. he climb breakout offered some improvement over no breakout for different blunder roll angles. Compared to Figure 4-1, there was an improvement of about 200 ft for the higher roll angles (30^{o} and 45^{o}). Outside of about 4.5 nmi the improvement for the 15^{o} roll angle was more significant, bringing the MLS to zero. This means that even if the longitudinal separation between the aircraft had gone to zero (the aircraft were side by side) there was no collision in the simulation. The smallest roll angle (5^{o}) didn't result in a collision for any distances from the runway because there was always enough time for the trail aircraft to climb 500 ft. It can be seen in the figure that the MLS decreases slightly with increasing distance from the runway for the higher roll angles.

5.2.2 Blunder Headings

The climb breakout results for different blunder headings is shown in Figure 5-1. Compared to Figure 4-2, there is an improvement of approximately 100 to 200 ft for the higher blunder headings. There is a more significant improvement in the MLS for the lowest

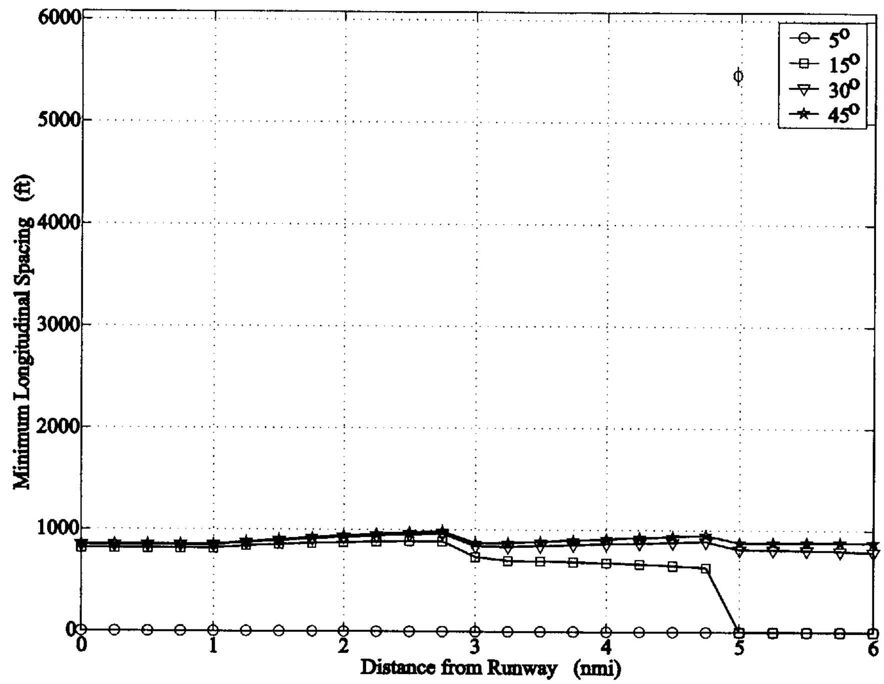

Figure 5-1: Separation Curves for Different Blunder Roll Angles and Climb breakout

