Federal Aviation Administration

DOT/FAA/AFS400/2019/R/25
Flight Technologies and Procedures Division, AFS-400
Washington, DC 20591

Safety Study of Closely Spaced Parallel Operations Utilizing Paired Approach

April 2019

Technical Report

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

DOT/FAA/AFS400/2019/R/25

Brad Nelson, FAA
Mark Williams, SAIC
Luke Wood, ATSI

Flight Research and Analysis Group
Oklahoma City, Oklahoma 73169

Submitted by:

WADE EK TERRELL
2019.07.08 14:41:52
-05'00'

Wade E.K. Terrell
Manager, Flight Research and Analysis Group

Approved by:

Digitally signed by MARK W
STEINBICKER
Date: 2019.07.12 13:24:49 -04'00'

Mark Steinbicker
Manager, Flight Technologies and Procedures Division

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AFS400/2019/R/25		

4. Title and Subtitle	5. Report Date
Safety Study of Closely Spaced Parallel Operations Utilizing Paired Approach	April 2019
6. Author(s)	**7. Performing Organization Code**
Brad Nelson, FAA; Mark Williams, SAIC; Luke Wood, ATSI	AFS-430
8. Performing Organization Name and Address	**9. Type of Report and Period Covered**
Flight Research and Analysis Group 6500 S MacArthur Blvd., STB Annex, Room 217 Oklahoma City, OK 73169	Technical Report

10. Sponsoring Agency Name and Address
Federal Aviation Administration
Flight Technologies and Procedures Division, AFS-400
470 L'Enfant Plaza, SW
Washington, DC 20024

11. Supplementary Notes

12. Abstract

The Federal Aviation Administration (FAA) Flight Research and Analysis Group was requested by the NextGen – Technology Development and Prototyping Division/Navigation Branch (ANG-C51) to conduct a safety study to analyze the collision safety limit (CSL) for paired approach operations. The paired approach concept aims to increase airport capacity by performing simultaneous dependent approaches to parallel runways with centerlines spaced less than 2,500 ft apart. A paired approach operation consists of a lead aircraft flying to a runway, with a trailing aircraft approaching a parallel runway. The trailing aircraft, is abeam (i.e., perpendicular to) or some distance behind the lead aircraft. This distance is termed in-trail distance. Two primary hazards associated with a paired approach operation are collision risk and wake encounter risk. Collision risk tends to increase as in-trail distance decreases. Wake encounter risk tends to increase as in-trail distance increases. For this reason, the trailing aircraft should maintain a position in a protection zone to mitigate risk associated with these hazards. The forward and aft boundaries of the protection zone are referred to as the CSL and the wake safety limit (WSL), respectively.

This study analyzes collision risk in the event of a course deviation by the lead aircraft. The closest in-trail distances deemed acceptable for the operation, referred to as collision safety limits, are identified. Experimental methods employed in this study utilized fast-time simulations to assess collision risk for various in-trail starting distances at select locations along the approach. Major factors contributing to the collision safety limit include the difference in speed between the lead and trailing aircraft, runway centerline spacing, and the type of runway approach alignment (i.e., straight-in or offset). Reduction in collision safety limit in-trail distances is achieved for paired approach operations with smaller runway centerline spacing, straight-in approaches, or where the lead aircraft is flying faster than the trailing aircraft (referred to as aircraft speed expansion). However, these reductions may be offset by the increase in wake encounter potential.

13. Key Words	14. Distribution Statement
Collision Safety Limit (CSL) Interval Management (IM) Paired Approach (PA) Protection Zone Runway Centerline Spacing (RCLS) Test Criterion Violation (TCV)	Uncontrolled
15. Security Classification of This Report	**16. Security Classification of This Page**
Unclassified	Unclassified

DOT F1700.7

Table of Contents

Executive Summary **9**
1 Introduction **11**
1.1 Background 12
1.2 Purpose 13
2 Objectives and Scope **14**
3 Methodology **15**
3.1 Fast-Time Simulation 15
3.2 Test Design and Scenarios 15
3.2.1 Test Design and Scenarios –Airport Configurations 22
3.2.2 Test Design and Scenarios – Modified Special Case Airport Configurations 23
3.3 Simulation Assumptions 24
3.4 Independent Variables 25
3.5 Dependent Variables 25
4 Data Analysis **26**
4.1 Collision Risk 26
4.2 CSL Analysis 29
4.2.1 CSL Analysis – Generic Airport Configurations 33
4.2.2 CSL Analysis – Specific Airport Configurations 38
4.2.2.1 KBOS 38
4.2.2.2 KSEA 43
4.2.2.3 KSFO 48
4.2.3 CSL Analysis – Modified Airport Configurations 52
4.2.3.1 Initial IAS of 150 kts with Transition to FAS 52
4.2.3.2 Constant IAS of 150 kts 56
4.3 CSL Analysis Summary 58
5 Conclusions **61**
References **63**
Acknowledgments **64**
Appendix A: Risk Analysis – Probability of a Collision **65**
Appendix B: Aircraft IAS **68**
Appendix C: Error Distributions **71**
Appendix D: Scenario Creation and Simulation Runs **73**
Appendix E: Aircraft Count **76**
Appendix F: Generic and Specific Approach Supplemental Graphs & Tables **77**
Appendix G: Example of Simulation Output File **119**
Appendix H: Definitions **120**
Appendix I: Acronyms **124**

List of Figures

Figure 1-1: Paired Approach Concept 11
Figure 1-2: Paired Approach Hazard Area and Approach Geometry 13
Figure 3-1: Paired Approach with Aircraft Deviation 16
Figure 3-2: Paired Approach Aircraft Scenario Release Positions (Straight-In Approach) 17
Figure 3-3: Paired Approach Aircraft Scenario Release Positions (Offset Approach) 17
Figure 3-4: TCV Volume 18
Figure 4-1: KSFO CSL Collision Risk Tolerance 27
Figure 4-2: KGEN CSL Comparison of Aircraft Pairing Combinations 29
Figure 4-3: KGEN vs KSFO CSL Comparison of RCLS 30
Figure 4-4: Example CSL for CAT C Leading CAT D 31
Figure 4-5: Example of Initiation Points 32
Figure 4-6: KGEN Runway Configuration 33
Figure 4-7: KGEN CSL for CAT C Leading CAT D (Straight-In with 2,500 ft RCLS) 34
Figure 4-8: KGEN CSL for CAT C Leading CAT D (3° Offset with 2,500 ft RCLS) 35
Figure 4-9: KBOS Runway Configuration 38
Figure 4-10: KBOS CSL for CAT C Leading CAT D (Straight-In with 1,500 ft RCLS) 39
Figure 4-11: KBOS CSL for CAT C Leading CAT D (2° Offset with 1,500 ft RCLS) 40
Figure 4-12: KSEA Runway Configuration 43
Figure 4-13: KSEA CSL for CAT C Leading CAT D (Straight-In with 800 ft RCLS) 44
Figure 4-14: KSEA CSL for CAT C Leading CAT D (Straight-In with 1,700 ft RCLS) 45
Figure 4-15: KSFO Runway Configuration 48
Figure 4-16: KSFO CSL for CAT C Leading CAT D (3° Offset with 750 ft RCLS) 49
Figure 4-17: KSFO CSL for CAT C Leading CAT D (Special Case - Initial 150 kts to FAS) .. 53
Figure 4-18: KSFO CSL Comparison (Initial 150 kts to FAS vs Initial 170 kts to FAS) 54
Figure 4-19: KSFO CSL for CAT C Leading CAT D (Special Case - Constant 150 kts) 56
Figure 4-20: KSFO CSL Comparison (Constant 150 kts vs Initial 150 kts to FAS) 57
Figure B-1: Simulation Speeds 70
Figure D-1: Nodes for an Airport Runway Configuration (Example) 73
Figure E-1: Comparison of Number of Aircraft Pairs 76
Figure F-1: KGEN CSL for CAT B Leading CAT A (Straight-in with 2,500 ft RCLS) 78
Figure F-2: KGEN CSL for CAT B Leading CAT D (Straight-in with 2,500 ft RCLS) 79
Figure F-3: KGEN CSL for CAT C Leading CAT E (Straight-in with 2,500 ft RCLS) 80
Figure F-4: KGEN CSL for CAT D Leading CAT E (Straight-in with 2,500 ft RCLS) 81
Figure F-5: KGEN CSL for CAT D Leading CAT F (Straight-in with 2,500 ft RCLS) 82
Figure F-6: KGEN CSL for CAT B Leading CAT A (3° Offset with 2,500 ft RCLS) 83
Figure F-7: KGEN CSL for CAT B Leading CAT D (3° Offset with 2,500 ft RCLS) 84
Figure F-8: KGEN CSL for CAT C Leading CAT E (3° Offset with 2,500 ft RCLS) 85
Figure F-9: KGEN CSL for CAT D Leading CAT E (3° Offset with 2,500 ft RCLS) 86
Figure F-10: KGEN CSL for CAT D Leading CAT F (3° Offset with 2,500 ft RCLS) 87
Figure F-11: KBOS CSL for CAT B Leading CAT A (Straight-in with 1,500 ft RCLS) 88
Figure F-12: KBOS CSL for CAT B Leading CAT D (Straight-in with 1,500 ft RCLS) 89
Figure F-13: KBOS CSL for CAT C Leading CAT E (Straight-in with 1,500 ft RCLS) 90
Figure F-14: KBOS CSL for CAT D Leading CAT E (Straight-in with 1,500 ft RCLS) 91
Figure F-15: KBOS CSL for CAT D Leading CAT F (Straight-in with 1,500 ft RCLS) 92
Figure F-16: KBOS CSL for CAT B Leading CAT A (2° Offset with 1,500 ft RCLS) 93

List of Figures (Continued)

Figure F-17: KBOS CSL for CAT B Leading CAT D (2° Offset with 1,500 ft RCLS).....94
Figure F-18: KBOS CSL for CAT C Leading CAT E (2° Offset with 1,500 ft RCLS) 95
Figure F-19: KBOS CSL for CAT D Leading CAT E (2° Offset with 1,500 ft RCLS).....96
Figure F-20: KBOS CSL for CAT D Leading CAT F (2° Offset with 1,500 ft RCLS) 97
Figure F-21: KSEA CSL for CAT B Leading CAT A (Straight-in with 800 ft RCLS).....98
Figure F-22: KSEA CSL for CAT B Leading CAT D (Straight-in with 800 ft RCLS).....99
Figure F-23: KSEA CSL for CAT C Leading CAT E (Straight-in with 800 ft RCLS).....100
Figure F-24: KSEA CSL for CAT D Leading CAT E (Straight-in with 800 ft RCLS).....101
Figure F-25: KSEA CSL for CAT D Leading CAT F (Straight-in with 800 ft RCLS).....102
Figure F-26: KSEA CSL for CAT B Leading CAT A (Straight-in with 1,700 ft RCLS).....103
Figure F-27: KSEA CSL for CAT B Leading CAT D (Straight-in with 1,700 ft RCLS).....104
Figure F-28: KSEA CSL for CAT C Leading CAT E (Straight-in with 1.700 ft RCLS).....105
Figure F-29: KSEA CSL for CAT D Leading CAT E (Straight-in with 1,700 ft RCLS).....106
Figure F-30: KSEA CSL for CAT D Leading CAT F (Straight-in with 1,700 ft RCLS).....107
Figure F-31: KSFO CSL for CAT B Leading CAT A (3° Offset with 750 ft RCLS) 108
Figure F-32: KSFO CSL for CAT B Leading CAT D (3° Offset with 750 ft RCLS) 109
Figure F-33: KSFO CSL for CAT C Leading CAT E (3° Offset with 750 ft RCLS).....110
Figure F-34: KSFO CSL for CAT D Leading CAT E (3° Offset with 750 ft RCLS).....111
Figure F-35: KSFO CSL for CAT D Leading CAT F (3° Offset with 750 ft RCLS).....112

List of Tables

Table 3-1: RECAT Phase 1.5 Wake Categories 19
Table 3-2: Aircraft Pair Combinations 20
Table 3-3: Airport Arrivals by Aircraft Wake Category for 2017 21
Table 3-4: Airport Configuration Parameters 22
Table 4-1: KSFO CSL Collision Risk Tolerance 28
Table 4-2: KGEN CSL for All Aircraft Pairs (Straight-In and 3° Offset) 36
Table 4-3: KGEN CSL for CAT C Leading CAT D (Straight-In and 3° Offset) 37
Table 4-4: KBOS CSL for All Aircraft Pairs (Straight-In and 2° Offset) 41
Table 4-5: KBOS CSL for CAT C Leading CAT D (Straight-In and 2° Offset) 42
Table 4-6: KSEA CSL for All Aircraft Pairs (Straight-In with 800 ft & 1,700 ft RCLS) 46
Table 4-7: KSEA CSL for CAT C Leading CAT D (Straight-In with 800 ft & 1,700 ft RCLS) 47
Table 4-8: KSFO CSL for All Aircraft Pairs (3° Offset) 50
Table 4-9: KSFO CSL for CAT C Leading CAT D (3° Offset) 51
Table 4-10: KSFO CSL IAS Comparison (Initial 150 kts vs Initial 170 kts Baseline) 55
Table 4-11: CSL at Threshold Distance Limits for Speed Bin from -1 kts to 1 kts 60
Table A-1: 99% Confidence Intervals for NTZ Penetration Rates 66
Table B-1: Aircraft IAS during Simulations 68
Table B-2: Aircraft IAS Distributions 69
Table B-3: Airport Runway Configuration Information 70
Table C-1: Lateral Distribution Cumulative Probabilities (CRM vs Gaussian) 71
Table C-2: Standard Deviations of Aircraft Displacement during Approach 72
Table D-1: Scenario Composition 74
Table D-2: Simulation Input Variables Associated with a Scenario 75
Table F-1: CSL at Threshold Distance Limits for Speed Bin from -10 kts to -5 kts 113
Table F-2: CSL at Threshold Distance Limits for Speed Bin from -5 kts to -1 kts 114
Table F-3: CSL at Threshold Distance Limits for Speed Bin from 1 kts to 5 kts 115
Table F-4: CSL at Threshold Distance Limits for Speed Bin from 5 kts to 10 kts 116
Table F-5: CSL at Threshold Distance Limits for Speed Bin from 10 kts to 15 kts 117
Table F-6: CSL at Threshold Distance Limits for Speed Bin from 15 kts to 20 kts 118

Executive Summary

This report presents the results of a safety study that analyzed collision risk associated with the Paired Approach (PA) concept. The report is intended to inform the development of separation criteria.

The PA concept endeavors to increase airport capacity by enabling aircraft to fly simultaneous dependent approaches to parallel runways with centerlines spaced less than 2,500 feet (ft) apart. When PA operations are implemented, the trailing aircraft must maintain a position within a protection zone behind a forward collision safety limit (CSL), such that it is protected from collision in the event of a course deviation by the lead aircraft; and in front of an aft wake safety limit (WSL), such that it is protected against wake encounters associated with a non-deviating lead aircraft. This report describes potential locations of the forward CSL with respect to collision risk. Potential locations for aft WSL placement on the trailing aircraft's approach are being evaluated by the Volpe Center.

During this safety study, high-fidelity models of PA scenarios were developed and simulated using Monte Carlo methodology. The resultant data was analyzed to determine potential safety limitations associated with a CSL for PA operations, which includes the minimum in-trail distance between the aircraft throughout the approach and the associated diagonal distance. The CSL results should be used in conjunction with the WSL results in the development of a protection zone.

The report does not address wake turbulence avoidance, Traffic Collision Avoidance System (TCAS), Airborne Collision Avoidance System X (ACAS-X), PA avionics, radar separation standards, Air Traffic Control (ATC) monitoring equipment and procedures, missed approach procedures, or controlled flight into terrain.

A principal safety concern in PA operations is the risk of collision due to an aircraft course deviation (sometimes referred to as a blunder). Scenarios were created to estimate the probability of collision for potential CSL locations. Approach configurations at three major airports and one generic airport were assessed. CSL collision risk is a function of runway approach course alignment, runway spacing, runway threshold stagger, airport elevation, fleet mix, navigation systems, aircraft speeds, and the trailing aircraft's position relative to the lead aircraft. Therefore, preferred CSL locations may differ for each approach configuration.

Simulations in this study consisted of two aircraft initialized on their respective final approach courses with the lead aircraft unexpectedly deviating toward the trailing aircraft's final approach course. This study focused on the risk of collision based on the starting geometry of the aircraft without controller intervention. It is assumed controller intervention would reduce collision risk. The Methodology, Section 3, describes the testing conducted and scenarios used to identify parameters having considerable influence on the CSL.

The Data Analysis, Section 4, identifies CSL in-trail distances considering different levels of risk acceptance. Figure 4-1 depicts the CSL in-trail distances for various levels of probability from 1×10^{-7} to 1×10^{-10} for aircraft wake category (CAT) C leading CAT D. For example, the in-trail distances may be reduced if able to accept a probability of 1×10^{-7} per operation. The results show that for maximum speed expansion allowed in this study, when the lead aircraft is flying faster than the trailing aircraft, the effects of varying collision risk tolerance have a minimal effect on the

CSL. As aircraft speed differences shift to compression, when the lead aircraft is flying slower than the trailing aircraft, the CSL varies substantially with regard to tolerable risk. A target level of safety of 1×10^{-9} was used as a baseline for the conclusions drawn from this report.

This study focused on the risk of a mid-air collision; therefore, this report was limited to collision risk associated with the CSL due to a course deviation of the lead aircraft.

Final analysis of data indicated that the variance in CSL between differing aircraft pairs was insignificant, with no distinguishable trends. Additionally, reduced CSL in-trail distances may be attained for airport configurations with:

- Smaller runway centerline spacing (RCLS) vs larger RCLS (see Figure 4-3)
- Straight-in approaches vs offset approaches (see Figure 4-7 vs Figure 4-8)
- Aircraft pair speed expansion vs aircraft pair speed compression (see Figure 4-19)

Analysis concluded that delta (Δ) speed, which is the speed difference between the lead and trailing aircraft, was the principal contributor to CSL placement. Runway approach alignment was a secondary contributor, followed by RCLS as the tertiary contributor.

For all evaluated combinations, results indicate that the closest reasonable in-trail spacing is achieved when the speed compression between the aircraft is 5 kts or less. Further improvements may be attained for airport configurations with smaller RCLS, and for straight-in approaches versus offset approaches. Results also determined that aircraft wake-category pairing has minimal impact on CSL in-trail spacing.

