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Safety Study of Reducing Diagonal Separation from 2.0 Nautical Miles to 1.5 Nautical Miles for Dependent Approaches to Parallel Runways Spaced between 4,300 feet and 9,000 feet

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12. Abstract
The Federal Aviation Administration (FAA) Flight Standards Closely Spaced Parallel Operations team evaluated the risk of dual dependent parallel operations associated with reducing the diagonal separation between aircraft from 2.0 nautical miles (NM) to 1.5 NM for parallel dependent approaches at runway centerline spacing (RCLS) of 4,300 feet or greater and less than or equal to 9,000 feet. The FAA Safety Management System acceptable level of risk of 1.0×10^{-9} per operation was used as the success criteria. The results show that the risk is acceptable up to an RCLS of 8,200 feet with no evasion by the trailing aircraft or intervention by the controller. With controller intervention, the RCLS can be increased to 8,300 feet.

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Executive Summary

The purpose of this technical report is to explain the results of an evaluation of the collision risk of aircraft performing simultaneous dual dependent approaches with radar diagonal separation reduced from 2.0 nautical miles (NM) to 1.5 NM.

The evaluation was conducted to satisfy a request from the Federal Aviation Administration (FAA) Air Traffic Organization (ATO) to determine the collision risk of dual dependent approaches to parallel runways spaced 4,300 feet (ft) or greater, with a diagonal separation between paired aircraft of 1.5 NM. Air Traffic Control (ATC) currently requires a diagonal separation of 2.0 NM. An aircraft fleet mix representative of the traffic at major airports such as Dallas Fort Worth International, San Francisco International, John F. Kennedy International, etc., was used with a 20% heavy mix (300,000 pounds or more).

An evaluation of the collision risk associated with a course deviation, or blunder, by the lead aircraft in the pair was conducted. The FAA Safety Management System (SMS) acceptable level of risk of 1.0×10^{-9} per operation for a catastrophic event was used as the success criteria for this study.

As runway centerline spacing increases, the longitudinal spacing between the lead aircraft and the trailing aircraft in the dependent pair must decrease to maintain the diagonal spacing. The results indicate that parallel dependent approaches can be conducted with a minimum of 1.5 NM of radar separation diagonally between dependent aircraft pairs when runway centerline spacing (RCLS) is 8,200 ft or less. This assumes no evasive maneuvers by the trailing aircraft or intervention by the controller. Given that ATC has the ability to intervene and correct potential loss of separation and aircraft deviations, the evaluation reveals this minimum spacing can be increased from 8,200 ft to 8,300 ft. This assumes that controller responses are not influenced by runway separation and therefore represents a conservative evaluation. This also assumes no changes to existing sectors, equipment, control personnel, positions, or procedures.

1 Introduction

FAA Order JO 7110.65V, paragraph 5-9-6, *Simultaneous Dependent Approaches*, requires controllers to provide a minimum of 1,000 ft vertical or 3.0 NM lateral radar separation between aircraft during the turn onto the final approach course. Additionally, controllers are required to provide a minimum of 2.0 NM of radar separation diagonally between successive aircraft on adjacent localizer/azimuth courses when RCLS is more than 4,300 ft, but no more than 9,000 ft apart. [1]

There are no requirements for a no transgression zone (NTZ), a normal operation zone, final monitor controllers, or discrete communications frequencies for each runway.

The ATO requested a collision risk evaluation for reducing the current 2.0 NM diagonal separation, or stagger, to 1.5 NM.

1.1 Background

At the request of ATO, Flight Technologies and Procedures Division (AFS-400), had previously conducted an evaluation of reducing the required diagonal separation between paired aircraft on simultaneous dependent approaches on closely spaced parallel runways spaced between 2,500 ft and 4,300 ft. The results of that study show that with the required separation reduced from 1.5 NM to 1.0 NM, runways separated by 2,500 ft to 3,200 ft meet the acceptable level of collision risk. Between 3,200 ft and 4,300 ft, 1.5 NM diagonal separation is still required. Based on the results of that study, ATO then requested an evaluation of reducing the required diagonal spacing for runways spaced greater than 4,300 ft, but not greater than 9,000 ft.