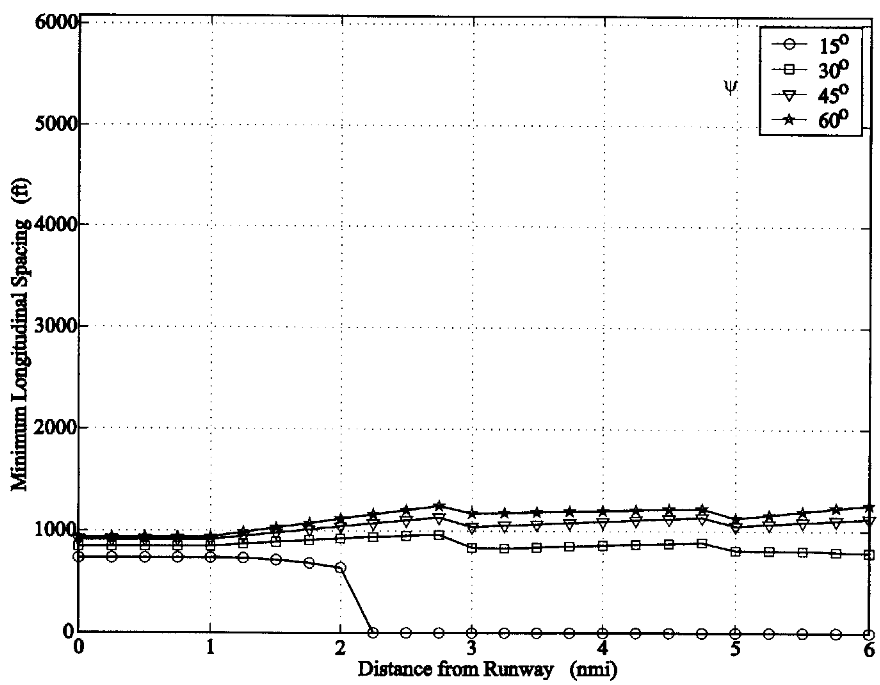

Figure 5-2: Separation Curves for Different Blunder Headings and Climb breakout

blunder heading outside about 2 nmi from the runway. The improvement is close to 1000 ft at some from the runway. This large improvement is possible because the trail aircraft has enough time to gain sufficient altitude in order to avoid a collision. This benefit is not realized inside of 2 nmi because of the reduction in lateral spacing close to the runway.

5.2.3 Delay Times

Figure 5-3 shows the climb breakout with different system delay times, for a 30° roll angle and 30° heading blunder. There is again an improvement of only approximately 200 ft. in the MLS for delay times of 10 seconds or less. There is virtually no improvement at all, for delay times of 15 seconds or greater.

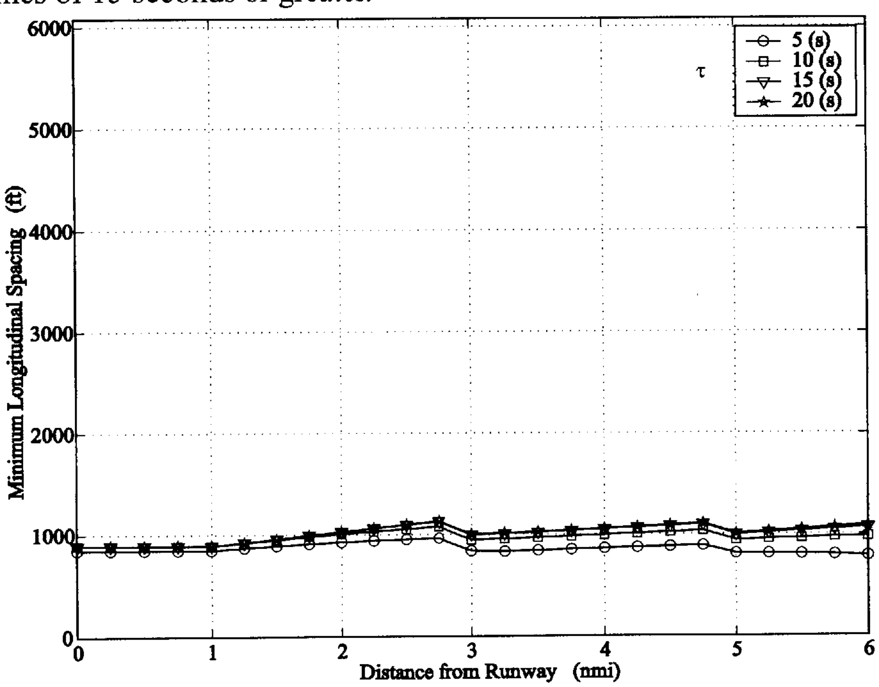

Figure 5-3: Separation Curves for Different Delay Times and Climb breakout

5.3 Turn Breakout

5.3.1 Blunder Roll Angles

The turn breakout for different blunder roll angles are shown in Figure 5-4. This maneuver offered significant improvement in MLS compared to the climb breakout maneuver. There is a large improvement over all distances from the runway for blunder roll angles that are less than that of the breakout roll angle (30^o). This is because the trail aircraft is turning at a rate equal to or greater than that of the lead aircraft. Close to the runway (inside approximately 2 nmi) there is minimal improvement for blunder roll angles that are greater than or equal to the breakout roll angle. Farther from the runway the improvement is significant even for the blunder roll angles that are greater than the breakout roll angles. The figure also shows that for any of the roll angles that were considered, the turn breakout reduces the MLS to zero outside of 2 nmi.