While the PA concept continues to evolve prior to final PA implementation, further investigation of potential wake turbulence encounters by the trailing aircraft are suggested. Wake encounter risk caused by a non-deviating lead aircraft, a deviating lead aircraft crossing the path of a trailing aircraft, a lead aircraft executing a missed approach, or a deviating trailing aircraft encountering the wake of a lead aircraft have a potential impact on PA operations.

1 Introduction

This report presents the results of a safety study conducted to analyze collision risk associated with the Paired Approach (PA) concept.[1, 2] This safety evaluation was conducted by the Federal Aviation Administration (FAA) Flight Technologies and Procedures Division, Flight Research and Analysis Group to assist in the development of separation criteria for use in PA operations in collaboration with the NextGen – Technology Development and Prototyping Division/Navigation Branch (ANG-C51).

The PA concept endeavors to increase airport capacity in low visibility conditions by enabling aircraft to fly simultaneous dependent approaches to parallel runways with centerlines spaced at least 700 ft, but less than 2,500 ft apart.[3, 4] The procedure requires Automatic Dependent Surveillance-Broadcast (ADS-B) on both the lead target aircraft and the trailing interval management (IM) aircraft. The PA concept is depicted in Figure 1-1.[5] The trailing aircraft must maintain a position within a protection zone behind a forward collision safety limit (CSL), such that it is protected from collision in the event of a course deviation by the lead aircraft; and in front of an aft wake safety limit (WSL), such that it is protected against wake encounters associated with a non-deviating lead aircraft.

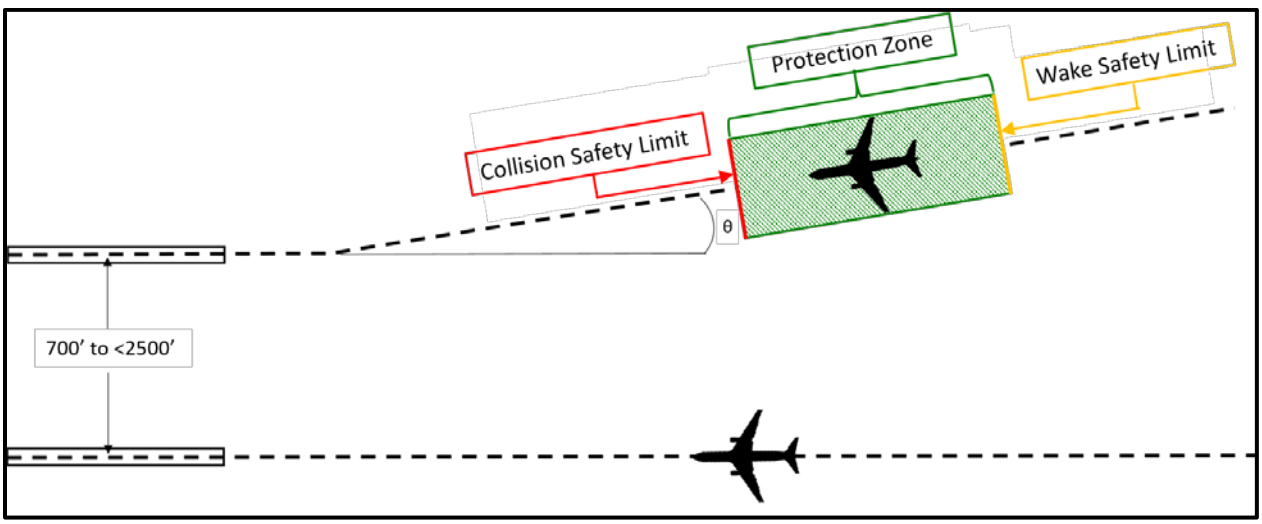

Figure 1-1: Paired Approach Concept

The CSL is the in-trail distance meeting the chosen probability of collision, assuming no buffer is added. When PA operations are implemented, a safety buffer may be incorporated for further protection from collision. This report identifies potential locations for placement of the CSL on the trailing aircraft's approach with respect to collision risk. Wake encounter risk caused by a

[1] Definitions of important terms referenced in this study are included in Appendix H.

[2] Acronyms referenced in this study are included in Appendix I.

[3] Flight Systems Laboratory. *DOT-FAA-AFS-400-09, Flight Crew Performance Study for Paired Approach Operations.* Flight Technologies and Procedures Division, Federal Aviation Administration, January 2016.

[4] Runways spaced less than 700 ft are considered a single runway for wake purposes. Wake avoidance procedures are not required for runways spaced 2,500 ft or greater.

[5] The offset angle θ can range from 0° (i.e., a straight-in approach) up to 3° (i.e., an offset approach).

non-deviating lead aircraft, a missed approach executed by the lead aircraft, a deviating lead aircraft crossing the path of the trailing aircraft, or a deviating trailing aircraft encountering the wake of a lead aircraft was not evaluated in this study. Potential locations for WSL placement on the trailing aircraft's approach are being evaluated by the United States Department of Transportation Volpe Center.

1.1 Background

When visual approaches cannot be conducted, capacity at busy airports has been significantly increased by using closely spaced parallel operations (CSPO).[6] CSPO are conducted on close parallel runways. Close parallel runways are defined as two parallel runways whose extended runway centerline spacing (RCLS) is less than 4,300 ft.[7] The RCLS between parallel runways is one of the main parameters that affects airport capacity by determining whether CSPO can be performed in place of single runway approach operations. In the previous two decades, the introduction of High Update Rate (HUR) surveillance systems, ADS-B, precise navigation capabilities, improved modeling techniques,[8] offset approaches, and specific air traffic equipment and procedures have contributed to reductions in minimum RCLS requirements for many CSPO. A recent Flight Standards study indicated that simultaneous independent CSPO approaches may be conducted down to a minimum RCLS of 2,500 ft.[9] Runway configurations with RCLS less than 2,500 ft must look to other CSPO, such as Simultaneous Offset Instrument Approach (SOIA), simultaneous dependent approaches conducted under FAA Order JO 7110.308B, or PA.[10]

PA procedures are intended to facilitate Instrument Meteorological Conditions (IMC) approaches to closely spaced parallel runways with a minimum RCLS of 700 ft. The procedures are supported by advanced avionics, including ADS-B Out on the lead aircraft and ADS-B In on the trailing aircraft. The trailing aircraft must be equipped with flight deck based interval management (FIM) equipment, including a Cockpit Display of Traffic Information (CDTI) and ADS-B Guidance Display (AGD) that assist the trailing aircraft in maintaining a safe position with respect to the lead aircraft. The CDTI serves as a situational awareness display during the PA operation. The AGD provides IM speed information to the cockpit.

The PA concept and geometry is comprised of simultaneous dependent approaches to parallel runways. The lead aircraft flies an instrument landing system (ILS) approach to one runway; and the trailing aircraft flies a straight-in or offset approach on an Area Navigation/Required Navigation Performance (RNAV/RNP)[11] approach to the adjacent parallel runway, as illustrated in Figure 1-2. The trailing aircraft maintains a desired position between the forward CSL and the aft WSL, which is referred to as the protection zone. This protection zone is intended to protect the trailing aircraft from possible collision and wake encounters from the lead aircraft. The forward

---

[6] Federal Aviation Administration, *NextGen Implementation Plan*, 2016.

[7] Air Traffic Organization, *Order JO 7110.65X, Air Traffic Control*. Federal Aviation Administration, October 12, 2017.

[8] Flight Systems Laboratory, *DOT-FAA-AFS-450-63, Geometrical Models for Aircraft in Terminal Area Risk Analyses*, Flight Technologies and Procedures Division, Federal Aviation Administration, April 2011.

[9] Flight Systems Laboratory, *DOT/FAA/AFS400/R/22, Safety Study of Closely Spaced Parallel Operations with High Update Rate*, Flight Technologies and Procedures Division, Federal Aviation Administration, May 2018.

[10] Flight Standards Service. *Order JO 8260.3D, United States Standards for Terminal Instrument Procedures (TERPS)*. Federal Aviation Administration, February 16, 2018. Current minimum RCLS is 750 ft for SOIA.

[11] The term "RNAV/RNP" is utilized in this study to signify RNAV(GPS) and RNAV(RNP) approaches with flight director guidance flown with a lateral 2σ (95%) total system error (TSE) of 0.08 NM.

CSL protects against the collision hazard area and the aft WSL protects against the wake hazard area.

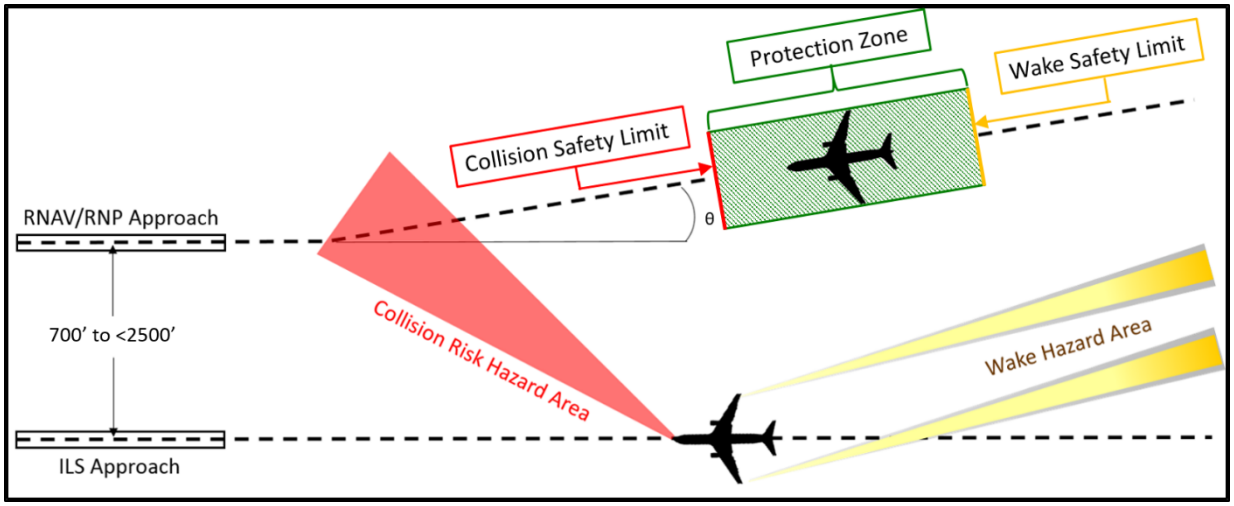

Figure 1-2: Paired Approach Hazard Area and Approach Geometry

Controllers set up aircraft pairs by assessing incoming air traffic and selecting pairs based on equipage, wake category, or other criteria. The aircraft are paired within the protection zone approximately 15 to 20 nautical miles (NM) from the runway threshold. Controllers then issue IM clearance to the trailing aircraft with a time or distance based assigned spacing goal (ASG) relative to the lead aircraft's position. Once IM clearance is obtained, the flight crew inputs the ASG into the FIM equipment. The FIM equipment provides speed guidance to the flight crew in order to manage the ASG, maintaining a position within the protection zone. This continues until a planned termination point is reached. PA operations depend on the ability of ground automation to compute an ASG that will keep the aircraft within the protection zone with enough time for an air traffic controller to respond appropriately in the event of an encroachment of the CSL or WSL.

1.2 Purpose

The purpose of this study was to assist in the development of PA concepts leading to the implementation of PA operations. Paired approach operations facilitate instrument flight rules approaches to closely spaced parallel runways less than 2,500 ft when low visual meteorological conditions or instrument meteorological conditions prevents the conduct of visual operations to Category I minima. Implementation of PA procedures will maintain safety while potentially delivering additional capacity and efficiency benefits by increasing airport throughput.

2 Objectives and Scope

The objective for this study was to conduct analyses to determine CSL placement. CSL placement was attained by assessing the probability of collision risk during PA operations. High-fidelity models of PA scenarios were developed and simulated using Monte Carlo methodology. The resultant output data was analyzed to determine procedural safety limitations of the CSL for PA operations, which are documented within this report. These safety limitations include the minimum in-trail distance of the trailing aircraft from the lead aircraft throughout the approach and the associated diagonal distance between the aircraft for the collision probabilities examined. The CSL results will be used in conjunction with the WSL results in the development of a protection zone.

The scope of this report is limited to collision risk associated with the CSL due to a course deviation of the lead aircraft. The report does not address wake turbulence avoidance, Traffic Collision Avoidance System (TCAS),[12] Airborne Collision Avoidance System X (ACAS-X), PA avionics, radar separation standards, controlled flight into terrain, or the interaction between flight crews, controllers, and PA avionics, such as delegation of responsibilities (e.g., speed issuance).

[12] TCAS was not evaluated in this study. The design of TCAS is not conducive for use during closely spaced parallel operations. TCAS in traffic advisory (TA) only mode, issues a caution to the pilot without a resolution. A TA does not provide adequate information for the pilot to evade another aircraft or make a maneuver contrary to an air traffic control (ATC) climb or descend breakout clearance. The use of TCAS in resolution advisory (RA) mode provides maneuvering information to the pilot; however, it can be assumed that during a closely spaced approach the system may issue an excessive amount of nuisance alerts.

3 Methodology

Experimental methods employed in this study utilized fast-time simulations to assess collision risk associated with PA operations. Section 3.1 describes the testing conducted through the creation of fast-time simulation scenarios to identify parameters having considerable influence on CSL determination. Section 3.2 cites the final set of parameters determined to significantly impact collision risk. Additional information on scenario design is located in Appendix D.

3.1 Fast-Time Simulation

The primary analysis tool for this evaluation was the Airspace Simulation and Analysis Tool – Next Generation (ASATng). ASATng is a Monte Carlo simulation tool developed by Air Traffic Simulation, Incorporated (ATSI) for aviation related safety assessments. Monte Carlo simulations can run millions of simulations for a scenario by repeatedly sampling values from probability distributions for input variables.[13] This will produce a wide range of output results that encompass possible outcomes associated with the varied inputs. In a real-time simulation, only a small amount of variables can be simulated; therefore, fast-time simulation is preferred. Monte Carlo simulations are able to quantify the probability of risk associated with a flight operation. A fast-time simulation must be carefully constructed to accurately determine the probability of collision.

ASATng uses high fidelity models of components of an aviation scenario to ascertain the probability of collision. A wide range of parameters covering operational aspects, such as aircraft performance, aircraft fleet mix, atmospheric conditions, navigation system performance, Air Traffic Control (ATC) monitoring equipment, and ATC surveillance equipment, enable very efficient and realistic modeling of complex scenarios. ASATng also uses official FAA databases of navigation and surveillance facilities, runways, fixes, etc.

3.2 Test Design and Scenarios

A principal safety concern in PA operations is the risk of collision due to an aircraft course deviation (sometimes referred to as a blunder). ASATng was utilized to create operational scenarios to estimate the probability of collision at potential CSL locations. Approach configurations at Boston Logan International Airport (KBOS), Seattle-Tacoma International Airport (KSEA), and San Francisco International Airport (KSFO) were assessed. In addition, a generic airport (KGEN) runway configuration was assessed at an RCLS of 2,500 ft.[14] CSL collision risk is a function of runway approach alignment, runway spacing, runway stagger, airport elevation, fleet mix, navigation systems, aircraft speeds, and the trailing aircraft's position relative to the lead aircraft. Therefore, preferred CSL locations may differ for each approach configuration.

[13] Assessment of collision risk using Monte Carlo techniques requires a significant number of simulations to be performed per scenario as described in Appendix E.

[14] Approach configuration design for scenarios (e.g., runway centerline spacing) was designated by the NextGen – Technology Development and Prototyping Division/Navigation Branch (ANG-C51). PA operations will be limited to parallel runways with centerlines spaced less than 2,500 ft apart.

ASATng simulations consisted of two aircraft initialized on their respective final approach courses with the lead aircraft unexpectedly deviating toward the trailing aircraft's final approach course as depicted in Figure 3-1.[15] Aircraft were released simultaneously to assess the risk associated with a random course deviation in relation to the in-trail distance of the trailing aircraft. To assess collision risk, the trailing aircraft continued the approach without controller intervention. This study focused on the risk of collision based on the starting geometry of the aircraft. It is assumed controller intervention would reduce collision risk. The methodology used to determine collision risk is described in Appendix A.

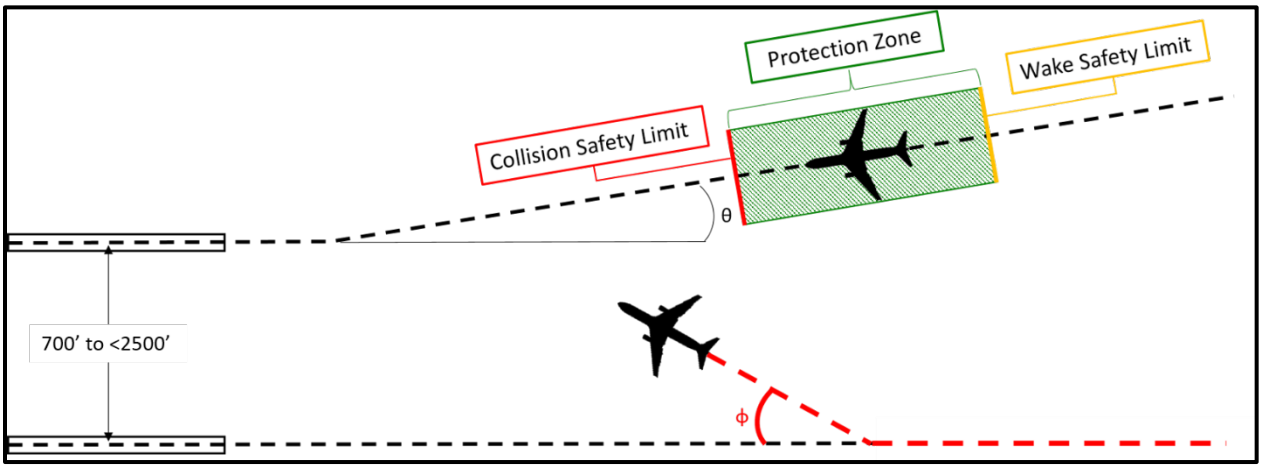

Figure 3-1: Paired Approach with Aircraft Deviation

[15] The deviation angle φ can range from 15° to 35°.

Aircraft release positions in the simulations are depicted in Figure 3-2 for a straight-in approach and Figure 3-3 for an offset approach. Lead aircraft release positions were initially placed at 20 NM from runway threshold, followed by 1 NM decrements until 1 NM from the threshold. Trailing aircraft release positions were established with respect to the lead aircraft, starting abeam of the lead aircraft and continuing at 0.1 NM increments until the point where the collision risk met or exceeded a target level of safety (TLS). Lead and trailing aircraft were released simultaneously during each simulation. Once released, the lead aircraft immediately initiated a turn toward the trailing aircraft's approach course to achieve the assigned deviation angle.