Previous studies by AFS-400 have refined several parameters utilized in the fast time simulation, such as blunder angle and severity, controller response times, pilot response times, aircraft dynamics, and the shape of the test criteria violation (TCV) volume. The TCV volume is centered on the endangered aircraft center of gravity. If the center of gravity of the blundering aircraft penetrates the TCV volume, a collision is assumed to have occurred.

As RCLS increases, the longitudinal spacing between the lead aircraft and the trailing aircraft in the dependent pair must decrease to maintain the same diagonal spacing. As the approach courses become further separated, the probability of a collision from a lead aircraft blundering into the path of the trailing aircraft increases until it exceeds the FAA SMS acceptable level of risk.

1.2 Purpose

The purpose of the evaluation was to satisfy a request from the FAA ATO to determine the collision risk of dual dependent approaches to parallel runways spaced 4,300 ft or greater with a diagonal separation between paired aircraft of 1.5 NM. Decreasing the required diagonal spacing required between successive aircraft on the adjacent approach course will enable more aircraft to land at the airport in any given amount of time under limited visual conditions. With the increase expected in air traffic, ATO is investigating methods to increase National Airspace System (NAS) capacity.

2 Objectives and Scope

This evaluation was performed to determine if dependent parallel operations could be conducted within the FAA SMS acceptable level of risk per operation, with the reduction in diagonal separation as described above.

This evaluation considered a reduction in diagonal separation between aircraft from 2.0 NM to 1.5 NM for parallel dependent approaches for runway centerlines spaced 4,300 ft or greater and less than or equal to 9,000 ft.

In addition to the vertical and lateral separations to be maintained, the following requirements are applicable:

- Approach types for this dependent parallel operation must be any combination of Instrument Landing System, Ground Based Augmentation System Landing System, Wide Area Augmentation System Localizer Performance with Vertical Guidance, and Global Positioning System Required Area Navigation, and Required Navigation Performance approaches; [3,4]
- The minimum applicable radar separation between aircraft on the same final approach course must be provided; and
- Missed approach procedures must not conflict.

ATC procedures do not require a final monitor controller for these parallel dependent approaches. Radar separation is provided all the way to the threshold by the radar position, terminal radar team, in accordance with 7110.65V, paragraph 2-10-2.c.1.(a). This evaluation was based on the use of a Monopulse Secondary Surveillance Radar with an update rate of 4.8 seconds, specifically, an Airport Surveillance Radar-9.

3 Methodology

3.1 Fast Time Simulation

The primary analysis tool for this study was Flight Systems Laboratory (AFS-400)'s Airspace Simulation and Analysis Tool-new generation (ASAT^{ng}). ASAT^{ng} is a multifaceted fast time simulation tool for aviation-related safety assessments which uses high fidelity models of all components of an aviation scenario to evaluate the overall risk of the operation.

With no controller intervention, the maximum acceptable RCLS that met the acceptable level of collision risk with a diagonal separation of 1.0 NM was 3,200 ft. [2] For continuity with that study, this evaluation began at 3,200 ft.

3.2 Simulation Parameters

A wide range of parameters were used to realistically model these complex operational scenarios. These parameters include:

- Aircraft fleet mix;
- Pilot response times;
- Controller response times;
- Aircraft performance;
- Atmospheric conditions;
- Navigation system performance; and
- ATC monitoring and surveillance equipment.

3.3 Simulation Conditions

To determine the minimum diagonal separation without evasive maneuvers by the trailing aircraft, the fast time simulations were conducted using the following conditions:

- Aircraft were established on the final approach course. Aircraft complied with approach control directed speeds up to the point of configuring for the final approach; the aircraft did not slow until within 2.0 NM prior to the final approach fix;
- Every run included a blunder by the lead aircraft;
- No evasive maneuvers were made by the trailing aircraft;
- Blunder angles were established within the following ranges: 5° to 15°; 15° to 25°; 25° to 35°;
- A 1.5 NM diagonal separation was set at the start of the blunder;
- Blunders were initiated uniformly along the final approach course; and
- Aircraft fleet mix included a 20% heavy aircraft which is representative of the traffic at major airports such as Dallas Fort Worth International, San Francisco International, John F. Kennedy International, etc.