5.3.2 Blunder Headings

The turn breakout shows mixed results for different blunder headings. There is a significant advantage for the smallest blunder heading considered at all distances from the runway. Closer to the runway there is little or no improvement for blunder headings between 30^o and 45^o, as seen in Figure 5-5. It can also be seen in the figure that for blunder headings greater than that of the breakout heading there is a severe increase in the MLS. This is a result of a combination of factors. It should first be noted that this only occurs if the breakout turn heading is less than the blunder turn heading. The two main factors in these problem trajectories are: 1) the trail is traveling faster than the lead, and 2) the lead is turn-

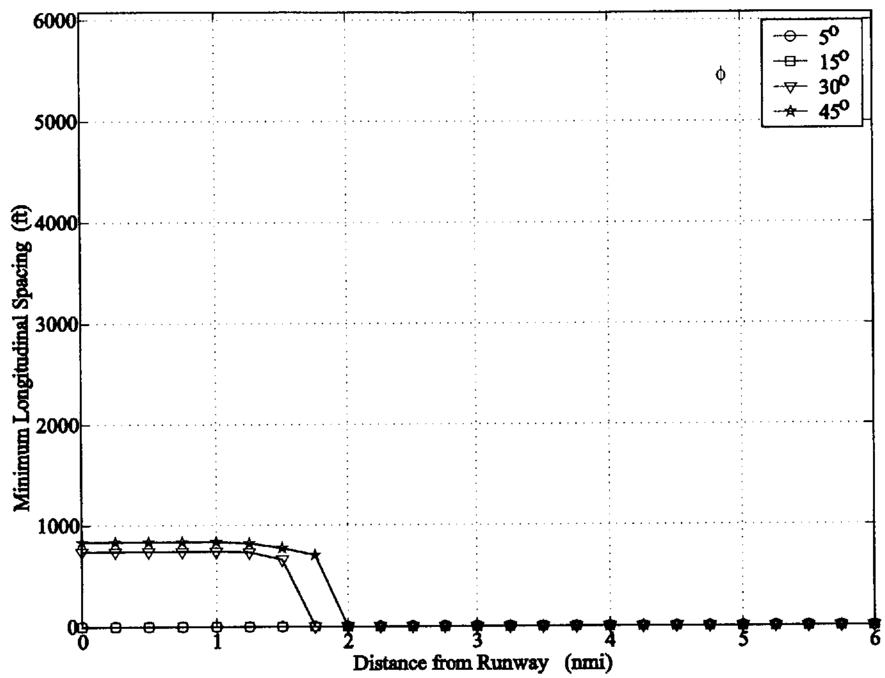

Figure 5-4: Separation Curves for Different Blunder Roll Angles and Turn Breakout