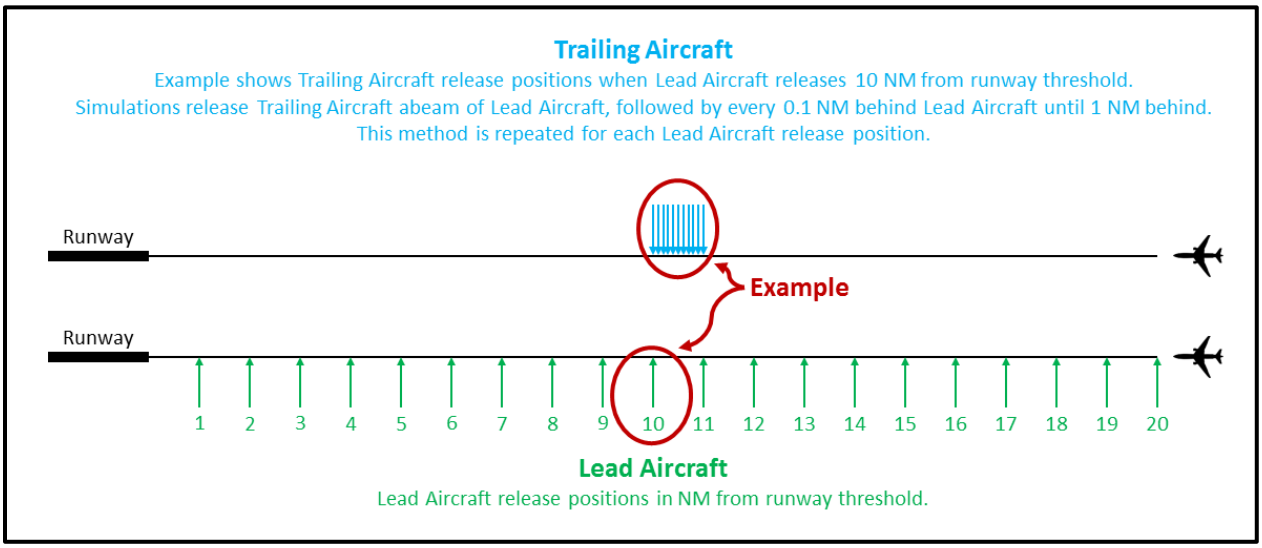

Figure 3-2: Paired Approach Aircraft Scenario Release Positions (Straight-In Approach)

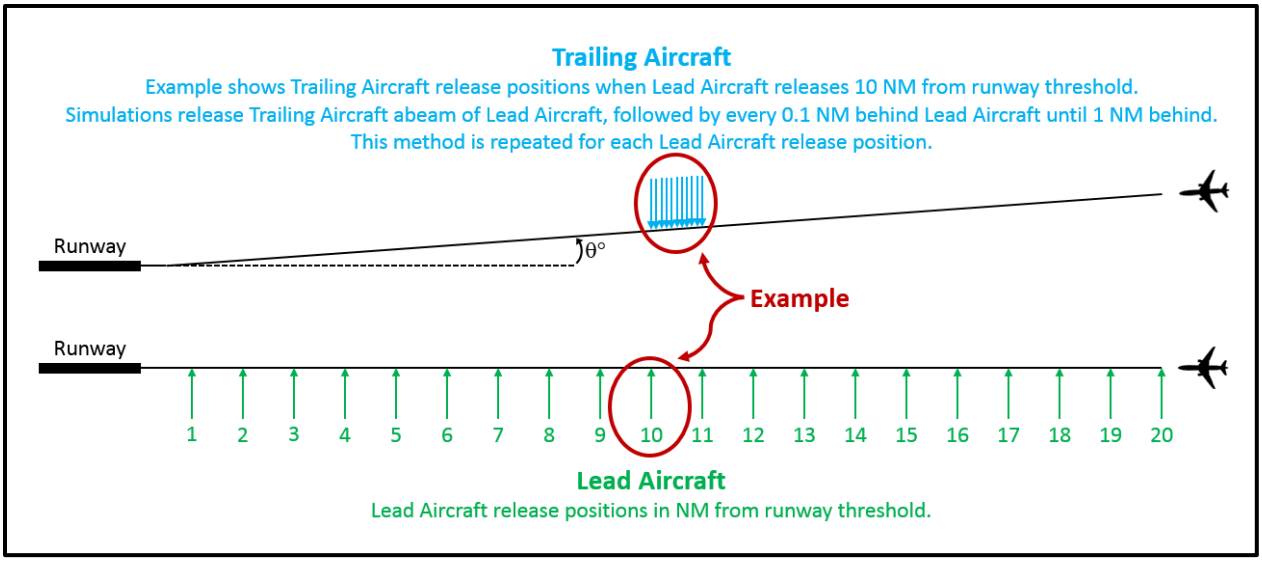

Figure 3-3: Paired Approach Aircraft Scenario Release Positions (Offset Approach)

Aircraft speeds varied throughout each simulation as described in Appendix B. Collision risk varied significantly based upon Δspeed. In order to mimic speed differences between aircraft during a PA flight test in February 2019, scenarios were set up with the lead aircraft flying a constant 170 knots (kts) indicated air speed (IAS) prior to the final approach segment; while the trailing aircraft utilized speeds sampled from a uniform distribution within the range of 170 – 10 kts to 170 + 20 kts. Aircraft simulations within the final approach segment utilized speeds sampled from Johnson distributions according to aircraft type.

The Flight Research and Analysis Group simulated the lateral and vertical paths of the lead aircraft using parameters associated with a Category I ILS instrument approach with a glideslope of 2.85°; while the trailing aircraft used parameters associated with an approach flown with an RNAV/RNP navigation specification with flight director at a glidepath of 3°.[16] Lead and trailing aircraft lateral and vertical probability distributions are described in Appendix C. The lead aircraft deviated toward the approach course of the trailing aircraft at varying angles. The deviation angles were sampled from uniform distributions over the intervals [15°; 25°] and [25°; 35°]. These deviations are commonly referred to as 20° and 30° deviations. Level and descending aircraft deviations were assumed to occur with equal probability.

Each simulation was monitored until the minimum three-dimensional distance between the aircraft pair, referred to as the closest point of approach (CPA), was achieved to determine if a test criterion violation (TCV) had occurred.[17] A TCV is considered a collision for an extremely improbable catastrophic event. A TCV occurs when the center of gravity of the deviating lead aircraft is within 265 ft laterally and 80 ft vertically of the trailing aircraft. The cylindrical TCV volume of the trailing aircraft is depicted in Figure 3-4.

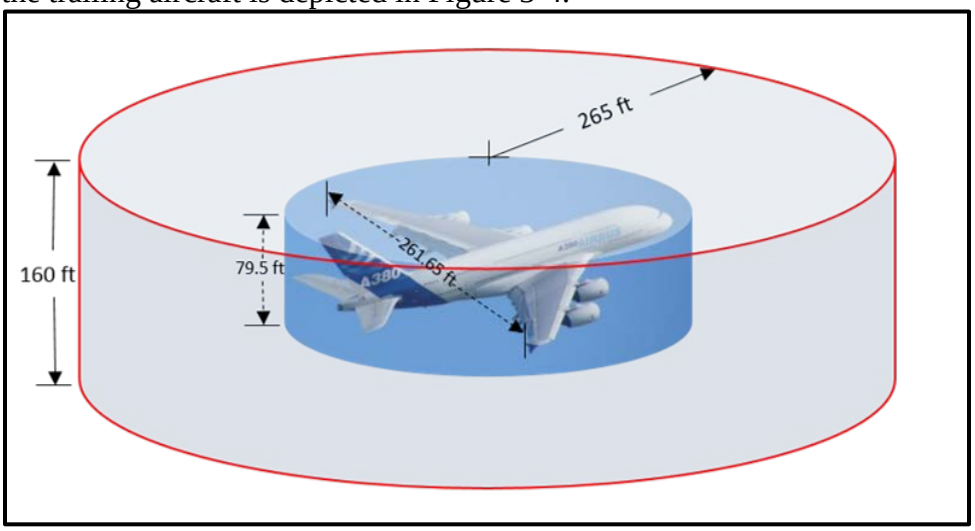

Figure 3-4: TCV Volume

[16] Approach configuration design (e.g., runway approach alignment, glidepath angles, offset angles, and runway stagger) was designated by the NextGen – Technology Development and Prototyping Division/Navigation Branch (ANG-C51).

[17] The three-dimensional distance between aircraft is monitored every two-tenths of a second to identify the CPA.

For this study, aircraft were paired for the purposes of wake turbulence separation minima by aircraft wake category (i.e., CAT A through CAT F)[18] instead of the maximum takeoff weight (MTOW) separation standard (i.e., super, heavy, large, and small). Prior to the wake turbulence recategorization (RECAT) initiative, the FAA classified aircraft for wake turbulence purposes based on the four MTOW weight classes of super, heavy, large, and small. This resulted in greater than necessary separation distances, especially within the heavy weight class.[19] Under RECAT Phase 1.5, aircraft are classified according to wingspan and the aircraft's ability to withstand a wake encounter, as well as the MTOW. This method results in six categories of aircraft for wake turbulence separation purposes as depicted in Table 3-1.

Table 3-1: RECAT Phase 1.5 Wake Categories

Aircraft Wake Category	CAT A	CAT B	CAT C	CAT D	CAT D	CAT E	CAT F	CAT F
Aircraft Weight Class	Super	Heavy	Heavy	Large	Large	Large	Small	Small
MTOW (Pounds)	≥ 300,000	≥ 300,000	≥ 300,000	< 300,000	> 41,000	> 41,000	< 41,000	< 15,500
Minimum Wingspan (ft)	> 245	> 175	> 125	> 125	> 90	> 65	N/A	Any
Maximum Wingspan (ft)	N/A	≤ 245	≤ 175	≤ 175	≤ 125	≤ 90	≤ 125	Any
Aircraft[20] (Examples)	A388	A332 A333 A343 A346 A359 B744 B748 B772 B77L B77W B788 B789	A306 A310 B762 B763 DC10 MD11	-	A319 A320 A321 B712 B733 B734 B737 B738 B739 B752 B753 DH8D E190 GLF5 GLEX MD88 MD90	CL60 CRJ2 CRJ7 CRJ9 E145 E170 E75L E75S GLF4 SF34	B350 BE20 BE40 C560 C56X C680 C750 CL30 CL35 E55P F2TH H25B	C208 C402 PC12

[18] Air Traffic Organization, *Order JO 7110.659C, Wake Turbulence Recategorization*. Federal Aviation Administration, February 29, 2016.

[19] For example, the current heavy-behind-heavy separation is four miles. This separation is appropriate for a B767 following a B747, but not necessary when the B747 is following the B767.

[20] Air Traffic Organization, *Order JO 7360.1D, Aircraft Type Designators*. Federal Aviation Administration, May 24, 2018.

The Volpe Center is addressing wake encounter concerns, distinctly those instances where lead aircraft are larger than trailing aircraft, via determination of WSL placement based on aircraft pairings shown in Table 3-2. For consistency, the same aircraft pairings were utilized to determine the CSL boundary of the protection zone. Aircraft were paired in the simulations as indicated in the table. These pairings were considered the most applicable in terms of wake encounters.

Table 3-2: Aircraft Pair Combinations

Combination	Lead Aircraft	Trailing Aircraft
1	CAT B	CAT A
2	CAT B	CAT D
3	CAT C	CAT D
4	CAT C	CAT E
5	CAT D	CAT E
6	CAT D	CAT F

Aircraft wake category in a PA operation affects the location of the CSL and the WSL. For CSL assessments, aircraft flight characteristics such as final approach Δspeeds between the aircraft pair and flight dynamics associated with the course deviation of the lead aircraft influence collision risk. For WSL assessments, wake vortex physics and aircraft dynamics parameters; namely wingspan, weight, final approach Δspeeds, and roll moment capability influence the risk of wake encounters. This study only analyzed the CSL.

Because trailing aircraft remain on approach regardless of the leader's deviation, only the trailing aircraft's speeds, regardless of wake category, affect the collision risk assessment. For simulations conducted in this study, CAT A was represented by the Airbus A320, which has similar approach speeds to the Airbus A380.[21] Wake CAT B was represented evenly in a 50/50 percentage split between the Airbus A330-300 (A333) and the Boeing 747-400 (B744). Wake CAT C was represented by the Boeing 767-300 (B763), CAT D was represented evenly in a 50/50 percentage split between the Airbus A320 (A320) and the Boeing 737-800 (B738), and CAT E by the a Embraer Regional Jet 145 (E145). The small CAT F aircraft were represented by the Saab-340 (SF34) turboprop aircraft.[22] Each aircraft type had different final approach speeds and dynamics.[23]

[21] The A320 was an appropriate Category A model because its final approach speeds are representative of an A380. Airbus Facts and Figures July 2018, Airbus Press Office.

[22] The SF34 was an appropriate Category F model because its final approach speeds are representative of a wide variety of other aircraft within the wake category; and its wingspan (~71 ft) and MTOW (~29,000 lbs.) fall in line with RECAT 1.5 description of Category F (see Table 3-2).

[23] Category B and Category D aircraft were represented by a 50/50 percentage split, representative of the approximate fleet mix of the analyzed airports.

Table 3-3 shows the arrival percentage of aircraft for each wake category during the one-year period from January 1, 2017 – December 31, 2017 at the three airports evaluated in this study.[24]

Table 3-3: Airport Arrivals by Aircraft Wake Category for 2017

Airport	CAT A (%)	CAT B (%)	CAT C (%)	CAT D (%)	CAT E (%)	CAT F (%)	Total (%)
KBOS	0.05	4.59	2.10	67.30	11.48	14.48	100.00
KSEA	0.00	3.61	2.81	75.32	16.93	1.32	100.00
KSFO	0.56	11.20	1.19	63.27	19.63	4.16	100.00
Average	0.20	6.47	2.03	68.63	16.01	6.65	100.00

[24] The total number of actual approaches to the three airports analyzed for 2017 were comprised of hundreds of different aircraft models, but the majority of approaches were executed by a select few. Of the total approaches, over 70%, 80%, 90%, and 98% were performed by 10, 14, 23, and 61 aircraft models, respectively. The 10 most prevalent aircraft models (i.e., 70%) were the Wake Category D A319, A320, A321, B737, B738, B739, DH8D, & E190; and Category E CRJ2 & E75L. The inclusion of the Wake Category D B752; Category E CRJ7 & E75S; and Category F C402 comprised the 14 aircraft accounting for 80% of all approaches. The addition of the Wake Category B A332, B744, B772, B77W, & B789; Category C B763; Category D B712 & B753; and Category E CRJ9 comprised the 23 aircraft accounting for 90% of all approaches.

3.2.1 Test Design and Scenarios –Airport Configurations

Scenarios were created and evaluated for KBOS, KSEA, and KSFO. These three airports are considered prime candidates for PA operations. KGEN was modeled as a typical Core 30 airport configuration at the upper limit of RCLS for a PA operation. Parameters were set and evaluated as described in Table 3-4:

Table 3-4: Airport Configuration Parameters

Parameters \ Airport	KGEN Offset	KGEN Straight-In	KBOS Offset	KBOS Straight-In	KSEA Straight-In	KSEA Straight-In	KSFO Offset
ILS Approach Glideslope	2.85°	2.85°	2.85°	2.85°	2.85°	2.85°	2.85°
RNAV/RNP Glidepath	3°	3°	3°	3°	3°	3°	3°
RCLS	2,500 ft	2,500 ft	1,500 ft	1,500 ft	800 ft	1,700 ft	750 ft
ILS Runway Length	10,000 ft	10,000 ft	8,851 ft	8,851 ft	11,901 ft	9,426 ft	10,602 ft
RNAV/RNP Runway Length	10,000 ft	10,000 ft	7,864 ft	7,864 ft	9,426 ft	8,500 ft	11,870 ft
Field Elevation	2,500 ft	2,500 ft	19 ft	19 ft	432 ft	432 ft	13 ft
ILS FAF Dist from TH[25]	5.00 NM	5.00 NM	5.39 NM	5.39 NM	4.67 NM	4.68 NM	5.74 NM
RNAV/RNP FAF Dist from TH	4.76 NM	4.76 NM	5.13 NM	5.13 NM	4.43 NM	4.48 NM	5.44 NM
Approach Offset Angle	3°	0°	2°	0°	0°	0°	3°
Runway TH Stagger[26]	0 ft	0 ft	990 ft	990 ft	0 ft	0 ft	0 ft
Lead Approach Localizer	I-GEN	I-GEN	I-BOS	I-BOS	I-SNQ	I-SZI	I-SFO
Lead LOC-TH Dist	11,000 ft	11,000 ft	10,909 ft	10,909 ft	12,908 ft	10,437 ft	11,694 ft
Lead Runways	36R	36R	4R	4R	16L	16C	28L
Trailing Runways	36L	36L	4L	4L	16C	16R	28R

[25] Final approach fix (FAF) distances were taken from approach plates where applicable, others were determined using the appropriate GS angle and FAF altitude evaluated in this study for the trailing aircraft.

[26] Parallel runways with aligned runway thresholds (i.e., no stagger) and negligible stagger (i.e., less than 30 ft) are depicted as 0 ft throughout this report.

3.2.2 Test Design and Scenarios – Modified Special Case Airport Configurations

Scenarios were created to determine the effect of speed variance on placement of the CSL. More specifically, scenarios were created to assess lead and trailing aircraft maintaining a constant speed differential throughout the approach. A baseline airport configuration at KSFO was used for comparative purposes. The modified configurations consisted of:

- Simulations with lead aircraft flying a constant 150 kts (instead of 170 kts) prior to the final approach segment; while the trailing aircraft utilized speeds sampled from a uniform distribution within the range of 150 – 10 kts to 150 + 20 kts. Aircraft simulations within the final approach segment utilized final approach IAS.
- Simulations with lead and trailing aircraft maintaining a constant speed differential. The lead aircraft maintained a constant speed of 150 kts throughout the entire approach (instead of 170 kts at initiation followed by a deceleration to a final approach speed [FAS]). Scenarios were conducted for trailing aircraft speeds of 140 kts, 145 kts, 150 kts, 155 kts, 160 kts, 165 kts, and 170 kts.