3.4 Simulation Fleet Mix

The fleet mix used in this study and the study in reference 2, was developed to be a representation of the traffic observed in the NAS. It was developed using data obtained from the Extended Traffic Management System count of aircraft at all major airports in the NAS, that operate simultaneous instrument approaches. The Extended Traffic Management System count data suggests that on average, the percentage of heavy aircraft in the NAS is approximately 5%. During peak intervals, this percentage can increase to a higher level, but it has never been greater than 20%. Not all aircraft types are used, and this particular fleet mix reflects a conservative representation of NAS traffic as it includes a higher percentage of heavy aircraft. The mix was comprised of 20% heavy aircraft (10% Boeing 747-400 and 10% Airbus A330-200), 40% Boeing B737-800, and 40% Embraer Regional Jet ERJ-145.

3.5 Assumptions

Several assumptions were made as to the requirements for and the conduct of the operation.

- There was no requirement for a NTZ;
- There was no requirement for a normal operation zone;
- There was no requirement for final monitor controllers;
- There was no requirement for or discrete communications frequencies for each runway;
- The approaches were conducted in accordance with FAA Order JO 7110.65V, *Air Traffic Control*;
- The controllers provided the required diagonal radar separation between paired aircraft all the way to the runway threshold and the required radar separation between subsequent pairs;
- Aircraft did not slow until within 2.0 NM prior to the final approach fix;
- No evasive maneuvers were made by the trailing aircraft;
- The simulation was released at each run with the aircraft placed to be “at risk”; and
- Wake vortex encounters need not be considered for RCLS greater than 2,500 ft.

4 Data Analysis

The FAA SMS acceptable level of risk per operation was used as the success criteria. A collision between aircraft is the catastrophic event used to determine the acceptable level of risk specified in the FAA SMS. The TCV shape used in this study was a cylinder, with a radius of 265 ft and a height of 160 ft (±80) centered on the trailing aircraft's center of gravity. [5] If the blundering aircraft center of gravity penetrated this TCV cylinder, a TCV, i.e., a collision, was assumed to have occurred. Several human in the loop data collection efforts (DCEs) conducted since July, 2009 have been used to refine the controller response time, pilot response time, and aircraft dynamics used in the $ASAT^{ng}$ fast time simulations to study various runway spacings and proposed operations within the NAS.

In each $ASAT^{ng}$ simulation run, the closest point of approach was recorded along with the position of the blundering aircraft relative to the trailing aircraft. Although, it was possible for the blundering aircraft's center of gravity to penetrate the cylinder without resulting in a collision, for simplicity, every TCV was considered to result in a collision.

4.1 Collision Risk

Fast time simulation runs were performed in accordance with the conditions in section 3, by aircraft fleet mix, blunder angle, blunder type, runway separation, and diagonal separation of 1.5 NM. These simulation runs included lead aircraft blunders, but did not include any trailing aircraft evasions. Two types of blunders were simulated. The first type of blunder was a level blunder, i.e., the blundering aircraft maintained the altitude it had when the blunder was initiated. The second type of blunder was a descending blunder, i.e., the blundering aircraft continued its descent rate while maneuvering.

4.1.1 Collision Risk for Various Runway Spacings with No Evasion

From analysis of actual blunder data collected, the rate of a blunder has been determined for 10 degree intervals for all observed blunders, see table 4-1. [6] Controllers monitor the approaches, and in the event of an apparent blunder, the controller will intervene to instruct the aircraft to return to course. An additional rate of 1 in 100 is used for a non-responding blunder (NRB), see appendix A.