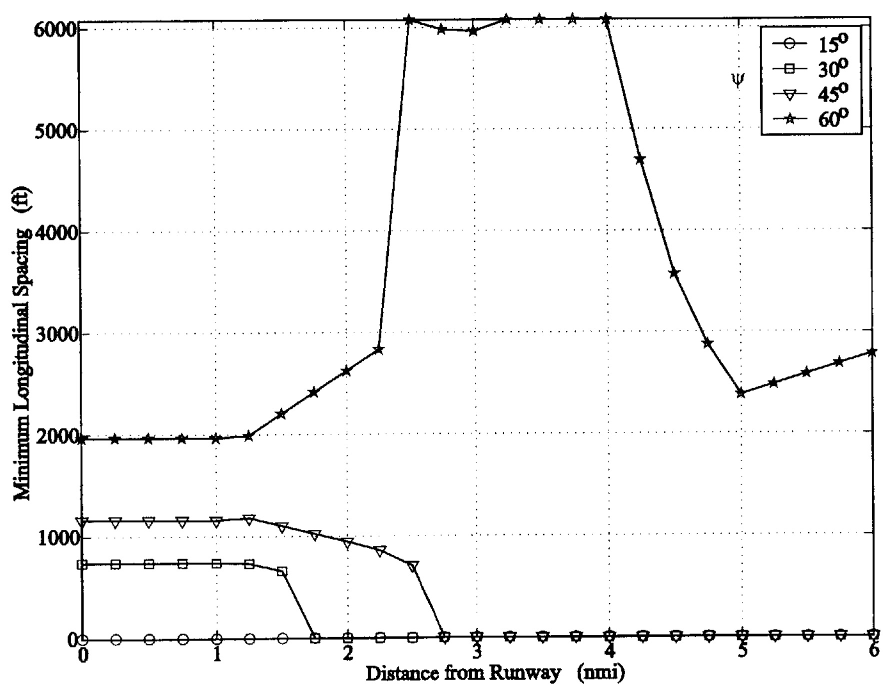

Figure 5-5: Separation Curves for Different Blunder Headings and Turn Breakout

ing farther than the trail. These two factors combine to put the aircraft on converging paths which results in a collision. It should be noted however that the time for these collisions to occur is comparatively very large (~60 seconds.). A sample of trajectories for this situation is shown in Figure 5-6. The figure shows that the trajectories are converging and are quite long corresponding to a large time for a collision to occur. It is likely that during this time period, other factors would come into play to prevent a collision (e.g., air traffic controller instructions).

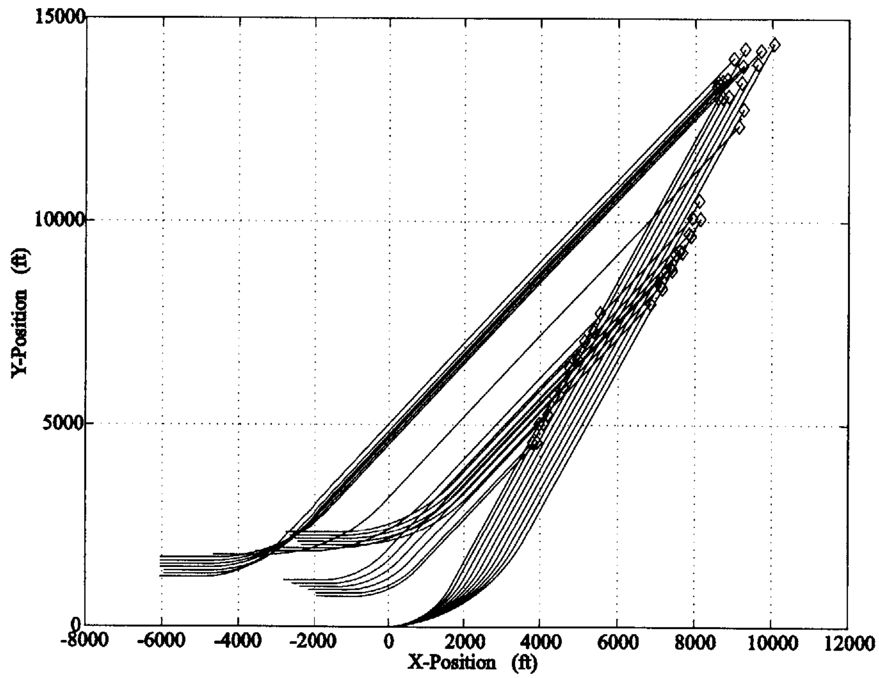

Figure 5-6: Trajectories That Cause Large Separation Requirements

5.3.3 Delay Times

The turn breakout for different delay times is shown in Figure 5-7. The figure shows that for delay times greater than 10 seconds there is little improvement in MLS. A delay time of 10 seconds offers some improvement outside of 2 nmi. This improvement for 10 seconds increases with distance from the runway. A delay time of 5 seconds offers no improvement inside of 1.5 nmi. Outside that distance there are no collisions for a delay time of 5 seconds.