3.3 Simulation Assumptions

Unless noted otherwise, the following assumptions were made regarding the requirements and conduct of PA operations for this study:

- Lead aircraft speed prior to the final approach fix (FAF) maintained a constant 170 kts IAS until a variable deceleration point (see Appendix B)[27]
- Trailing aircraft speed prior to the FAF maintained a constant speed sampled from a uniform distribution from 170 – 10 kts to 170 + 20 kts IAS until a variable deceleration point (see Appendix B)[28]
- Lead aircraft were equipped with ADS-B Out and trailing aircraft were equipped with ADS-B In
- Lead aircraft were flown using Category I ILS
- Trailing aircraft were flown using RNAV/RNP with flight director (i.e., flight director and/or autopilot required)
- Vertical guidance was utilized
- Altimeter settings were based on local airport conditions
- Temperature profile was based on the International Standard Atmosphere with winds at zero knots under the assumption that temperature variance would impact each aircraft similarly
- Final approach course aligned with the extended runway centerline 0.43 NM from the runway threshold for scenarios with an offset approach
- Wind speed was set to zero knots under the assumption that wind speed would have a similar impact on each aircraft during a parallel approach or an offset approach
- Level and descending course deviations were varied at values ranging from 15° to 35°. These values were determined from deviation data taken by MITRE Center for Advanced Aviation System Development[29] at 12 airports during fiscal years 2008 through 2012, during Simultaneous Independent Parallel Instrument Approaches conducted in less than visual conditions. Probability density functions were developed from data obtained from simulations. Deviation angles from these probability density functions were sampled and applied to each simulation.

[27] Additional simulations were performed utilizing alternate speed profiles as described in Section 3.2.3.

[28] Additional simulations were performed utilizing alternate speed profiles as described in Section 3.2.3.

[29] Massimini, S.V., G.C. McNeil, N. Tene, *MP090245, Frequency and Severity of Deviations during Simultaneous Independent Approaches to Parallel Runways – A 2009 Update*, The MITRE Corporation Center for Advanced Aviation System Development, September 2009.

3.4 Independent Variables

Independent variables are parameters controlled by the experimenter. Changing an independent variable has no impact on other independent variables. Independent variables are parameters that, when changed, directly affect the outcome of the results. The following parameters were used to model the complex operational scenarios in this study:

- Aircraft pairing fleet mix
- Aircraft wake category
- Aircraft performance
- Airport elevation
- Atmospheric conditions
- Course deviations
- FAF distance to runway threshold
- IAS inside the FAF
- IAS prior to FAF
- Localizer distance to runway threshold
- Navigation system performance
- RCLS
- Runway lengths

3.5 Dependent Variables

Dependent variables are variables that change in response to independent variables. If an independent variable is changed, then an effect is seen in the dependent variables. The following dependent variables were assessed in this study:

- TCV rate, which correlates to the probability of a collision (N.B., a TCV is considered a collision in a paired approach operation)
- Δspeed, which is the speed difference between the lead and trailing aircraft

4 Data Analysis

As described in Methodology (see Section 3), collision risk was assessed for approach configurations at four airports: KGEN, KBOS, KSEA, and KSFO. Unless otherwise noted, scenarios for PA operations were set up for straight-in approaches and/or offset approaches with the:

- Aircraft pair combinations of wake categories B leading A, B leading D, C leading D, C leading E, D leading E, and D leading F
- Lead aircraft course deviations 20° level, 20° descending, 30° level, and 30° descending
- Lead aircraft using Category I ILS and trailing aircraft flying RNAV/RNP
- Lead aircraft release positions from 20 NM to 1 NM from runway threshold in 1 NM decrements
- Trailing aircraft release positions starting abeam the lead aircraft and continuing at 0.1 NM increments until the point where the collision risk met or exceeded a likelihood of risk

The analysis methodology used to determine collision risk is described in Appendix A. Course deviation probability density functions of 20° and 30° have been created from data collected during actual simultaneous independent parallel instrument approaches during instrument flight conditions. The four mutually exclusive types of deviation events (previously noted in the scenario configurations above) were considered in this study.

The study measured the in-trail distance of the trailing aircraft at the point where the collision risk met or exceeded a probability of collision, such as 1×10^{-9} per operation. This was done by starting the trailing aircraft abeam of the lead aircraft and increasing the in-trail distance by 0.1 NM until the desired collision risk value was exceeded. The CSL is the closest in-trail distance to exceed the chosen probability of collision, assuming no buffer is added.

4.1 Collision Risk

Risk is the composite of predicted severity and likelihood (i.e., probability) of the potential effect of a hazard. To represent an event with the highest severity, a hazard was selected which produced a catastrophic effect. The likelihood of that catastrophic effect is very low and classified as extremely improbable (i.e., less than 1×10^{-9}).

In this research, the hazard is an unexpected deviation of the lead aircraft toward the trailing aircraft's final approach course. The effect of the hazard is the potential for an incursion by the lead aircraft into the TCV volume of the trailing aircraft, which is considered a mid-air collision (classified as catastrophic).

Analysis performed on data from this report generated results to identify CSL in-trail distances considering different levels of risk acceptance.[30] Figure 4-1 depicts the CSL in-trail distances for various levels of probability from 1×10^{-7} to 1×10^{-10} for CAT C leading CAT D aircraft at KSFO.

For example, the in-trail distances may be reduced when using what is referred to as an extremely remote event of less than 1×10^{-7} per operation in lieu of the extremely improbable event referenced throughout this report.[31] The results show that for the maximum speed expansion allowed in this study, when the lead aircraft is flying faster than the trailing aircraft, the effects of varying collision risk tolerance have a minimal effect on CSL. As aircraft speed differences shift to compression, when the lead aircraft is flying slower than the trailing aircraft, the CSL varies substantially with regard to tolerable risk. A target level of safety of 1×10^{-9} was used as a baseline for the remainder of the analysis in this report. These calculations were performed without changing the TCV volume of the trailing aircraft. For Figure 4-1 and Table 4-1, in order to maintain a CSL with the indicated TLS, a distance greater than the indicated value should be selected for each distance from runway threshold.

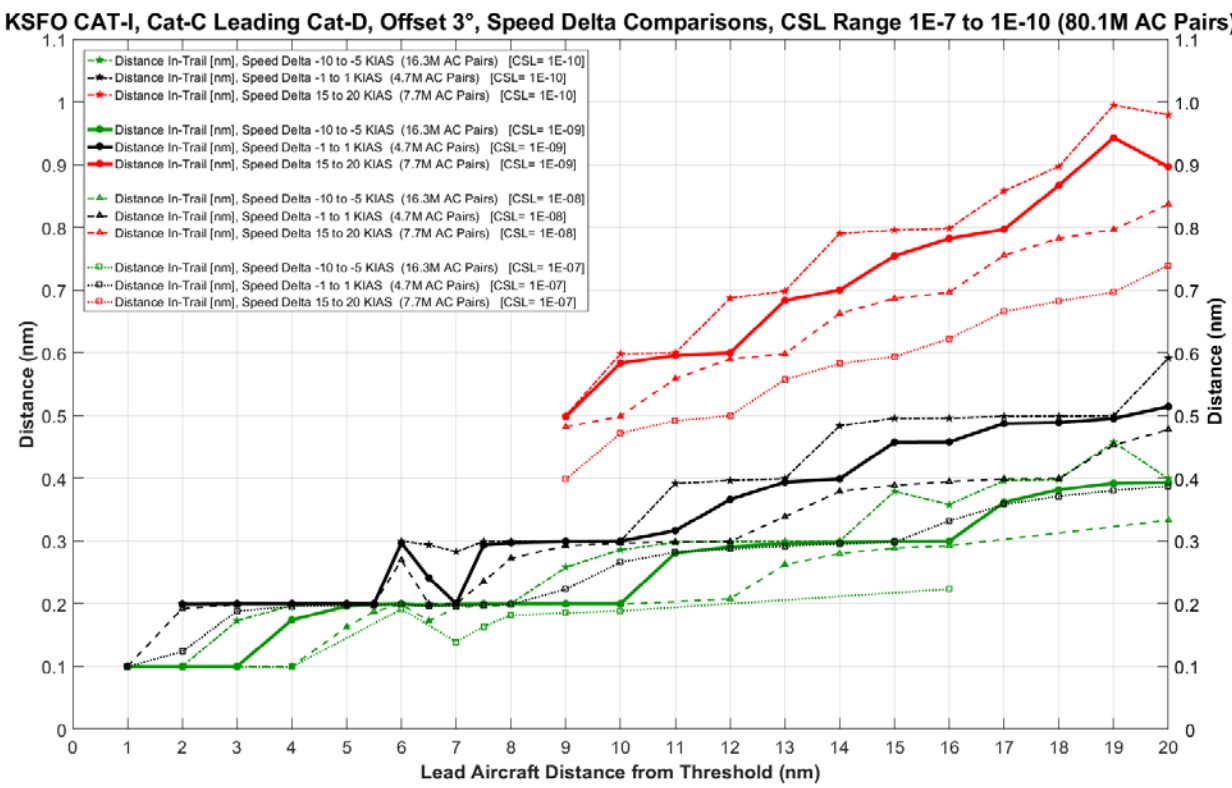

Figure 4-1: KSFO CSL Collision Risk Tolerance

[30] An example of an abbreviated output file generated by ASATng for used in determining collision risk in this study is included in Appendix G.

[31] Air Traffic Organization, *Safety Management System Manual, Air Traffic Control*, Table 3.5, Federal Aviation Administration, April 2019.

Table 4-1 identifies the trailing aircraft's CSL in-trail distance (in NM) behind the lead aircraft for CAT C leading CAT D aircraft at KSFO. An in-trail distance is given at discrete points along the approach course. The table indicates CSL locations as risk tolerance levels changed from 1×10^{-7} per operation to 1×10^{-10} per operation. The CSL in-trail distance increased by roughly 0.1 NM for each order of magnitude change from 1×10^{-7} to 1×10^{-10}.

Table 4-1: KSFO CSL Collision Risk Tolerance

	OFFSET			
Lead Aircraft Distance from TH (NM)	TLS 1×10^{-7}	TLS 1×10^{-8}	TLS 1×10^{-9}	TLS 1×10^{-10}
20	0.64	0.77	0.87	0.90
19	0.61	0.73	0.83	0.97
18	0.59	0.70	0.79	0.88
17	0.58	0.69	0.78	0.80
16	0.56	0.66	0.70	0.79
15	0.53	0.60	0.69	0.77
14	0.50	0.59	0.68	0.74
13	0.49	0.58	0.60	0.69
12	0.47	0.54	0.60	0.62
11	0.44	0.50	0.58	0.60
10	0.40	0.48	0.50	0.59
9	0.36	0.40	0.47	0.50
8	0.24	0.29	0.30	0.36
7	0.19	0.20	0.28	0.30
6	0.19	0.20	0.25	0.30
5	-	0.19	0.20	0.20
4	0.10	0.17	0.20	0.20
3	0.10	0.10	0.19	0.20
2	0.10	0.10	0.16	0.20
1	0.10	0.10	0.10	0.15

4.2 CSL Analysis

During data analysis of the paired approach concept, parameters were examined that were theorized to affect the outcome of the study. Section 4.2.1 and Section 4.2.2 present data analysis associated with parameters determined to influence placement of the CSL. Section 4.2.3 presents comparative data analysis with results generated in Section 4.2.1 and Section 4.2.2.

The Δspeed between aircraft had a significant role in CSL determination. Therefore, results were analyzed by Δspeed bins in addition to the composite analysis. The bins represented the difference in speed between the two aircraft at the CPA of each simulation. Bins with negative Δspeed indicate an aircraft pair where the lead aircraft was flying faster than the trailing aircraft, which is referred to as aircraft expansion. Bins with positive Δspeed indicate an aircraft pair where the trailing aircraft was closing on the lead aircraft, which is referred to as aircraft compression. These included bins of -10 kts to less than -5 kts, -5 kts to less than -1 kts, -1 kts to less than 1 kts, 1 kts to less than 5 kts, 5 kts to less than 10 kts, 10 kts to less than 15 kts, and 15 kts to 20 kts.

Each airport approach configuration was analyzed for six aircraft wake-category pair combinations. Initial results for KGEN indicate aircraft pairing would not impact the location of the CSL in a significant manner. Therefore, a comparative analysis was performed between the six aircraft pair combinations. The combinations did not significantly influence the determination of the CSL, as depicted in Figure 4-2. Each color represents a different speed bin for each of the six aircraft pair combinations. The braiding of these lines suggests that there is no correlation between aircraft pairing and CSL determination. Additional analysis for KSFO reaffirmed the assumption (see Table 4-9).

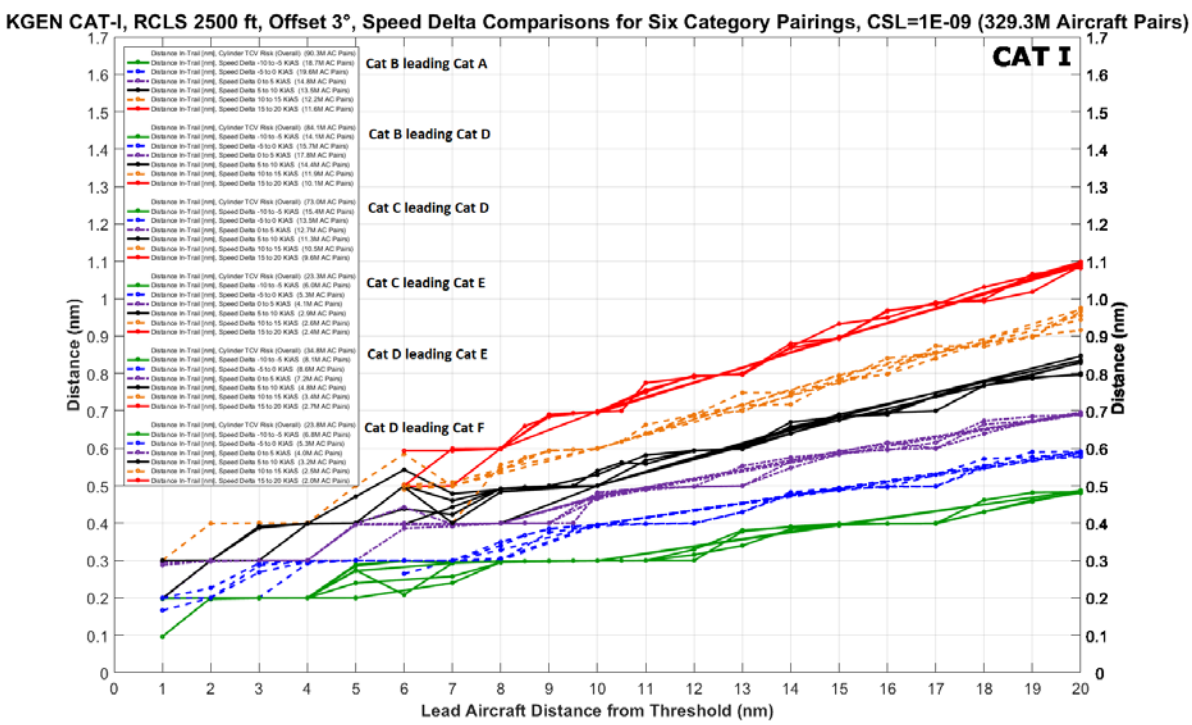

Figure 4-2: KGEN CSL Comparison of Aircraft Pairing Combinations

Runway configurations with RCLS values of 750 ft at KSFO, 800 ft and 1,700 ft at KSEA, 1,500 ft at KBOS, and 2,500 ft at KGEN, were utilized in this study. RCLS had an impact on CSL determination. Figure 4-3 represents the airport runway configurations with the smallest (KSFO) and the largest (KGEN) RCLS analyzed in this study. Both configurations consisted of aligned runway thresholds with a 3° offset. A correlation existed between RCLS and CSL placement represented by the distinguishable gap between solid (KGEN) and dashed (KSFO) lines in the figure. Results indicated that smaller RCLS yielded a lower value for CSL placement. Other factors, such as offset angle and runway threshold stagger, may contribute to the placement of the CSL.

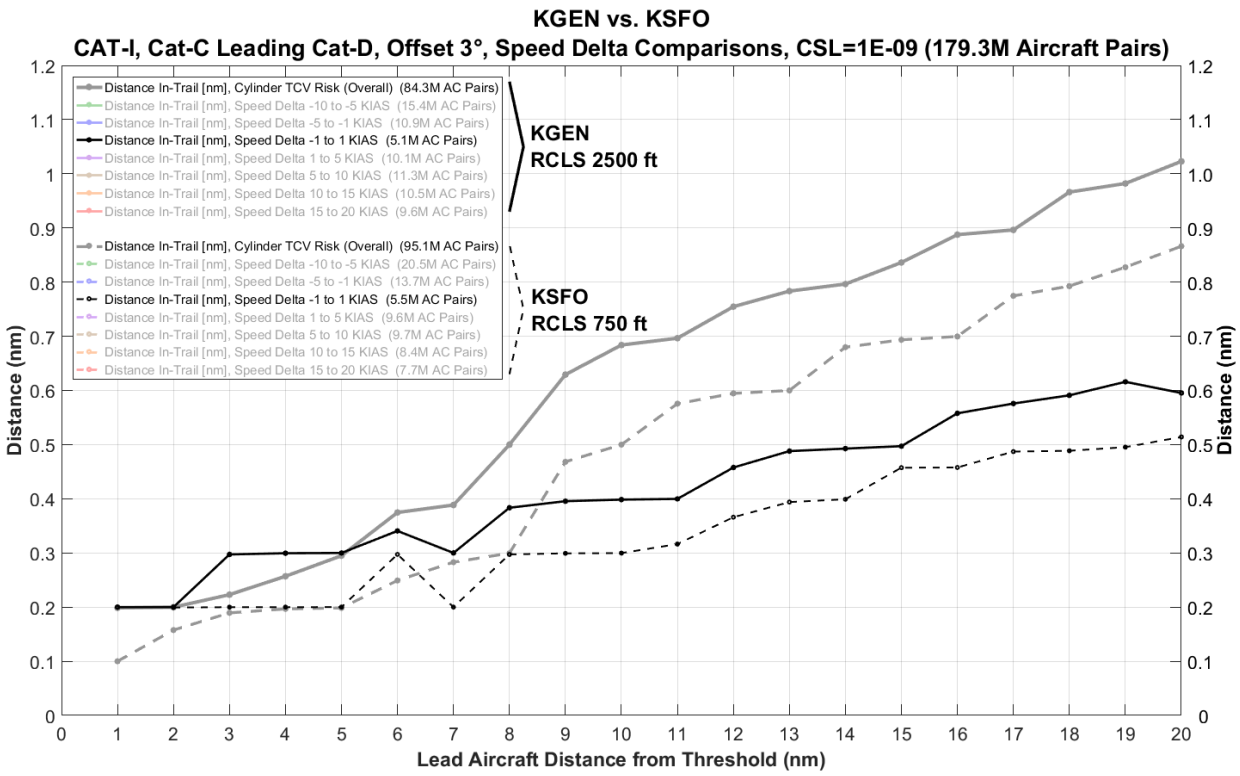

Figure 4-3: KGEN vs KSFO CSL Comparison of RCLS

Figure 4-4 is an example of the graphical depiction of data generated for this study. Each color represents a different speed bin. The colors associated with legends remain consistent for figures in this report. The paragraphs below describe similar trends exhibited across all airports analyzed in this study.