Table 4-1 Blunder Rates

Blunder Angle	Observed Blunder Rate	NRB rate
$5° \leq \Theta < 15°$	4.58E-05	4.58E-07
$15° \leq \Theta < 25°$	2.55E-05	2.55E-07
$25° \leq \Theta < 35°$	1.18E-05	1.18E-07

Table 4-2 contains the no intervention results of the collision risk analysis of the $ASAT^{ng}$ simulation runs for RCLS between 3,200 ft and 9,000 ft. For the collision risk analysis, see appendix A.

Table 4-2 Collision Risk (No Intervention)

RCLS	Collision Risk at 1.5 NM
3,200 to 7,300	0
7,400	2.50E-11
7,500	1.89E-11
7,600	4.20E-11
7,700	6.65E-11
7,800	7.99E-11
7,900	1.66E-10
8,000	2.68E-10
8,100	4.84E-10
8,200	7.19E-10
	1.14E-09
	1.59E-09
	2.24E-09
	2.79E-09
	3.62E-09
	4.00E-09
	4.31E-09
	4.19E-09

4.1.2 Collision Risk for a Runway Spacing of 8,300 ft with Intervention

Previously determined rates of ATC non-intervention are summarized in table 4-3. The controllers were left to their own training and experience in that DCE, on the actions required to maintain the diagonal separation at 3,600 feet runway spacing. Since it is reasonable to assume that the percentage of time they will intervene to maintain a required 1.0 NM separation will be the same as it would be for 1.5 NM, these same percentages are applied in this analysis. It is a conservative assumption that the controllers would react similarly to each blunder angle range at runways spacings that are greater than the 3,600 feet used in the DCE.

Table 4-3 ATC Non-Intervention Rate to Blunders for 3,600 ft RCLS and 1.0 NM Diagonal Radar Separation

Blunder Angle	**ATC Non-Intervention Rate**
$5° \leq \Theta < 15°$	15.9% (14 out of 88)
$15° \leq \Theta < 25°$	22.6% (19 out of 84)
$25° \leq \Theta < 35°$	27.5% (22 out of 80)

A key contributor to the difficulty in maintaining aircraft separation is compression. Compression is caused by the lead aircraft decelerating to the final approach speed at the final approach fix while the trailing aircraft is still at the speed assigned by ATC. This compression was shown to increase the risk of collision in the analysis. To allow the use of a 1.5 NM diagonal separation standard, the controller must use available techniques to maintain the required separation in order to take this compression into account.

Since the controllers did not intervene in all deviation events, often based on their judgment of the probability of a collision, the collision risk is calculated using a combination of the probability of TCV with controller intervention and the probability of TCV without controller intervention based on the percentages in table 4-3. Using the controller response time probability density function (PDF) determined from the 1.0 NM separation DCE data, the collision risk was calculated from the results of the ASAT^{ng} simulations. The simulations began at an RCLS of 9,000 ft. The RCLS was decreased until the SMS acceptable level of risk was met. The final RCLS was 8,300 ft and the results are tabulated in table 4-4. The highlighted band depicts the case of no controller intervention. For a description of the analysis, see appendix A.

Table 4-4 Collision Risk for 8,300 ft RCLS and 1.5 NM Diagonal Radar Separation

Blunder Angle (°)	P(Collision)	ATC Non-Response Rate (%)	ATC Response Rate (%)	P(Collision) * Rate	Subtotal	Total
5≤Θ<15	1.92E-10	15.91		3.06E-11	2.69E-10	9.78E-10
15≤Θ<25	4.48E-10	22.62		1.01E-10		
25≤Θ<35	4.98E-10	27.50		1.37E-10		
5≤Θ<15	3.21E-11		84.09	2.70E-11	7.09E-10	
15≤Θ<25	2.97E-10		77.38	2.30E-10		
25≤Θ<35	6.24E-10		72.50	4.52E-10		

5 Conclusions

This assessment was performed to evaluate the collision risk associated with reducing the current 2.0 NM diagonal radar separation to 1.5 NM for parallel dependent approaches to runways spaced 4,300 ft to 9,000 ft apart.