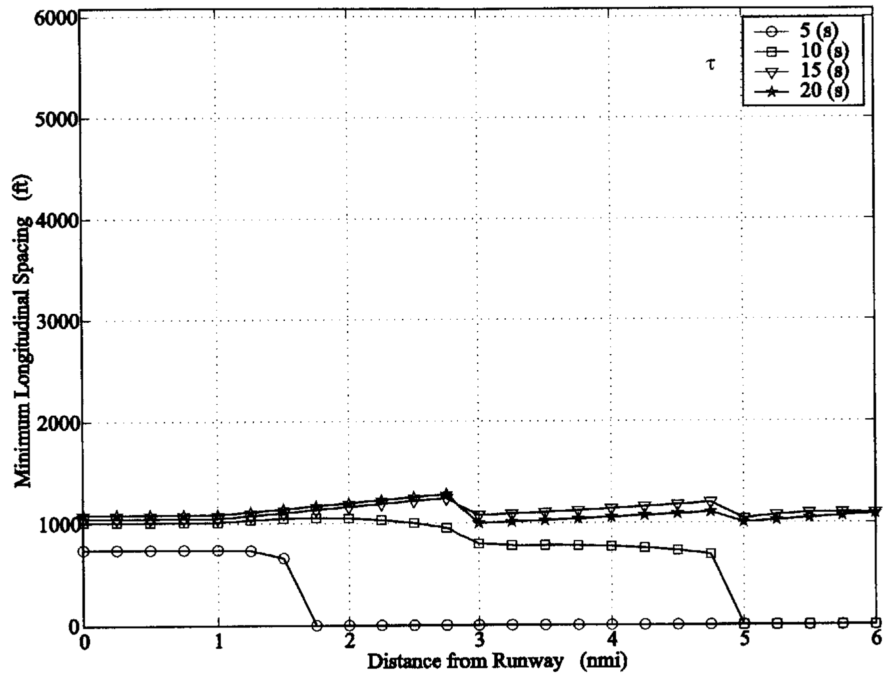

Figure 5-7: Separation Curves for Different Delay Times and Turn Breakout

5.4 Full Breakout

5.4.1 Blunder Roll Angles

The full breakout for different blunder roll angles is shown in Figure 5-8. The full breakout is a combination of both the turn and climb break outs and exhibits some of the characteristics of each. Far from the runway the full breakout provides the same improvement as the turn breakout. There is a large benefit for all roll angles. The behavior is similar to the turn close to the runway, and the addition of the climb component allows a slightly larger decrease in MLS than with the turn alone.