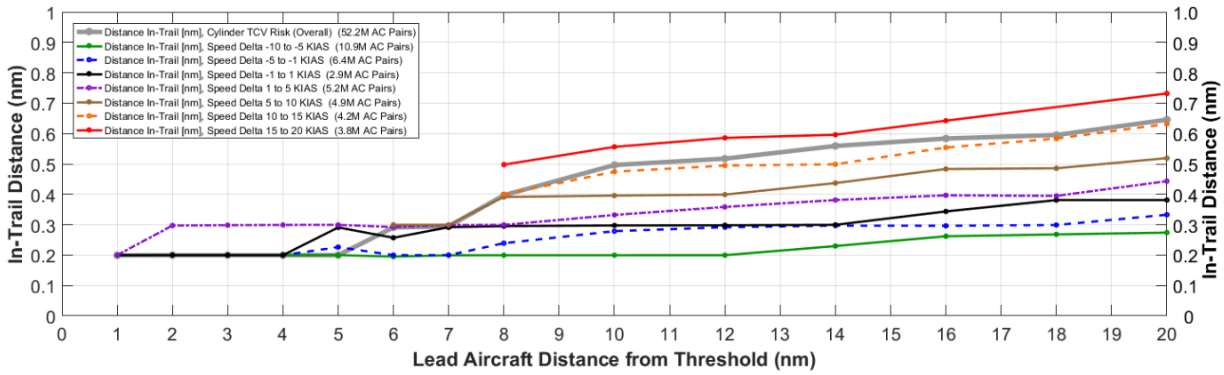

Figure 4-4: Example CSL for CAT C Leading CAT D

A trend was apparent throughout the course of the study that exhibited a slight spike in collision risk near the FAF for all airport configurations analyzed. This trend was attributed to more aircraft pairs experiencing compression near or around the FAF (see Appendix B). This was caused by the lead aircraft initializing at or attaining a final approach speed sooner than the trailing aircraft. Because the fastest final approach speed over the entire range of aircraft analyzed in this study was lower than the slowest initial speed analyzed, it was more likely for compression to occur starting at the slowdown point and progressing until reaching a peak near the FAF, where the risk of collision is increased (see Appendix B).

The gray line depicts the "overall" CSL for the operation at each specific location. Because the gray line represents the overall CSL; presumably, the location would fall near the mean where Δspeed was minimal between the purple line (1 kts to 5 kts) and blue line (-5 kts to -1 kts). However, it fell between the red line (15 kts to 20 kts) and orange line (10 kts to 15 kts). This was due to a significantly greater number of TCV's at higher speed compressions (denoted by the red line) compared to the total number of TCV's from all other speed bins. This is further demonstrated as the aircraft nears the FAF. The red line terminates due to a lack of aircraft pairs experiencing substantial speed compression, causing the gray line to be drawn toward the mean location between moderate compression and moderate expansion. This was consistent throughout all airport approach configurations.

For straight-in approaches, the CSL results for wake category pair CAT C leading CAT D are depicted as figures in Section 4.2.1 through Section 4.2.2. Because the analysis was performed with the lead aircraft flying an ILS approach, the lateral deviation from the extended runway centerline increases farther from the runway threshold. Figure 4-5 depicts the simulation initiation points of aircraft pairs farthest from the runway threshold to be potentially very close together (Simulation 1), these points move farther apart as the initiation gets closer to the threshold (Simulation 2). The aircraft then decelerated to final approach speeds, resulting in a slight increase of the CSL until reaching the FAF. The increase was caused by additional compression as the lead aircraft started decelerating prior to the trailing aircraft. CSL results of straight-in approaches for other wake category pairs are contained in Appendix F.

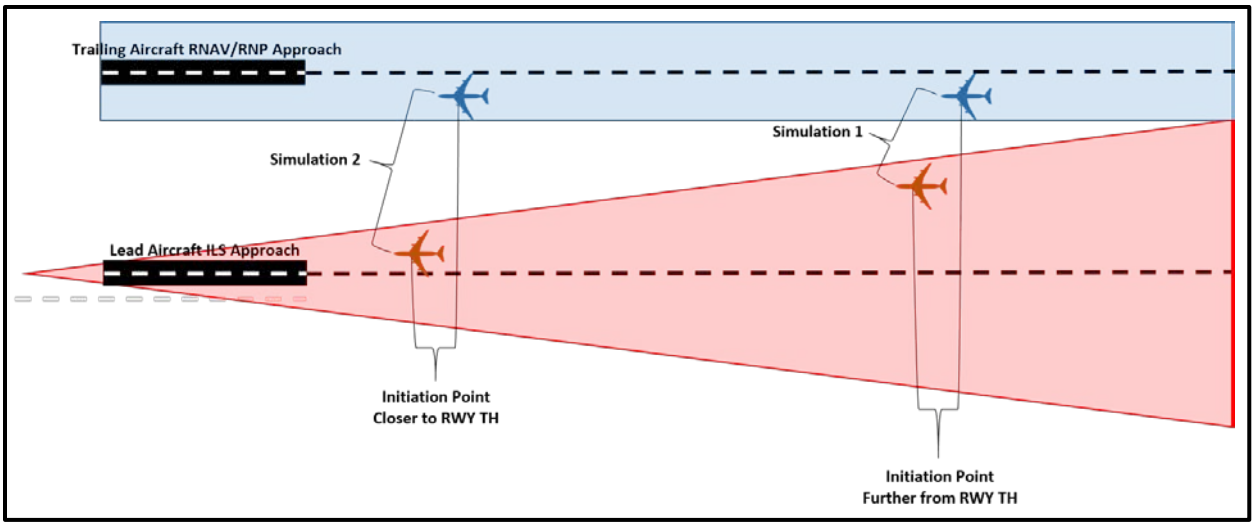

Figure 4-5: Example of Initiation Points

For offset approaches, the CSL results for wake category pair CAT C leading CAT D are depicted as figures in Section 4.2.1 through Section 4.2.2. In-trail distances for all speed bins represented decreased relatively linearly from 20 NM (from runway threshold) until the aircraft began deceleration to final approach speeds. This deceleration phase resulted in a stabilization of in-trail distances beginning approximately 2 NM from the FAF and continuing through the conclusion of the approach course. This stabilization was caused by additional compression as the lead aircraft began its deceleration to FAS sooner than the trailing aircraft, thus reaching its FAS while the trailing aircraft was potentially flying at the initial speed. Certain speed bins abruptly terminated at specific distances from runway threshold (e.g., the red line depicting 15-20 kts of compression). These instances were related to the total amount of aircraft pairings representing Δspeed at that location. When using the red line as an example, there were no pairings past 8 NM from runway threshold experiencing 15-20 kts of compression. Because CAT D aircraft final approach speeds (see Appendix B) were lower than those of the CAT C aircraft, it was impossible to experience more than 5 kts of compression inside the FAF, as evidenced by the purple line.

The FAA Flight Research and Analysis Group was asked to determine the CSL in-trail distances for six aircraft pairings. Four pairings of the six included CAT D aircraft, the most prevalent commercial aircraft at the airports analyzed, as previously indicated in Table 3-3. Only figures

dealing with CAT C leading CAT D are included in Section 4. Figures and tables for other category pair combinations are included in Appendix F.

The tables in the following subsections reflect the overall data analysis of the study. Unless otherwise indicated, all values in these tables represent trailing aircraft in-trail distances measured in nautical miles. For all tables and figures throughout the remainder of this report, a distance greater than the indicated value should be selected to ensure a CSL which will protect against an extremely improbable catastrophic event of less than 1×10^{-9}.

4.2.1 CSL Analysis – Generic Airport Configurations

The generic airport (KGEN) runway configuration is shown in Figure 4-6. Runways 36L and 36R are separated by an RCLS of 2,500 ft, with aligned runway thresholds. Simulations placed the lead aircraft on runway 36R and the trailing aircraft on runway 36L. Scenarios for both a straight-in approach and a single offset approach were conducted and analyzed.

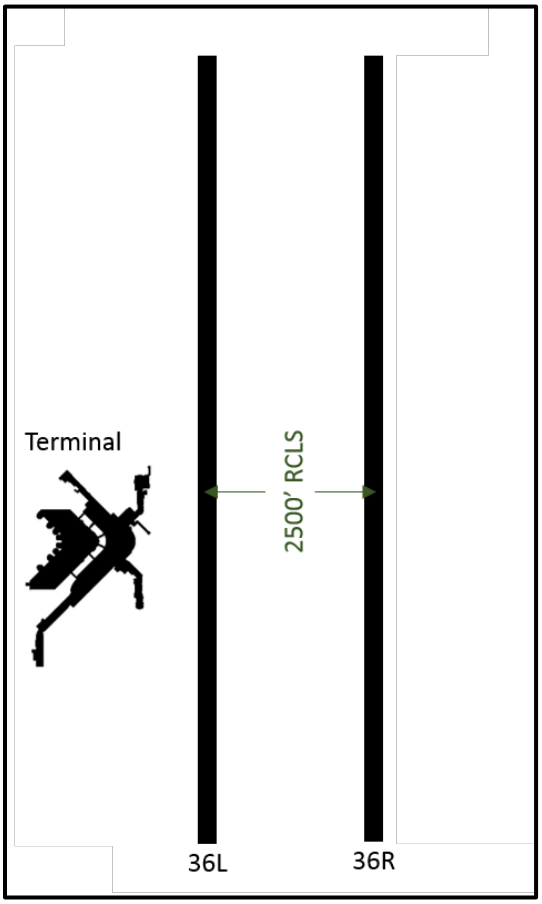

Figure 4-6: KGEN Runway Configuration

CSL results for a straight-in approach for wake category pair CAT C leading CAT D are depicted in Figure 4-7. Results for straight-in approaches display a slight slope from 20 NM (from runway threshold) until the deceleration phase when the CSL stabilizes. The aircraft then decelerated to final approach speeds, resulting in a slight increase of in-trail distances until reaching the FAF. The figure also depicts the diagonal distance between the aircraft.

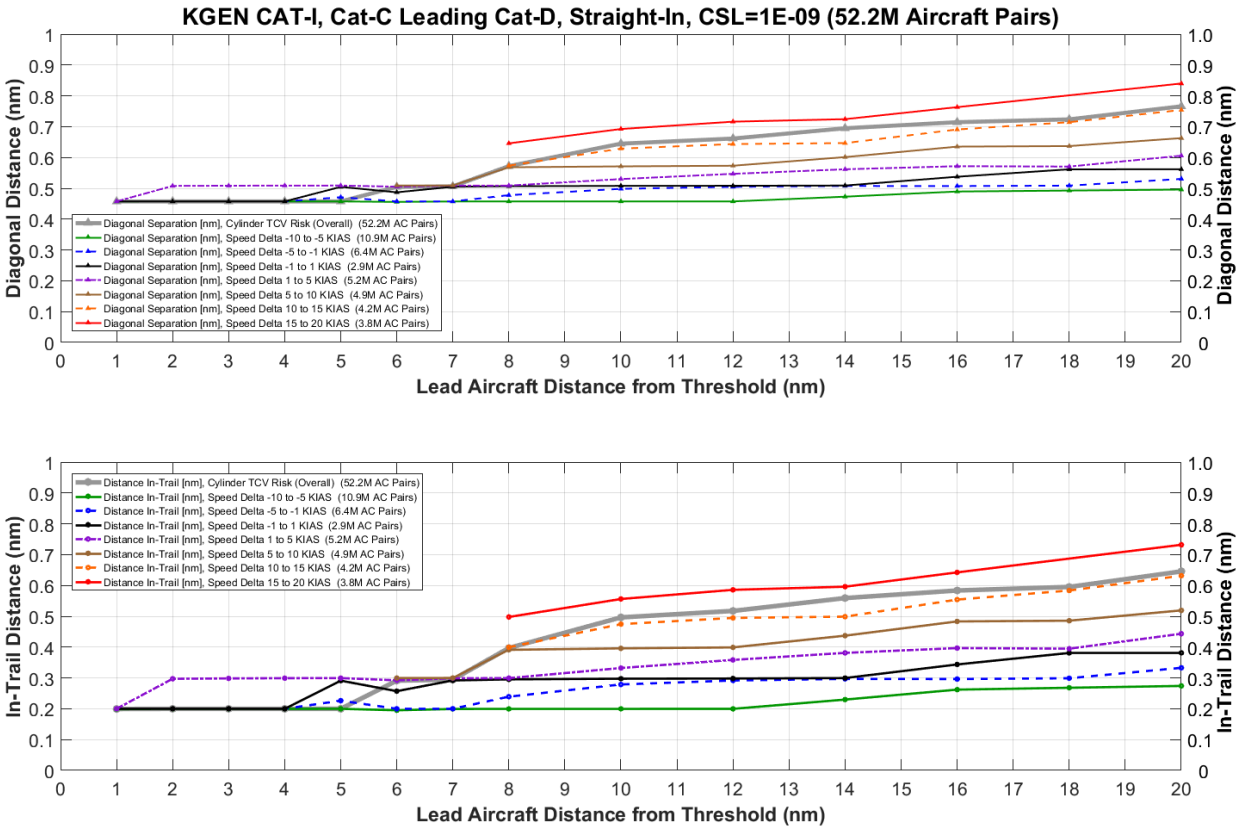

Figure 4-7: KGEN CSL for CAT C Leading CAT D (Straight-In with 2,500 ft RCLS)

CSL results for an offset approach for wake category pair CAT C leading CAT D are depicted in Figure 4-8. In-trail distances for all speed bins represented decreased relatively linearly from 20 NM (from runway threshold) through deceleration to final approach speeds. The figure also depicts the diagonal distance between the aircraft, which maintained a relatively linear decrease in separation throughout the entire approach course.

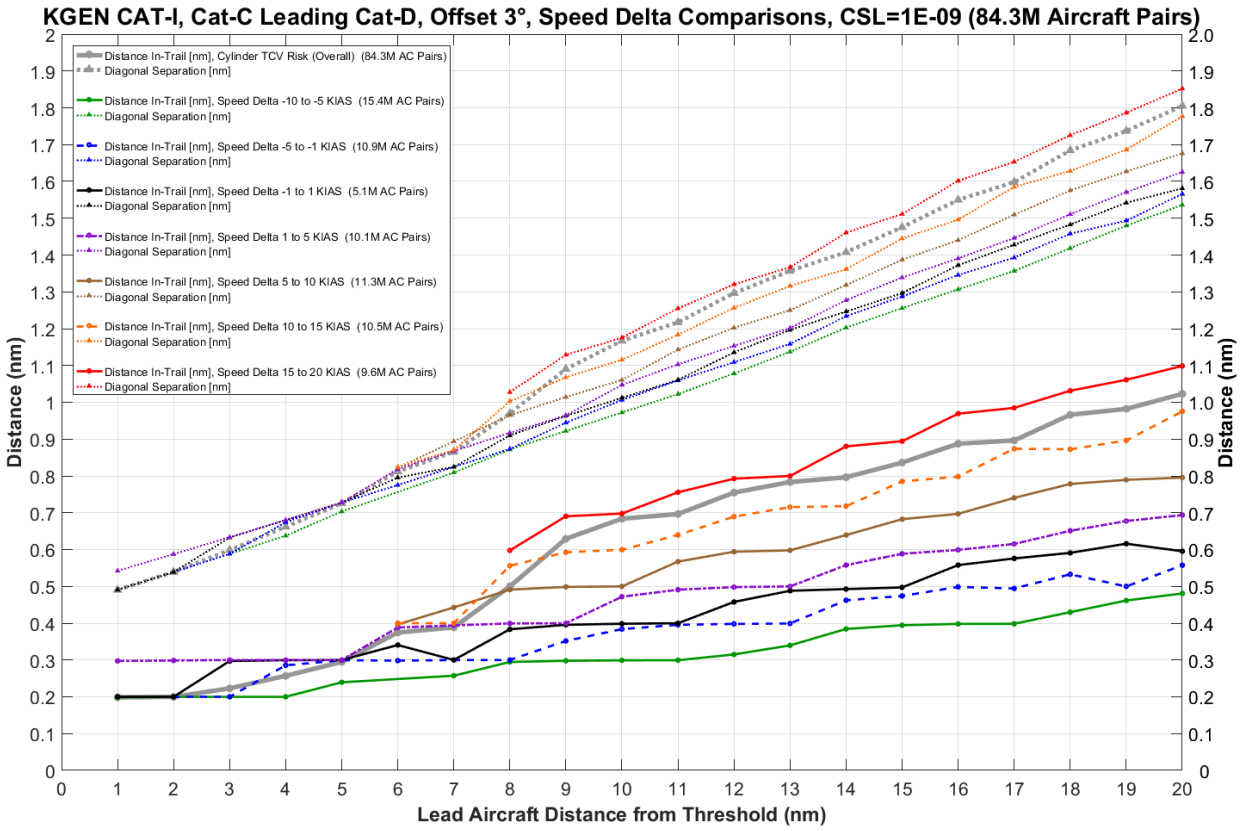

Figure 4-8: KGEN CSL for CAT C Leading CAT D (3° Offset with 2,500 ft RCLS)

Table 4-2 identifies the trailing aircraft's overall CSL in-trail distance (in NM) behind the lead aircraft for each aircraft pair with a collision risk of 1×10^{-9}.[32] An in-trail distance is given at discrete points along the approach course. The column titled "Worst Case" identifies the aircraft pair whose in-trail distance could serve as a CSL for all six wake-category combinations at the indicated distance from runway threshold.