Parallel dependent approaches conducted with a 1.5 NM radar separation diagonally between successive aircraft on adjacent localizer/azimuth courses with runway centerlines at least 3,200 ft apart, but no more than 8,200 ft apart meet the FAA SMS acceptable level of risk with no evasive maneuvers by the trailing aircraft and no intervention by controllers. Given that ATC has the ability to intervene and correct potential loss of separation and aircraft deviations, the study shows this minimum spacing can be increased from 8,200 ft to 8,300 ft. Figure 5-1 illustrates the geometries for the runway separations which have an acceptable level of risk. For runway centerlines separated by more than 8,300 ft, based on previous studies, the diagonal separation of 2.0 NM meets the acceptable level of risk. This assumes that controller responses are not influenced by runway separation and therefore represents a conservative evaluation. This also assumes no changes to existing sectors, equipment, control personnel, positions, or procedures.

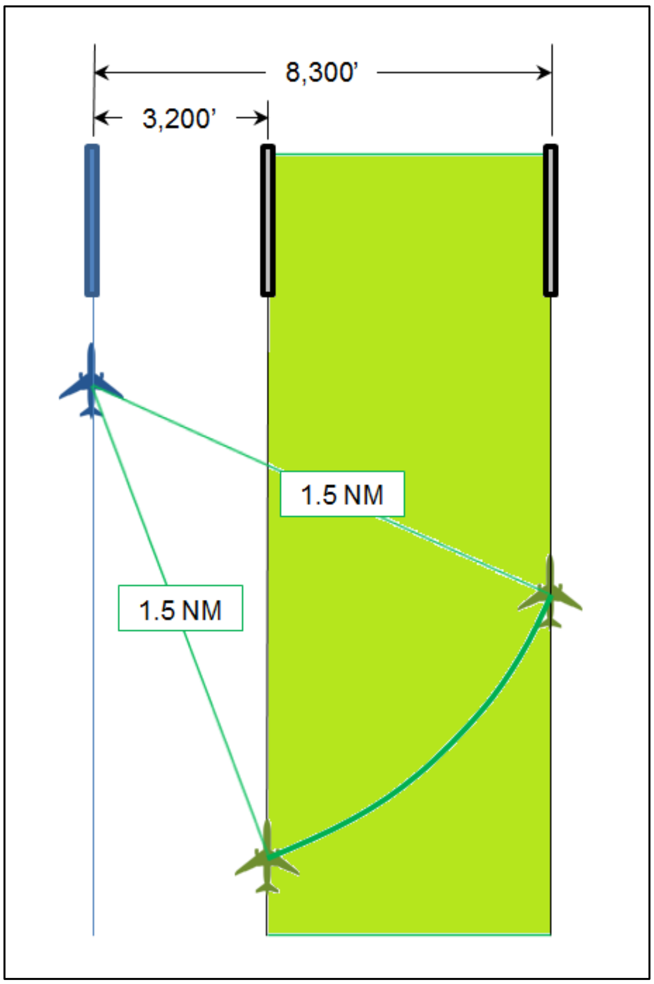

Figure 5-1: Runway Separations with Acceptable Levels of Risk

6 References

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Appendix A: Probability Density Functions

A.1 Probability of a Collision

Several events must occur simultaneously for a collision to occur during simultaneous instrument approaches. Clearly, a blunder must occur, or there would be no significant deviation from course, see figure A-1. Diagonal separation and RCLS must be below the thresholds where a collision would not occur if a blunder were to take place. For a given blunder angle and diagonal separation, there exists a certain RCLS, at which a TCV will not occur unless the lead aircraft's airspeed (V_L) is less than the trailing aircraft airspeed (V_T). If all of the above events develop in a manner supporting a collision, a TCV occurs if the controllers and pilots fail to react in sufficient time to separate the blundering and the evading aircraft.