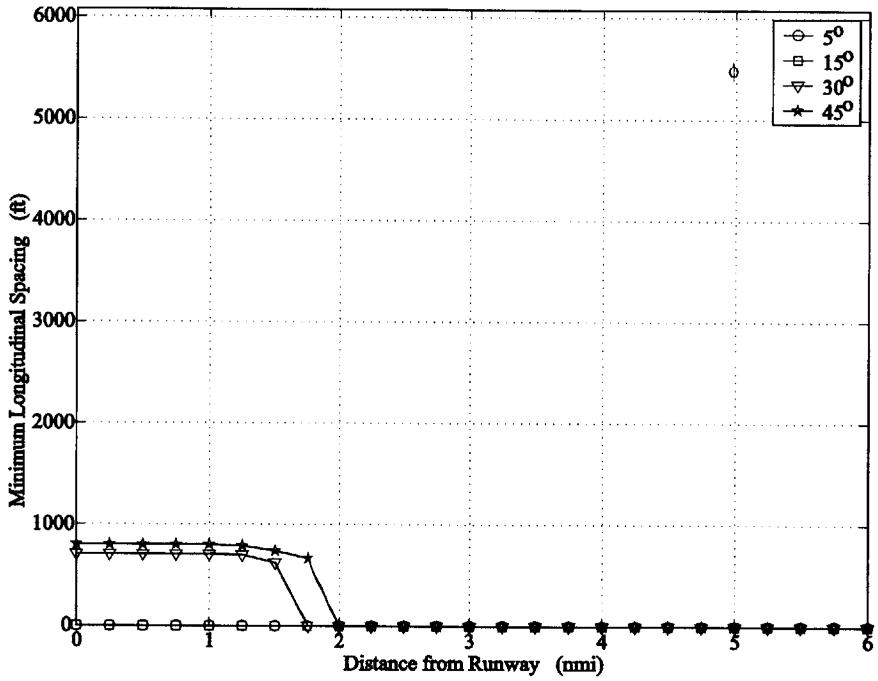

Figure 5-8: Separation Curves for Different Roll Angles and Full Breakout

5.4.2 Blunder Headings

The full breakout for different blunder headings is shown in Figure 5-9. Again because the full breakout is a combination of the climb and turn breakouts it offers some protection from the problems of the turn breakout. The full breakout eliminates the increase in MLS that occurred for blunder headings that were larger than the breakout headings. This is because the aircraft that is breaking out gains enough altitude with the climb maneuver before the aircraft converge and collide. Close to the runway there is a slight increase in the MLS for the higher blunder headings. This is because the aircraft are on converging trajectories and close to the runway, because the lateral separation is lower, the trail aircraft does not have enough time to climb out of danger.

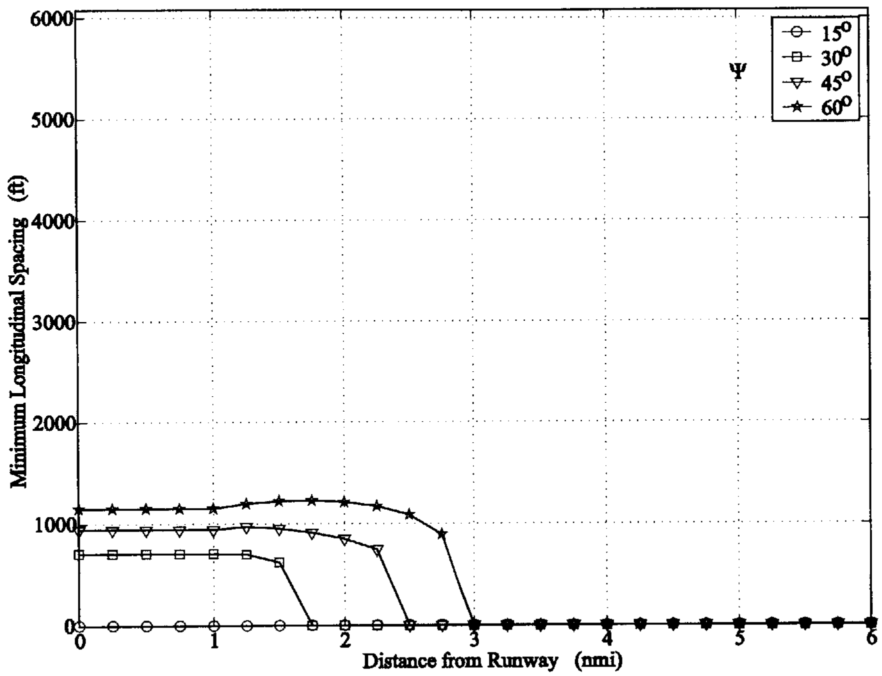

Figure 5-9: Separation Curves for Different Blunder Headings and Full Breakout

5.4.3 Delay Times

The full breakout for different delay times is shown in Figure 5-10. The only improvement over the turn breakout maneuver is a decrease in MLS at approximately 4 (nmi) from the runway for a 10 seconds delay time.