Table 4-2: KGEN CSL for All Aircraft Pairs (Straight-In and 3° Offset)

	STRAIGHT-IN							OFFSET						
Lead Aircraft Distance from TH (NM)	CAT B - A	CAT B - D	CAT C - D	CAT C - E	CAT D - E	CAT D - F	Worst Case	CAT B - A	CAT B - D	CAT C - D	CAT C - E	CAT D - E	CAT D - F	Worst Case
20	0.63	0.60	0.65	0.65	0.66	0.66	D - E	1.00	1.00	1.02	1.02	1.02	1.00	C - D
19	-	-	-	-	-	-	-	0.99	0.98	0.98	-	-	-	B - A
18	0.59	0.60	0.60	0.60	0.59	0.61	D - F	0.95	0.94	0.97	0.95	0.93	0.96	C - D
17	-	-	-	-	-	-	-	0.92	0.90	0.90	-	-	-	B - A
16	0.58	0.58	0.58	0.59	0.59	0.59	C - E	0.89	0.88	0.89	0.88	0.87	0.88	C - D
15	-	-	-	-	-	-	-	0.82	0.85	0.84	-	0.84	0.85	B - D
14	0.56	0.55	0.56	0.57	0.56	0.56	C - E	0.80	0.80	0.80	0.80	0.79	0.80	B - A
13	-	-	-	-	-	-	-	0.78	0.78	0.78	-	-	-	C - D
12	0.53	0.52	0.52	0.51	0.50	0.50	B - A	0.74	0.75	0.76	0.74	0.71	0.75	C - D
11	-	-	-	-	-	-	-	0.70	0.70	0.70	-	-	-	B - A
10	0.49	0.50	0.50	0.50	0.49	0.45	B - D	0.69	0.68	0.68	0.67	0.68	0.60	B - A
9	-	-	-	-	-	-	-	0.60	0.60	0.63	-	-	-	C - D
8	0.49	0.49	0.40	0.49	0.49	0.48	B - A	0.60	0.53	0.50	0.40	0.48	0.40	B - A
7	0.48	0.49	0.30	0.49	0.49	0.48	B - D	0.40	0.50	0.39	0.25	0.49	0.40	B - D
6	0.32	-	0.29	0.19	0.39	0.30	D - E	0.41	0.58	0.38	0.20	0.50	0.44	B - D
5	0.30	0.39	0.20	-	0.30	0.29	B - D	0.36	0.45	0.30	0.19	0.40	0.31	B - D
4	0.29	0.33	0.20	-	0.30	0.27	B - D	0.30	0.40	0.26	0.16	0.35	0.30	B - D
3	0.29	0.32	0.20	-	0.30	0.27	B - D	0.30	0.39	0.22	0.10	0.30	0.29	B - D
2	0.29	0.30	0.20	-	0.30	0.27	B - D	0.29	0.30	0.20	0.10	0.30	0.28	B - D
1	0.16	0.19	0.20	-	0.19	-	C - D	0.16	0.30	0.20	0.10	0.29	0.20	B - D

[32] For tables throughout this document, "-" indicates either no data available or given the trend of the data, Monte Carlo simulation runs were not required for the specific nodes.

Table 4-3 identifies the trailing aircraft's CSL in-trail distance (in NM) behind the lead aircraft for each speed bin with a collision risk of 1×10^{-9}. An in-trail distance is given at discrete points along the approach course. Aircraft pairs experiencing aircraft expansion can maintain closer in-trail distances than aircraft pairs experiencing aircraft compression.

Table 4-3: KGEN CSL for CAT C Leading CAT D (Straight-In and 3° Offset)

	STRAIGHT-IN							OFFSET						
Lead Distance from TH (NM) / Speed Bin	-10 to -5 kts	-5 to -1 kts	-1 to 1 kts	1 to 5 kts	5 to 10 kts	10 to 15 kts	15 to 20 kts	-10 to -5 kts	-5 to -1 kts	-1 to 1 kts	1 to 5 kts	5 to 10 kts	10 to 15 kts	15 to 20 kts
20	0.27	0.33	0.38	0.44	0.52	0.63	0.73	0.48	0.56	0.60	0.69	0.80	0.98	1.10
19	-	-	-	-	-	-	-	0.46	0.50	0.62	0.68	0.79	0.90	1.06
18	0.27	0.30	0.38	0.40	0.49	0.58	-	0.43	0.53	0.59	0.65	0.78	0.87	1.03
17	-	-	-	-	-	-	-	0.40	0.49	0.58	0.62	0.74	0.87	0.99
16	0.26	0.30	0.34	0.40	0.48	0.55	0.64	0.40	0.50	0.56	0.60	0.70	0.80	0.97
15	-	-	-	-	-	-	-	0.39	0.47	0.50	0.59	0.68	0.79	0.89
14	0.23	0.30	0.30	0.38	0.44	0.50	0.60	0.38	0.46	0.49	0.56	0.64	0.72	0.88
13	-	-	-	-	-	-	-	0.34	0.40	0.49	0.50	0.60	0.72	0.80
12	-	0.29	0.30	0.36	0.40	0.50	0.59	0.32	0.40	0.46	0.50	0.59	0.69	0.79
11	-	-	-	-	-	-	-	0.30	0.40	0.40	0.49	0.57	0.64	0.76
10	-	0.28	0.30	0.33	0.40	0.48	0.56	0.30	0.38	0.40	0.47	0.50	0.60	0.70
9	-	-	-	-	-	-	-	0.30	0.35	0.40	0.40	0.50	0.59	0.69
8	0.20	0.24	0.30	0.30	0.39	0.40	0.50	0.30	0.30	0.38	0.40	0.49	0.56	0.60
7	0.20	0.20	0.29	0.30	0.30	-	-	0.26	0.30	0.30	0.39	0.44	0.40	-
6	0.20	0.20	0.26	0.29	0.30	0.30	-	-	0.30	0.34	0.39	0.40	0.40	-
5	0.20	0.23	0.29	0.30	-	-	-	0.24	0.30	0.30	0.30	-	-	-
4	0.20	0.20	0.20	0.30	-	-	-	0.20	0.29	0.30	0.30	-	-	-
3	0.20	0.20	0.20	0.30	-	-	-	0.20	0.20	0.30	0.30	-	-	-
2	0.20	0.20	0.20	0.30	-	-	-	0.20	0.20	0.20	0.30	-	-	-
1	0.20	0.20	0.20	0.20	-	-	-	0.20	0.20	0.20	0.30	-	-	-

4.2.2 CSL Analysis – Specific Airport Configurations

The three specific airports addressed in this study were modeled using current airport configurations for KBOS, KSEA, and KSFO. The six wake-category aircraft pair combinations used for the generic airport simulations were also evaluated at the specific airports. These included categories: 1) B leading A, 2) B leading D, 3) C leading D, 4) C leading E, 5) D leading E, and 6) D leading F.

4.2.2.1 KBOS

The KBOS runway configuration is shown in Figure 4-9. Runways 4L and 4R are separated by an RCLS of 1,500 ft. There is a runway threshold stagger of 990 ft, with runway 4R located in closer proximity to the approaching aircraft. Simulations placed the lead aircraft on runway 4R and the trailing aircraft on runway 4L. Scenarios for a straight-in approach and a single offset approach of 2° were conducted and analyzed.

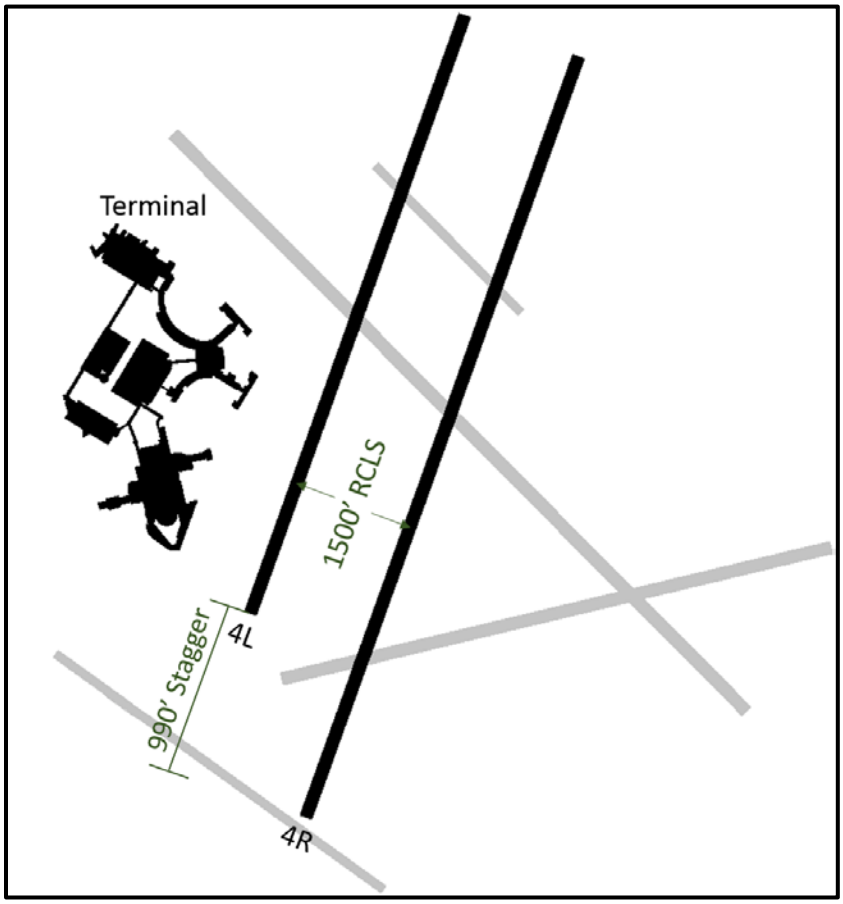

Figure 4-9: KBOS Runway Configuration

CSL results for a straight-in approach for wake category pair CAT C leading CAT D are depicted in Figure 4-10. Results for straight-in approaches display a slight slope from 20 NM (from runway threshold) until the deceleration phase when the CSL stabilizes. The aircraft then decelerated to final approach speeds, resulting in a slight increase of in-trail distances until reaching the FAF. The figure also depicts the diagonal distance between the aircraft.

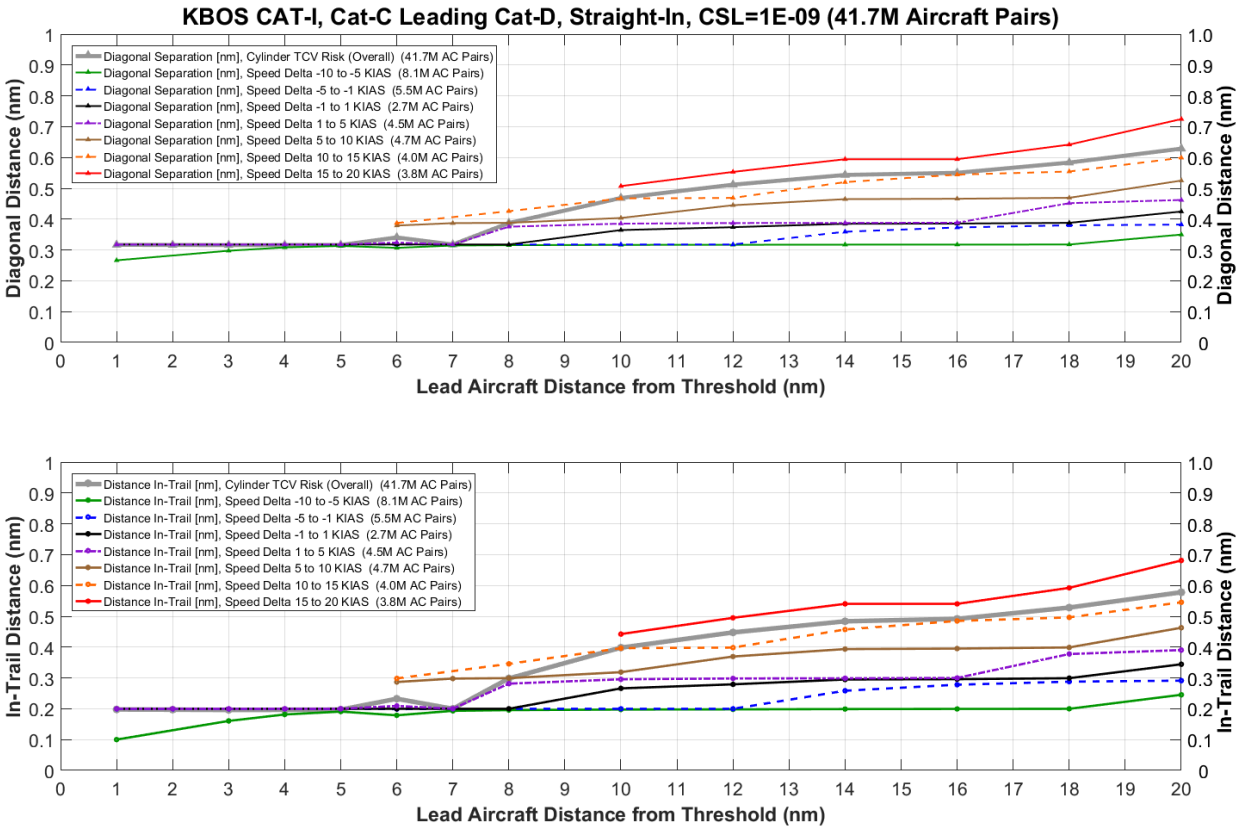

Figure 4-10: KBOS CSL for CAT C Leading CAT D (Straight-In with 1,500 ft RCLS)

CSL results for an offset approach for wake category pair CAT C leading CAT D are depicted in Figure 4-11. In-trail distances for all speed bins represented decreased relatively linearly from 20 NM (from runway threshold) through deceleration to final approach speeds. The figure also depicts the diagonal distance between the aircraft, which maintained a relatively linear decrease in separation throughout the entire approach course.

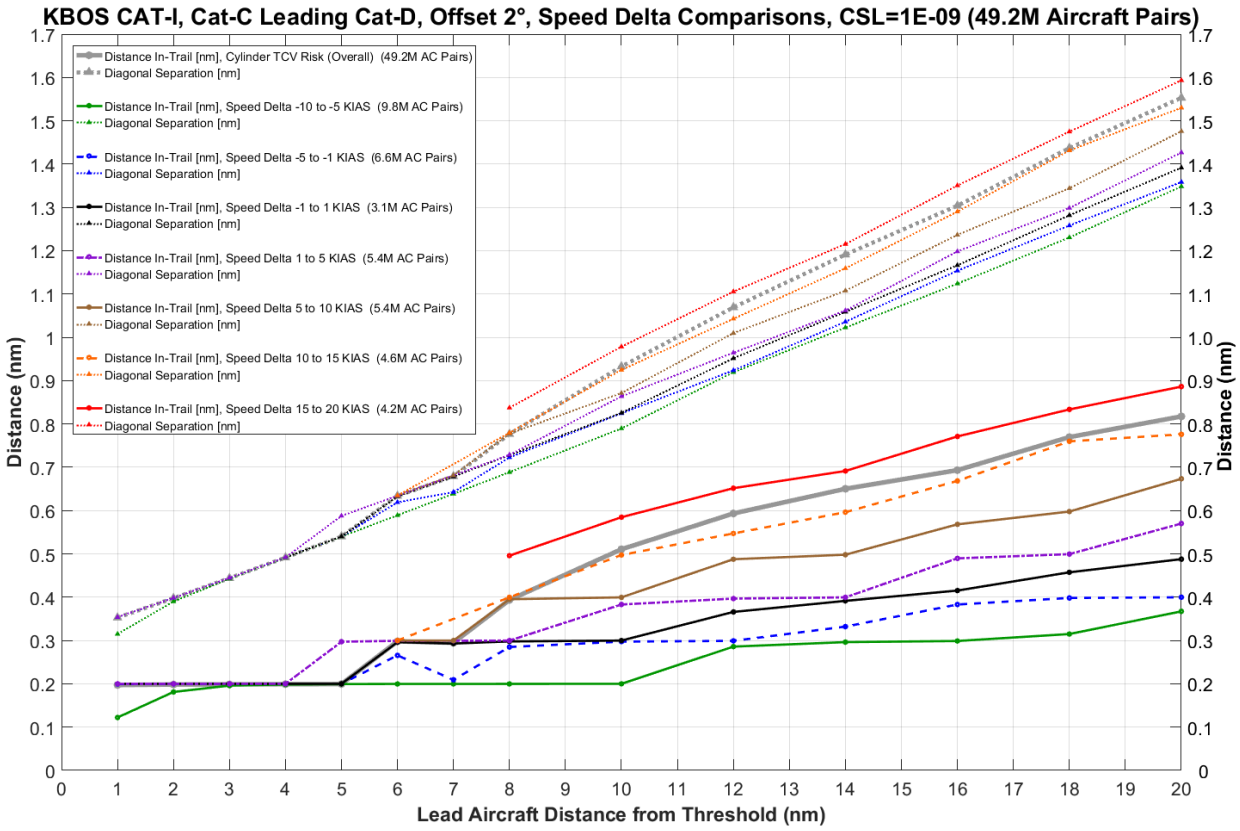

Figure 4-11: KBOS CSL for CAT C Leading CAT D (2° Offset with 1,500 ft RCLS)

Table 4-4 identifies the trailing aircraft's overall CSL in-trail distance (in NM) behind the lead aircraft for each aircraft pair with a collision risk of 1×10^{-9}. An in-trail distance is given at discrete points along the approach course. The column titled Worst Case identifies the aircraft pair whose in-trail distance could serve as a CSL for all six wake-category combinations at the indicated distance from runway threshold.