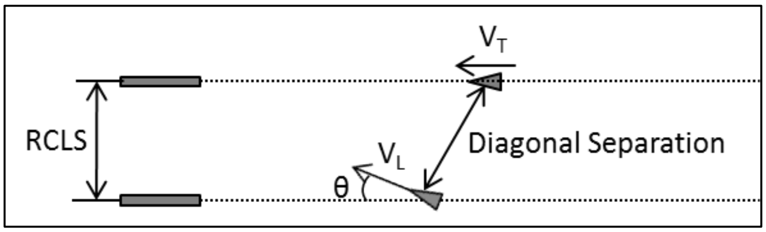

Figure A-1: Blunder Depiction

In addition, the blundering aircraft must not respond to a controller's directions to return to the localizer/azimuth course. This is called a NRB. The value used for NRB (1/100) has been used in numerous prior studies. [7, 8] This number is further validated by the calculations below, based on the results of an extensive blunder DCE performed by MITRE. [9] MITRE investigated over 1.8 million simultaneous approaches at 12 U.S. airports and observed 82 deviations of aircraft from their final approach courses that entered the NTZ, whether or not there was an aircraft on the parallel approach. These were determined to be blunders. Of these 82 blunders, all deviating aircraft corrected back to course. The report states that all deviating aircraft responded to controller instruction, if issued, highlighting the importance of controllers monitoring the approach. This data is consistent with an NRB rate of 1/100 NRB as follows.

If the random variable *X* represents the number of successes in *n* trials of a binomial experiment in which the probability of a single independent success is *p*, the probability that *X* = *x* is given by the binomial distribution equation:

$$(P \quad) \quad \left(\quad \right) P \quad (1P \quad) P \qquad \text{(A-1)}$$

If there are 82 trials (i.e., $n = 82$) and no successes (i.e., $x = 0$) then:

$$(P \quad) \quad \left(2P \right) \quad (1P \quad) P \quad (1P \quad) P \qquad \text{(A-2)}$$

Therefore, a distribution for the unknown parameter, *p*, the probability of a success given the empirical result of no successes in 82 trials can be based on equation A-2.
Since p represents a probability, its values must range between 0 and 1 and a PDF for the distribution derived from equation A-2 must integrate to the value 1 between those

bounds. This is enough information to derive a unique pdf for *p*, given the empirical result. Equation A-3 is that pdf and figure A-2 is its graph.

$$(\ ) \quad 83(1P \quad)P \qquad \text{(A-3)}$$

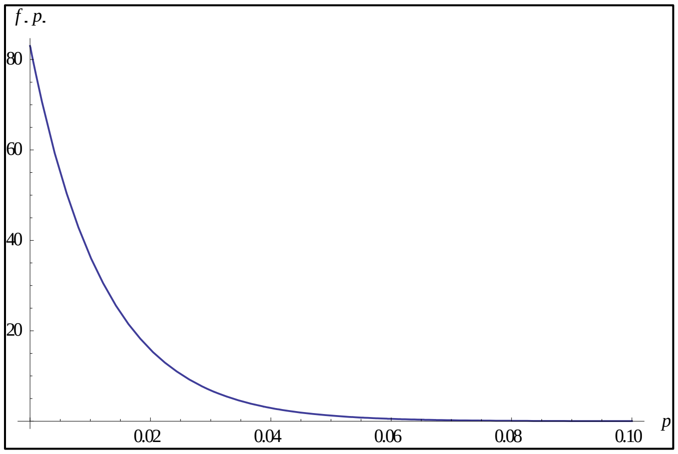

Figure A-2: Equation A-3 Graph

So, as *p* varies from 0 to 1, its likelihood (given the empirical result) is given by equation A-3, its pdf, and depicted by the graph in figure A-2.

The pdf (equation A-3) can be used to calculate likely values for *p*. For example, the median value for *p*, is the value p_m for which the integral from 0 to p_m is 0.5. This calculation shows that $p_m = 0.00832$. This value would then be the most realistic estimate, statistically, for *p*, given the empirical result. Thus, the value of 1/100 is a conservative estimate for the NRB factor in calculations below.