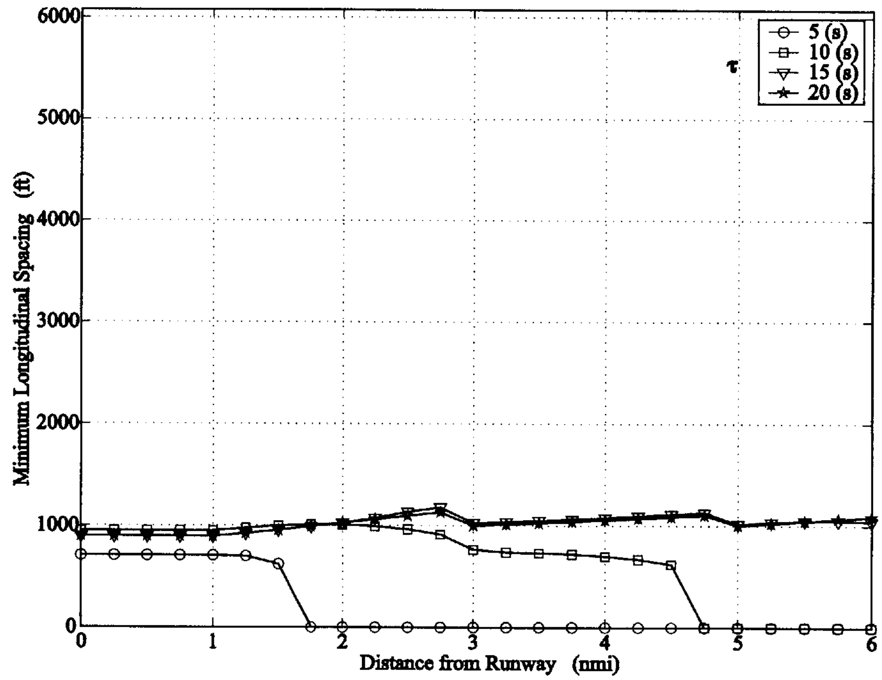

Figure 5-10: Separation Curves for Different Delay Times and Full Breakout

5.5 Sidestep and Oscillation Blunders

The results for these two blunder maneuvers, when a breakout was executed were very similar to the results when no breakout was used. The turn blunder again has a larger MLS for the variables considered. However, there was an instance where the MLS for the side-step blunder became very large (5000 ft). This occurred when the sidestep maneuver placed the lead aircraft on or near the trail aircraft's trajectory. The trail was moving faster than the lead and was therefore able to catch up to the lead aircraft. It should be noted however that in these situations the time for the trail to catch the lead and a collision to occur was quite large, and an ATC instruction to correct the situation is likely during that time.

5.6 Missed Approaches

During a paired approach there is always the possibility that one or both of the aircraft could perform a missed approach procedure. It was therefore necessary to determine the effects of either aircraft performing a missed approach at any point in the procedure. As modeled a missed approach consists of a 1.25 g load factor pull-up to a climb rate of 2000 ft/min with a level-off after 500 ft of altitude has been gained. Due to the potential loss of accurate lateral guidance during a missed approach, the trajectories also included a small turning component. Three different missed approach cases were considered: 1) The lead performed a missed approach and the trail continued on its approach, 2) The trail performed missed approach and the lead continued on its approach, 3) The trail and the lead aircraft performed missed approaches simultaneously and at staggered times.

The effect on MLS for three different missed approach scenarios can be seen in Figure 5-11. The missed approaches were examined with a roll angle of 30^o, a heading change of 15^o, and a time delay of 0 seconds. The 15^o heading reflects the reduced level of directional guidance expected during a missed approach. The error was always assumed to be in the direction of the other aircraft when performing the missed approach. Figure 5-11 shows that MLS is less for all of the missed approach cases than that for the blunder cases, and so missed approaches does not appear to be a driving factor for CAS requirements.