Table 4-4: KBOS CSL for All Aircraft Pairs (Straight-In and 2° Offset)

	STRAIGHT-IN							OFFSET						
Lead Aircraft Distance from TH (NM)	CAT B - A	CAT B - D	CAT C - D	CAT C - E	CAT D - E	CAT D - F	Worst Case	CAT B - A	CAT B - D	CAT C - D	CAT C - E	CAT D - E	CAT D - F	Worst Case
20	0.60	0.57	0.58	0.57	0.56	0.58	B - A	0.82	0.80	0.82	0.80	0.80	0.80	C - D
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	0.54	0.50	0.53	0.50	0.54	0.55	D - F	0.76	0.77	0.77	0.77	0.76	0.77	C - D
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0.50	0.50	0.49	0.50	0.50	0.50	B - A	0.69	0.69	0.69	0.69	0.69	0.70	D - F
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	0.49	0.48	0.48	0.49	0.47	0.48	B - A	0.66	0.65	0.65	0.65	0.66	0.64	B - A
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	0.46	0.46	0.45	0.45	0.45	0.44	B - A	0.59	0.59	0.59	0.59	0.59	0.59	C - D
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.40	0.40	0.40	0.40	0.40	0.37	B - A	0.52	0.52	0.51	0.51	0.50	0.48	B - A
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0.40	0.40	0.30	0.40	0.39	0.39	B - A	0.49	0.49	0.39	0.49	0.49	0.49	B - A
7	0.39	0.39	0.20	0.39	0.39	0.39	B - A	0.49	0.49	0.30	0.49	0.49	0.49	B - A
6	0.30	0.39	0.23	0.18	0.30	0.28	B - D	0.38	-	0.30	0.20	0.40	0.35	D - E
5	0.20	0.30	0.20	-	0.23	0.20	B - D	0.28	0.30	0.20	0.20	0.30	0.25	B - D
4	0.20	0.29	0.20	-	0.20	0.20	B - D	0.21	0.30	0.20	-	0.29	0.20	B - D
3	0.20	0.29	0.20	0.10	0.20	0.20	B - D	0.20	0.30	0.20	0.10	0.27	0.20	B - D
2	0.20	0.29	0.20	0.10	0.20	0.20	B - D	0.20	0.30	0.20	0.10	0.20	0.20	B - D
1	0.20	0.20	0.20	0.10	0.20	0.20	B - A	0.20	0.20	0.20	0.10	0.20	0.20	C - D

Table 4-5 identifies the trailing aircraft's CSL in-trail distance (in NM) behind the lead aircraft for each speed bin with a collision risk of 1×10^{-9}. An in-trail distance is given at discrete points along the approach course. Aircraft pairs experiencing aircraft expansion can maintain closer in-trail distances than aircraft pairs experiencing aircraft compression.

Table 4-5: KBOS CSL for CAT C Leading CAT D (Straight-In and 2° Offset)

	STRAIGHT-IN							OFFSET						
Lead Distance from TH (NM) / Speed Bin	-10 to -5 kts	-5 to -1 kts	-1 to 1 kts	1 to 5 kts	5 to 10 kts	10 to 15 kts	15 to 20 kts	-10 to -5 kts	-5 to -1 kts	-1 to 1 kts	1 to 5 kts	5 to 10 kts	10 to 15 kts	15 to 20 kts
20	0.25	0.29	0.34	0.39	0.46	0.55	0.68	0.37	0.40	0.49	0.57	0.67	0.78	0.89
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	0.20	0.29	0.30	0.38	0.40	0.50	0.59	0.32	0.40	0.46	0.50	0.60	0.76	0.83
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0.20	0.28	0.30	0.30	0.40	0.49	0.54	0.30	0.38	0.42	0.49	0.57	0.67	0.77
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	0.20	0.26	0.29	0.30	0.39	0.46	0.54	0.30	0.33	0.39	0.40	0.50	0.60	0.69
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	0.20	0.20	0.28	0.30	0.37	0.40	0.50	0.29	0.30	0.37	0.40	0.49	0.55	0.65
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.20	0.20	0.27	0.30	0.32	0.40	0.44	0.20	0.30	0.30	0.38	0.40	0.50	0.59
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0.20	0.20	0.20	0.28	0.30	0.35	0.30	0.20	0.29	0.30	0.30	0.40	0.40	0.50
7	0.19	0.20	0.20	0.20	0.30	-	-	0.20	0.21	0.29	0.30	0.30	-	-
6	0.18	0.20	0.20	0.21	0.29	0.30	-	0.20	0.27	0.30	0.30	0.30	0.30	-
5	0.19	0.20	0.20	0.20	-	-	-	0.20	0.20	0.20	0.30	-	-	-
4	0.18	0.20	0.20	0.20	-	-	-	0.20	0.20	0.20	0.20	-	-	-
3	0.16	0.20	0.20	0.20	-	-	-	0.20	0.20	0.20	0.20	-	-	-
2	-	0.20	0.20	0.20	-	-	-	0.18	0.20	0.20	0.20	-	-	-
1	0.10	0.20	0.20	0.20	-	-	-	0.12	0.20	0.20	0.20	-	-	-

4.2.2.2 KSEA

Two KSEA runway configurations are shown in Figure 4-12. Runways 16L and 16C are separated by an RCLS of 800 ft and runways 16C and 16 R by an RCLS of 1,700 ft. There are negligible runway threshold staggers for the runway pair 16L-16C and for runway pair 16C-16R. Simulations placed the lead aircraft on runway 16L for runway pair 16L-16C and runway 16C for runway pair 16C-16R. Scenarios for a straight-in approach were conducted and analyzed for both configurations.

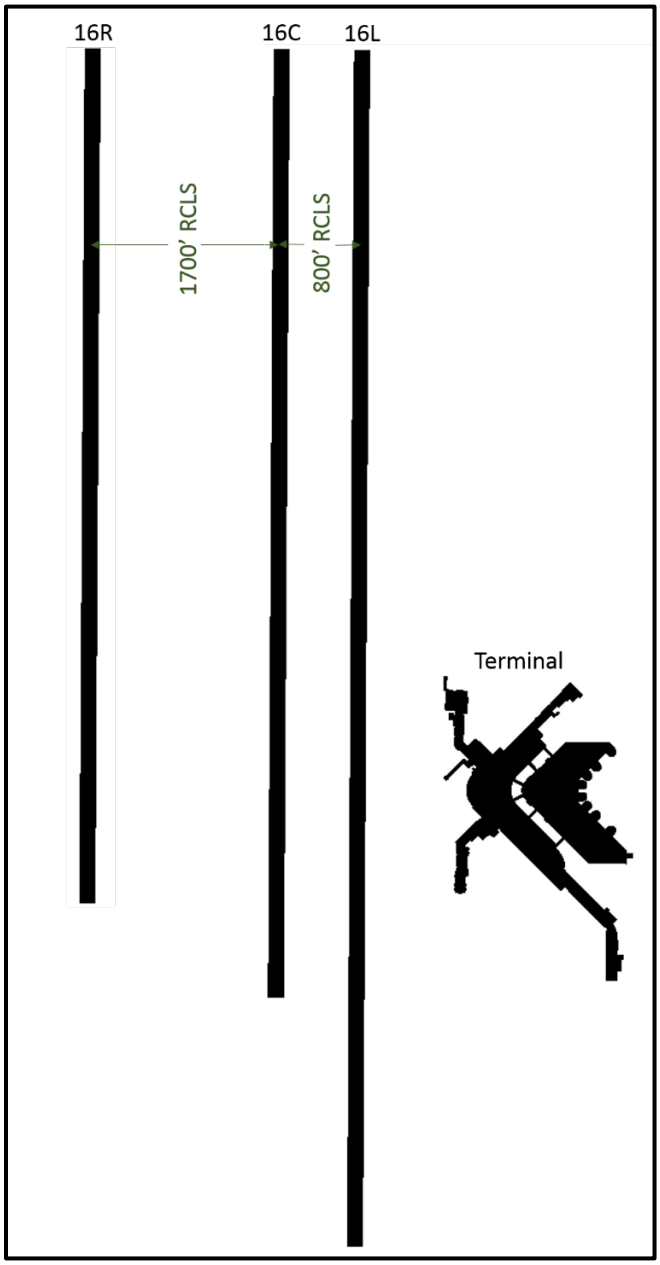

Figure 4-12: KSEA Runway Configuration

CSL results for a straight-in approach to runways 16L and 16C with an RCLS of 800 ft for wake category pair CAT C leading CAT D are depicted in Figure 4-13. Results for straight-in approaches display a slight slope from 20 NM (from runway threshold) until the deceleration phase when the CSL stabilizes. The aircraft then decelerated to final approach speeds, resulting in a slight increase of in-trail distances until reaching the FAF. The figure also depicts the diagonal distance between the aircraft.

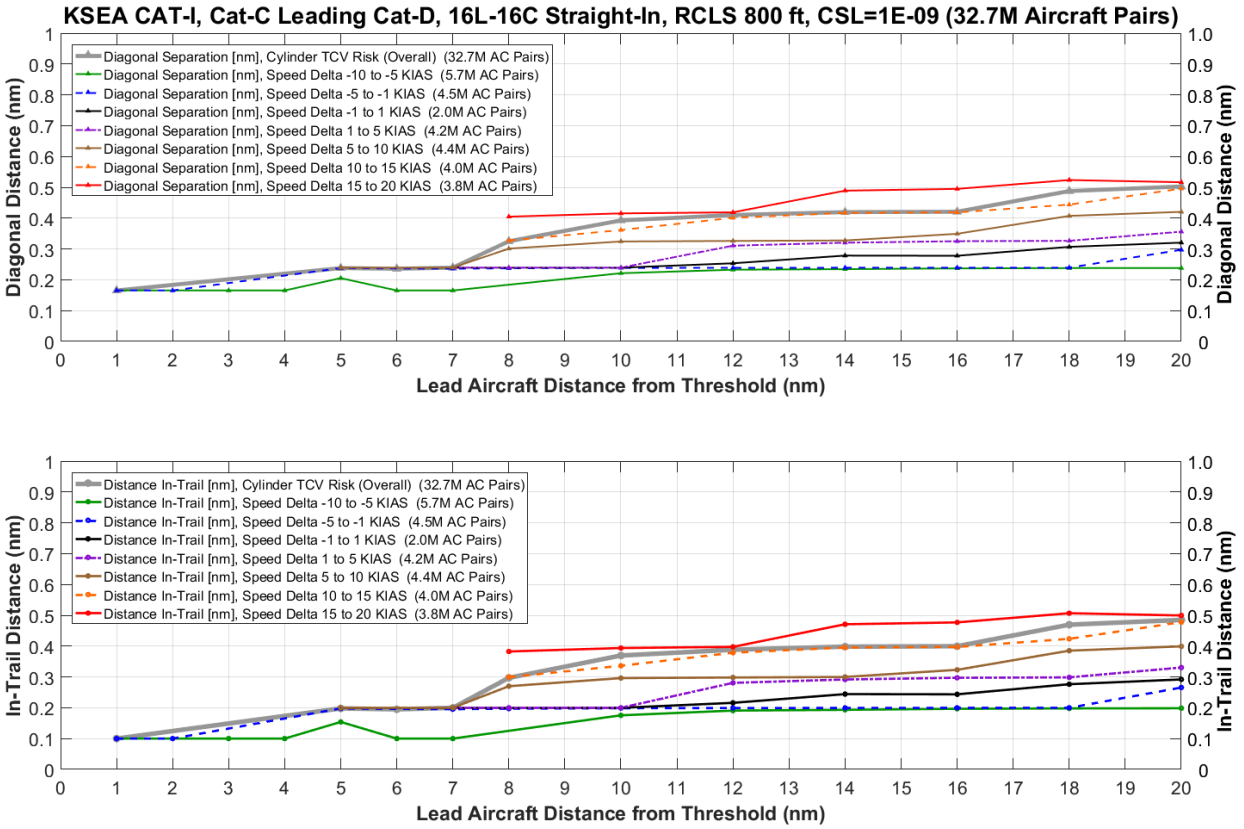

Figure 4-13: KSEA CSL for CAT C Leading CAT D (Straight-In with 800 ft RCLS)

CSL results for a straight-in approach to runways 16C and 16R with an RCLS of 1,700 ft for wake category pair CAT C leading CAT D are depicted in Figure 4-14. Results for straight-in approaches display a slight slope from 20 NM (from runway threshold) until the deceleration phase when the CSL stabilizes. The aircraft then decelerated to final approach speeds, resulting in a slight increase of in-trail distances until reaching the FAF. The figure also depicts the diagonal distance between the aircraft.

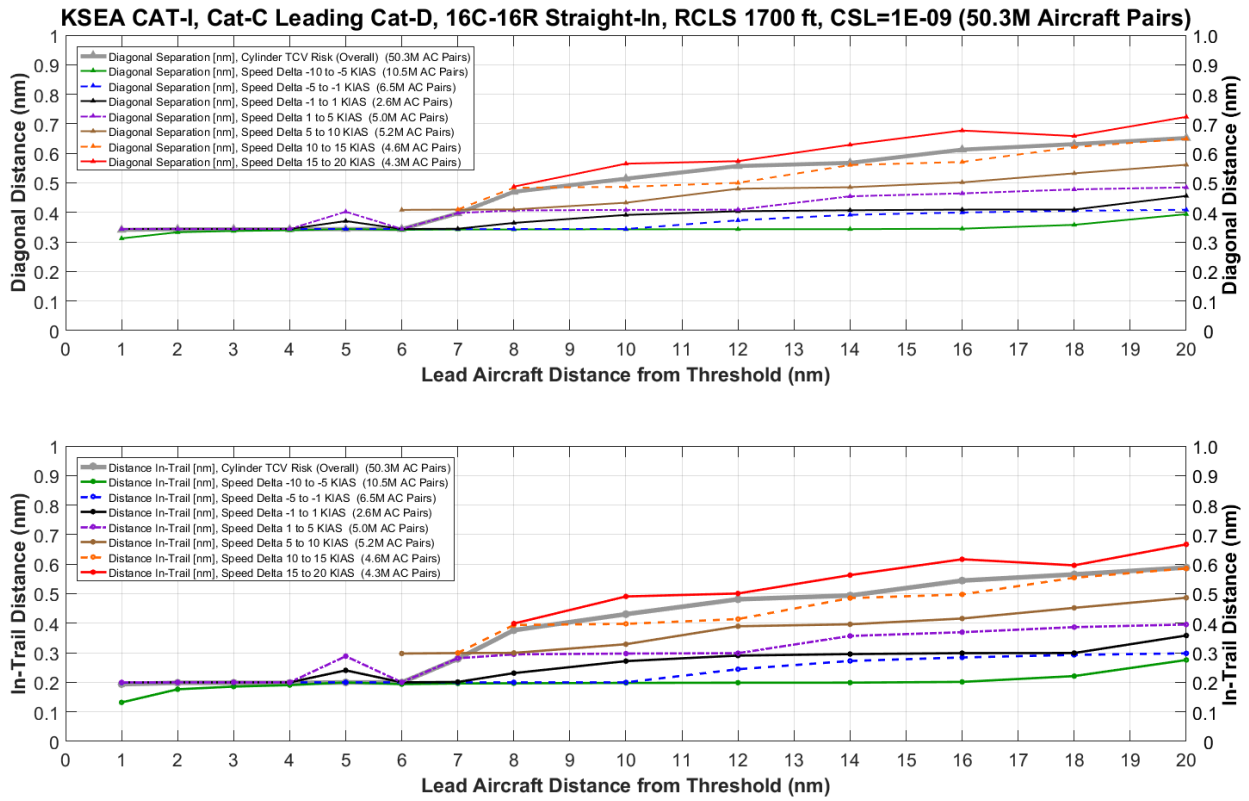

Figure 4-14: KSEA CSL for CAT C Leading CAT D (Straight-In with 1,700 ft RCLS)

Table 4-6 identifies the trailing aircraft's overall CSL in-trail distance (in NM) behind the lead aircraft for each aircraft pair with a collision risk of 1×10^{-9}. An in-trail distance is given at discrete points along the approach course. The column titled Worst Case identifies the aircraft pair whose in-trail distance could serve as a CSL for all six wake-category combinations at the indicated distance from runway threshold.

Table 4-6: KSEA CSL for All Aircraft Pairs (Straight-In with 800 ft & 1,700 ft RCLS)

	STRAIGHT-IN (800 ft RCLS)							STRAIGHT-IN (1,700 ft RCLS)						
Lead Aircraft Distance from TH (NM)	CAT B - A	CAT B - D	CAT C - D	CAT C - E	CAT D - E	CAT D - F	Worst Case	CAT B - A	CAT B - D	CAT C - D	CAT C - E	CAT D - E	CAT D - F	Worst Case
20	0.48	0.49	0.49	0.49	0.49	0.49	C - D	0.60	0.59	0.59	0.59	0.59	0.58	B - A
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	0.47	0.47	0.47	0.47	0.48	0.45	D - E	0.57	0.55	0.57	0.57	0.58	0.55	D - E
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0.43	0.40	0.40	0.44	0.40	0.43	C - E	0.54	0.52	0.54	0.54	0.50	0.51	C - D
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	0.40	0.40	0.40	0.40	0.40	0.40	C - D	0.50	0.50	0.49	0.49	0.49	0.49	B - A
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	0.39	0.39	0.39	0.39	0.39	0.39	C - D	0.48	0.48	0.48	0.48	0.48	0.47	C - D
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.37	0.36	0.37	0.36	0.35	0.30	C - D	0.40	0.40	0.43	0.44	0.44	0.39	C - E
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0.30	0.30	0.30	0.30	0.30	0.30	C - D	0.40	0.40	0.38	0.40	0.40	0.40	B - A
7	0.30	0.30	0.20	0.30	0.30	0.30	B - A	0.40	0.40	0.28	0.40	0.40	0.23	B - A
6	0.20	0.28	0.20	0.10	0.20	0.20	B - D	0.28	0.32	0.20	0.10	0.30	0.22	B - D
5	0.20	0.29	0.20	0.10	0.20	0.20	B - D	0.28	0.30	0.20	0.10	0.30	0.26	B - D
4	0.20	0.20	0.13	0.10	0.20	0.10	B - A	0.20	0.30	0.20	0.10	0.26	0.20	B - D
3	0.20	0.20	0.12	0.10	0.20	0.10	B - A	0.20	0.30	0.20	0.10	0.24	0.20	B - D
2	0.20	0.20	0.13	0.10	0.20	0.10	B - A	0.20	0.30	0.20	0.10	0.24	0.20	B - D
1	0.20	0.20	0.10	0.10	0.20	0.10	B - A	0.20	0.20	0.19	0.10	0.20	0.20	B - A

Table 4-7 identifies the trailing aircraft's CSL in-trail distance (in NM) behind the lead aircraft for each speed bin with a collision risk of 1×10^{-9}. An in-trail distance is given at discrete points along the approach course. Aircraft pairs experiencing aircraft expansion can maintain closer in-trail distances than aircraft pairs experiencing aircraft compression.