A collision involves two aircraft and results in two accidents, as defined by the National Transportation Safety Board. Assuming that a TCV will result in a collision, the probability of a collision can be expressed in mathematical terms by:

$$\text{P(Collision)} = \text{P(TCV}|\text{NRB} \cap \text{BL)} \times \text{P(NRB}|\text{BL)} \times \text{P(BL)} \qquad \text{(A-4)}$$

The symbol "∩" stands for "and". The symbol " | " stands for "given"; blunder is represented by BL. The first factor in the equation is expressed as:

$$\text{P(TCV}|\text{NRB} \cap \text{BL)}$$

This factor determines the probability that a TCV occurs given that a non-responding blunder has occurred. This is the TCV rate that is determined from the simulation. The second factor in the equation is expressed as:

$$\text{P(NRB}|\text{BL)}$$

This factor determines the probability that the blundering aircraft does not respond to controller instruction to return to course given that a blunder has occurred. The industry accepted value of this factor is 1/100. The last factor in the equation is expressed as:

$$P(BL)$$

This factor is the probability of a blunder of a specified angle such as 20 degrees. The probability and frequency of the occurrence of various blunder angles up to 35 degrees has been determined from blunder data captured from actual simultaneous approaches conducted in less than visual conditions.

A.2 Data Analysis

The TCV rate used in equation A-1 is the count of TCVs obtained from the fast time simulations for both level blunder and descending blunder scenarios divided by the total number of runs. There were 100,000 aircraft pairs generated for each of these blunder types (level blunder or descending blunder). Thus, the TCV count is divided by 200,000. Collision risk is then a sum of the P(Collision) for each range of angles for each RCLS. There were no TCVs at an RCLS less than 6,900 ft where the collision risk was 5.9×10^{-13}. Therefore, only the value of risk at an RCLS of 8,000 ft, where the risk approaches $1.0 \times 10^{-9,}$ and above are shown. It is observed that the TCV rate is sensitive to the magnitude of the blunder angle. In the closely spaced dependent stagger analysis, the 5 to 10 degree blunder angles had the highest TCV rate. However, in these scenarios for runways spaced between 4,300 ft and 9,000 ft, the 25 to 35 degree blunder angles resulted in the highest TCV rates as compared to the smaller blunder angles. Given the assumed approach speed ranges, there is an optimal blunder aircraft travel distance for increasing TCV counts. In closely spaced scenarios, that optimal distance is reached at lesser blunder angles and in these wider spaced scenarios, that distance is achieved at greater blunder angles.

Table A-1: Collision Risk for 1.5 NM Diagonal Separation with No Evasion

RCLS	BL Angle	TCV Rate	P(BL)	P(NRB|BL)	P(Collision)	Collision Risk
8000	5≤Θ<15	1.50E-04	4.58E-05	1/100	6.87E-11	2.68395E-10
	15≤Θ<25	3.25E-04	2.55E-05	1/100	8.29E-11	
	25≤Θ<35	9.90E-04	1.18E-05	1/100	1.17E-10	
8100	5≤Θ<15	1.95E-04	4.58E-05	1/100	8.93E-11	4.843E-10
	15≤Θ<25	7.60E-04	2.55E-05	1/100	1.94E-10	
	25≤Θ<35	1.71E-03	1.18E-05	1/100	2.01E-10	
8200	5≤Θ<15	2.65E-04	4.58E-05	1/100	1.21E-10	7.19425E-10
	15≤Θ<25	1.01E-03	2.55E-05	1/100	2.66E-10	
	25≤Θ<35	2.81E-03	1.18E-05	1/100	3.32E-10	
8300	5≤Θ<15	4.20E-04	4.58E-05	1/100	1.92E-10	1.13785E-09
	15≤Θ<25	1.76E-03	2.55E-05	1/100	4.48E-10	
	25≤Θ<35	4.22E-03	1.18E-05	1/100	4.98E-10	