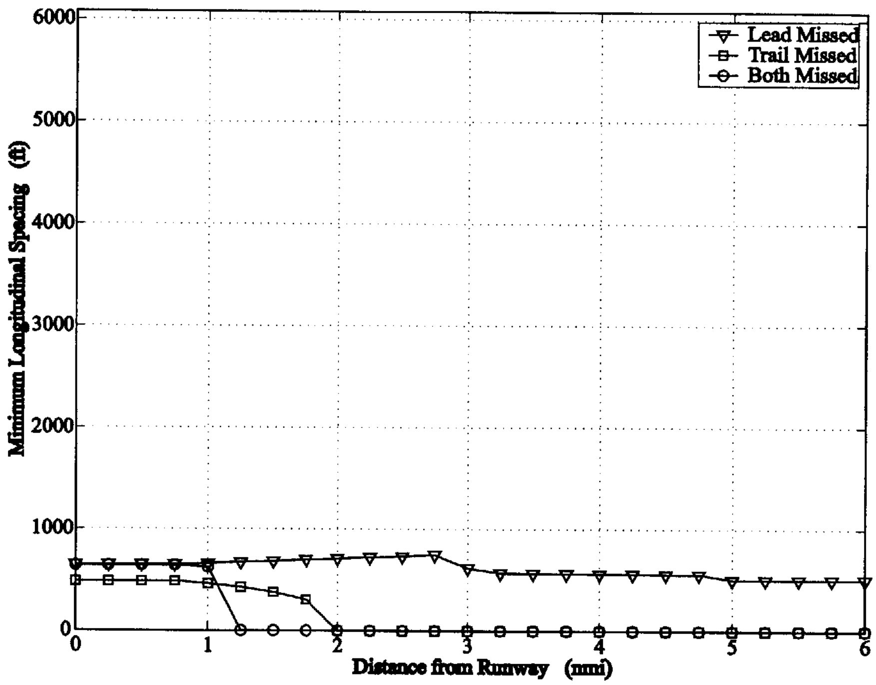

Figure 5-11: Separation Curves for Different Missed Approach Situations

CHAPTER 6

Conclusions

Examining the results in the previous chapters provides insight into several of the issues related to the MLS between the aircraft. The effectiveness of a CAS depends strongly on the assumptions made regarding the type of blunder that occurred, the type of breakout used, the overall system delay times and the accuracy with which any of the maneuvers are flown.

The results of the simulations show that the full breakout offers the most protection for all of the blunders considered. For blunders with turn headings less than that of the breakout turn heading it was found to be effective over all distances from the runway as long as the total system delay time was less than 10 seconds. This small delay time is a very strict design requirement to adhere to. The delays due to filtering and human response could easily reach 10 seconds. The full breakout does increase the MLS slightly close to the runway for blunder headings that are larger than the breakout headings. This occurs close to the runway for any breakout with a turn component. The climb breakout does not cause this increase in close to the runway, but unfortunately it does not perform nearly as well as the full breakout far from the runway.

The solution for the problems close to the runway may be to ensure that the breakout heading is always larger than the blunder heading, which would allow enough time to for the trail aircraft to gain sufficient altitude to avoid a collision. An adaptive guidance command could be used to ensure that the breakout heading is larger than the blunder heading. This would improve the separation performance but at the expense of increased pilot workload, training, and a potential increase in total system delay time.

Unfortunately, at 0.75 nmi, where the PZ is smallest, a CAS does not offer much improvement in the MLS for any of the blunders considered. In this area the aircraft will have to remain inside a guaranteed PZ. The lack of improvement near the threshold coupled with the compression that occurs effectively nullifies any advantage that could be realized farther from the runway with the addition of a CAS.

A CAS could still be useful for certain types of blunders that can potentially cause problems during the approach. These blunders may include slow drifting blunders or a sidestep blunder, which could cause large increases in the MLS. These blunders could be a result of a pilot lining up on the wrong parallel runway, for example. In these blunder situations closure rate is low and the time to collide is somewhat large, which would provide a CAS with ample time to detect the blunder and alert the flight crew to perform a breakout maneuver. Also during a missed approach the flight crews will no longer be performing the spacing task and therefore a CAS may be beneficial. The factors that induced the missed approach, however, may preclude the pilot from being able to follow his or her CAS breakout commands.

The most effective procedure may be to require the trail aircraft to have a target separation at the FAF that will place it inside the guaranteed PZ inside 1 nmi from the runway. A CAS could be included to warn against any of the problem blunders stated above and to aid in a missed approach procedure should it be needed.

Bibliography

FAA, 2000, "Aeronautical Information Manual", http://www.faa.gov/ATpubs/AIM

Hammer, J., 1999, "Study of the Geometry of a Dependant Approach Procedure to Closely Spaced Parallel Runways", 18th Digital Avionics Systems Conference, St. Louis, MO.

Mundra, A., 1999, "Paired Approach Operation Concept", http://www.caasd.org/cdti/PA_operational_concept_draft3.doc

Shank, E. M. and K. M. Hollister, 1994, "Precision Runway Monitor", *Lincoln Laboratory Journal*, Vol. 7, No. 2, MIT Lincoln Laboratory, Lexington, MA.

Stone, R., 1998, "Paired Approach Concept: Increasing IFR Capacity to Closely Spaced Parallel Runways", http://www.caasd.org/cdti/rocky/pairRocky.html

Winder, L. and J. Kuchar, 1999, "Evaluation of Collision Avoidance Maneuvers During Parallel Approach", *AIAA Journal of Guidance, Control and Dynamics, Vol. 22, No. 6.*