Table 4-7: KSEA CSL for CAT C Leading CAT D (Straight-In with 800 ft & 1,700 ft RCLS)

	STRAIGHT-IN (800ft RCLS)							STRAIGHT-IN (1700ft RCLS)						
Lead Distance from TH (NM) / Speed Bin	-10 to -5 kts	-5 to -1 kts	-1 to 1 kts	1 to 5 kts	5 to 10 kts	10 to 15 kts	15 to 20 kts	-10 to -5 kts	-5 to -1 kts	-1 to 1 kts	1 to 5 kts	5 to 10 kts	10 to 15 kts	15 to 20 kts
20	0.20	0.27	0.29	0.33	0.40	0.48	0.50	0.28	0.30	0.36	0.40	0.49	0.59	0.67
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	0.20	0.20	0.28	0.30	0.39	0.42	0.51	0.22	0.29	0.30	0.39	0.45	0.55	0.60
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	0.20	0.20	0.24	0.30	0.32	0.40	0.48	0.20	0.28	0.30	0.37	0.42	0.50	0.62
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	0.19	0.20	0.24	0.29	0.30	0.40	0.47	0.20	0.27	0.30	0.36	0.40	0.49	0.56
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	0.19	0.20	0.22	0.28	0.30	0.38	0.40	0.20	0.24	0.29	0.30	0.39	0.41	0.50
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	0.18	0.20	0.20	0.20	0.30	0.34	0.39	0.20	0.20	0.27	0.30	0.33	0.40	0.49
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	0.13	0.20	0.20	0.20	0.27	0.30	0.38	0.20	0.20	0.23	0.30	0.30	0.39	0.40
7	0.10	0.20	0.20	0.20	0.20	0.20	-	0.20	0.20	0.20	0.28	0.30	0.30	-
6	0.10	0.19	-	-	-	-	-	0.19	0.20	0.20	0.20	0.30	-	-
5	0.15	0.20	0.20	0.20	0.20	-	-	0.20	0.20	0.24	0.29	-	-	-
4	0.10	-	-	-	-	-	-	0.19	0.20	0.20	0.20	-	-	-
3	0.10	-	-	-	-	-	-	0.19	0.20	0.20	0.20	-	-	-
2	0.10	0.10	-	-	-	-	-	0.18	0.20	0.20	0.20	-	-	-
1	0.10	0.10	-	-	-	-	-	0.13	0.20	0.20	0.20	-	-	-

4.2.2.3 KSFO

The KSFO runway configuration is shown in Figure 4-15. Runways 28L and 28R are separated by an RCLS of 750 ft, with aligned runway thresholds. Simulations placed the lead aircraft on runway 28L and the trailing aircraft on runway 28R. Scenarios for a single offset approach of 3° were conducted and analyzed.

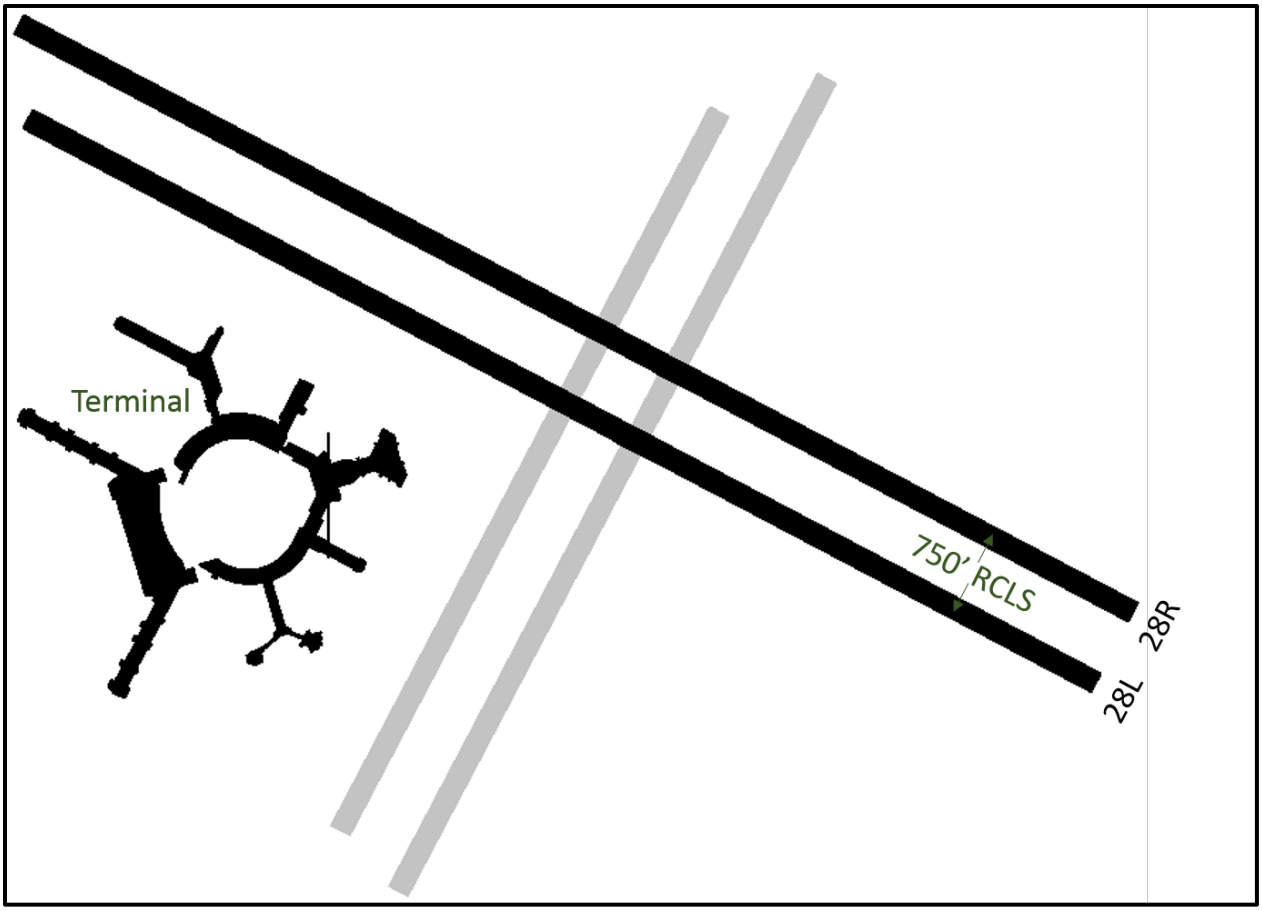

Figure 4-15: KSFO Runway Configuration

CSL results for an offset approach for wake category pair CAT C leading CAT D are depicted in Figure 4-16. In-trail distances for all speed bins represented decreased relatively linearly from 20 NM (from runway threshold) through deceleration to final approach speeds. The figure also depicts the diagonal distance between the aircraft, which maintained a relatively linear decrease in separation throughout the entire approach course.

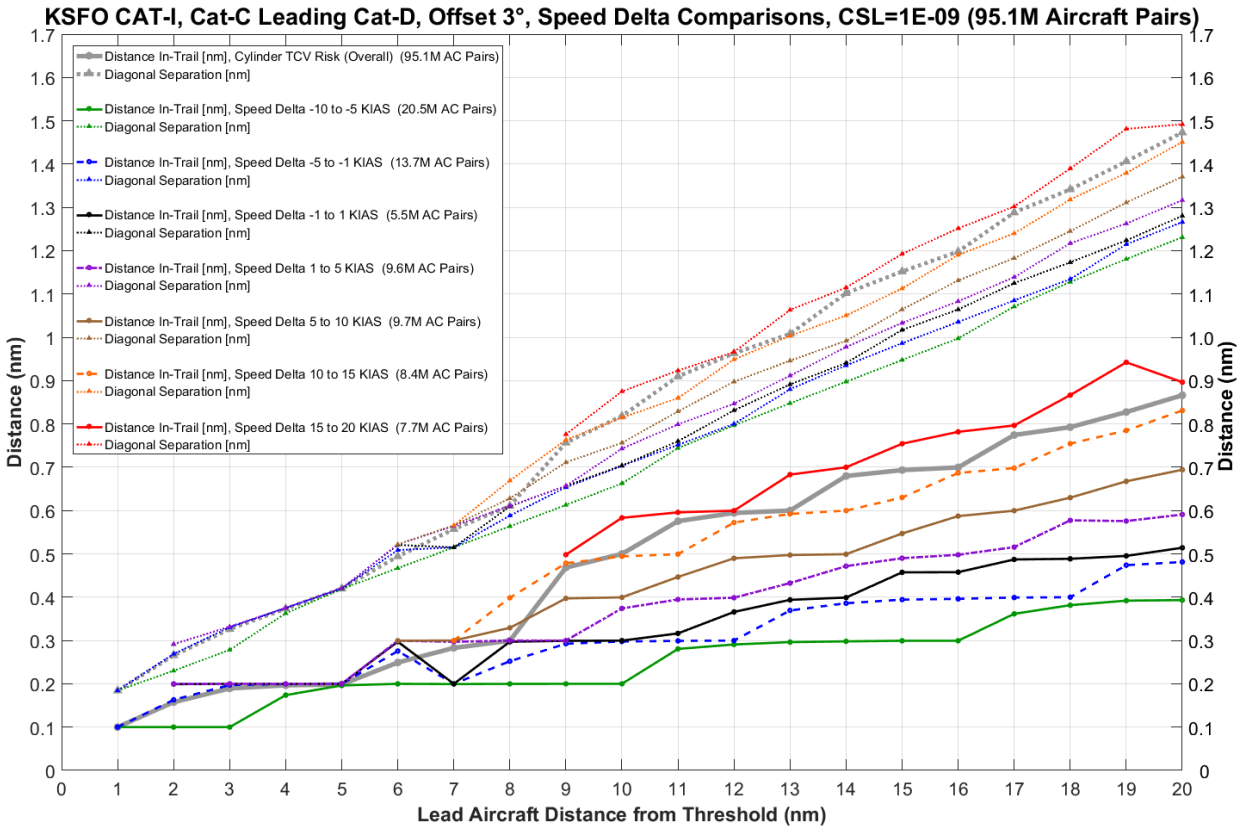

Figure 4-16: KSFO CSL for CAT C Leading CAT D (3° Offset with 750 ft RCLS)

Table 4-8 identifies the trailing aircraft's overall CSL in-trail distance (in NM) behind the lead aircraft for each aircraft pair with a collision risk of 1×10^{-9}. An in-trail distance is given at discrete points along the approach course. The column titled Worst Case identifies the aircraft pair whose in-trail distance could serve as a CSL for all six wake-category combinations at the indicated distance from runway threshold.

Table 4-8: KSFO CSL for All Aircraft Pairs (3° Offset)

	OFFSET						
Lead Aircraft Distance from TH (NM)	CAT B - A	CAT B - D	CAT C - D	CAT C - E	CAT D - E	CAT D - F	Worst Case
20	0.89	0.87	0.87	0.88	0.87	0.88	B - A
19	0.83	-	0.83	-	-	-	C - D
18	0.79	0.79	0.79	0.79	0.80	0.80	D - E
17	0.78	-	0.78	-	-	-	C - D
16	0.74	0.74	0.70	0.73	0.71	0.71	B - A
15	0.69	0.70	0.69	0.70	0.69	0.69	B - D
14	0.66	0.68	0.68	0.68	0.68	0.67	C - D
13	0.63	-	0.60	-	-	-	B - A
12	0.59	0.59	0.60	0.59	0.59	0.59	C - D
11	0.58	-	0.58	-	-	-	C - D
10	0.50	0.50	0.50	0.50	0.49	0.40	C - D
9	0.39	-	0.47	-	-	-	C - D
8	0.30	0.40	0.30	0.20	0.30	0.30	B - D
7	0.30	0.40	0.28	0.19	0.39	0.30	B - D
6	0.30	0.39	0.25	0.18	0.33	0.29	B - D
5	0.20	0.30	0.20	0.10	0.28	0.20	B - D
4	0.20	0.29	0.20	0.10	0.20	0.20	B - D
3	0.20	0.20	0.19	0.10	0.20	0.20	B - A
2	0.20	0.20	0.16	0.10	0.20	0.19	B - A
1	0.19	0.20	0.10	0.10	0.20	0.18	B - D

Table 4-9 identifies the trailing aircraft's CSL in-trail distance (in NM) behind the lead aircraft for each speed bin with a collision risk of 1×10^{-9}. An in-trail distance is given at discrete points along the approach course. Aircraft pairs experiencing aircraft expansion can maintain closer in-trail distances than aircraft pairs experiencing aircraft compression.

Table 4-9: KSFO CSL for CAT C Leading CAT D (3° Offset)

	OFFSET						
Lead Distance from TH (NM) / Speed Bin	-10 to -5 kts	-5 to -1 kts	-1 to 1 kts	1 to 5 kts	5 to 10 kts	10 to 15 kts	15 to 20 kts
20	0.39	0.48	0.51	0.59	0.69	0.83	0.90
19	0.39	0.47	0.50	0.58	0.67	0.79	0.94
18	0.38	0.40	0.49	0.58	0.63	0.76	0.87
17	0.36	0.40	0.49	0.52	0.60	0.70	0.80
16	0.30	0.40	0.46	0.50	0.59	0.69	0.78
15	0.30	0.39	0.46	0.49	0.55	0.63	0.75
14	0.30	0.39	0.40	0.47	0.50	0.60	0.70
13	0.30	0.37	0.39	0.43	0.50	0.59	0.68
12	0.29	0.30	0.37	0.40	0.49	0.57	0.60
11	0.28	0.30	0.32	0.40	0.45	0.50	0.60
10	0.20	0.30	0.30	0.37	0.40	0.49	0.58
9	0.20	0.29	0.30	0.30	0.40	0.48	0.50
8	0.20	0.25	0.30	0.30	0.33	0.40	-
7	0.20	0.20	0.20	0.30	0.30	0.30	-
6	0.20	0.27	0.30	0.30	-	-	-
5	0.20	0.20	0.20	0.20	-	-	-
4	0.17	0.20	0.20	0.20	-	-	-
3	0.10	0.20	0.20	0.20	-	-	-
2	0.10	0.16	0.20	0.20	-	-	-
1	0.10	0.10	-	-	-	-	-

4.2.3 CSL Analysis – Modified Airport Configurations

The modified configurations addressed in this study were modeled using the airport configuration for KSFO. Scenarios were conducted and analyzed for a single offset approach of 3° using a wake-category aircraft pair combination of CAT C leading CAT D. Modified airport configurations were created in order to test the effect of speed variance on CSL determination.

4.2.3.1 Initial IAS of 150 kts with Transition to FAS

During analysis, it was determined that specific aircraft speeds played little role in determining the risk associated with a paired approach operation. The main determinant of risk was the Δspeed between the lead and trailing aircraft. Scenarios for CAT C leading CAT D were developed in order to compare constant speed deltas with the parameters set forth in this study for the specific and generic airports.

A constant speed of 150 kts transitioning to FAS (instead of 170 kts transitioning to FAS) for the lead aircraft was chosen because it fell within the approach speed distribution for CAT C aircraft. The trailing aircraft was set up to sample speeds from a uniform distribution within the range of 150 – 10 kts to 150 + 20 kts until reaching the deceleration phase, which initiated the slowdown to final approach IAS. This was done purposefully to imitate the standard set-up of the simulations for the entirety of the analysis.

The CSL for offset approaches of 3° with a lead aircraft constant speed of 150 kts transitioning to FAS and trailing aircraft speeds ranging from 140 kts to 170 kts until decelerating to FAS, is depicted in Figure 4-17. The figure displays the trailing aircraft CSL for each of the individual speed bins for CAT C leading CAT D at KSFO.

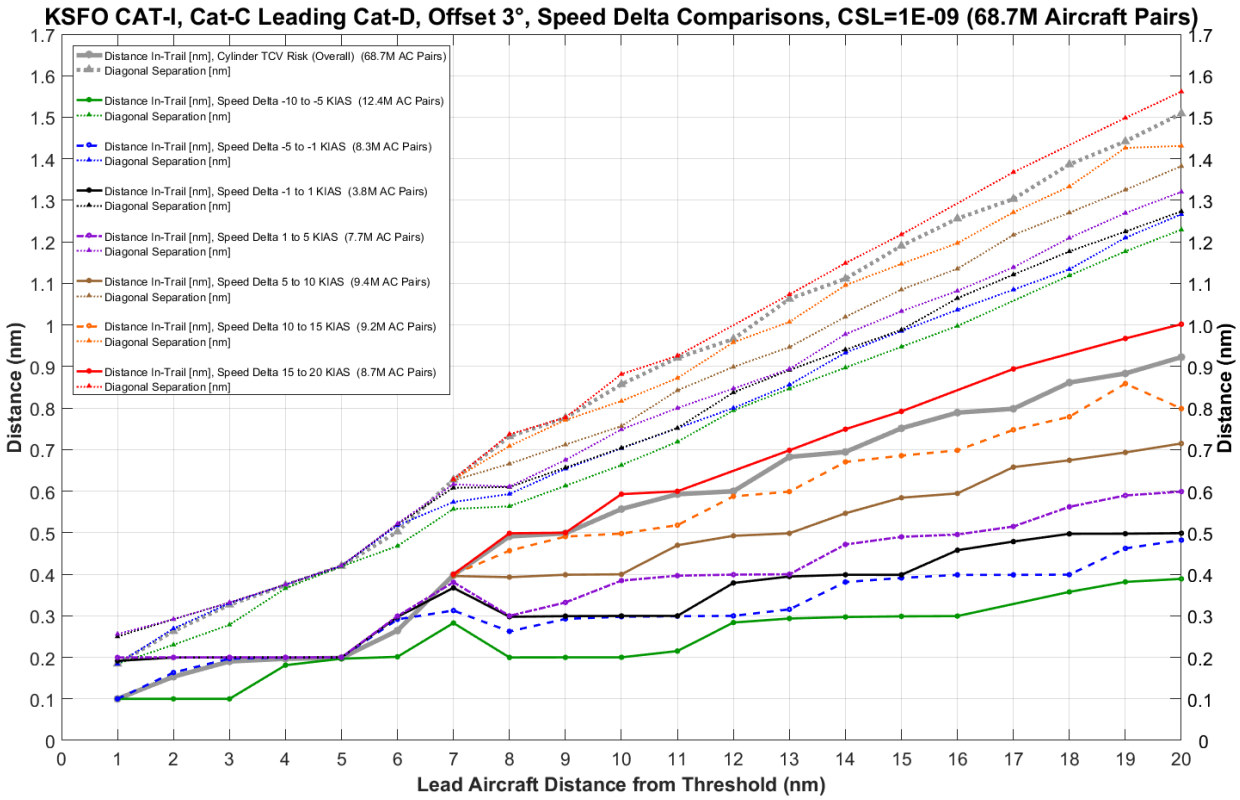

Figure 4-17: KSFO CSL for CAT C Leading CAT D (Special Case - Initial 150 kts to FAS)

Figure 4-18 depicts the CSL for offset approaches of 3° of a modified scenario with an initial IAS 150 kts (see Figure 4-17) overlaid on the original KSFO scenario results with initial IAS of 170 kts (see Figure 4-16) for comparison. The figure displays the trailing aircraft CSL for each of the individual speed bins for CAT C leading CAT D at KSFO. Differences between the resultant safety limits were negligible. Dashed lines represent results with initial IAS of 150 kts and solid lines represent results with initial IAS of 170 kts.

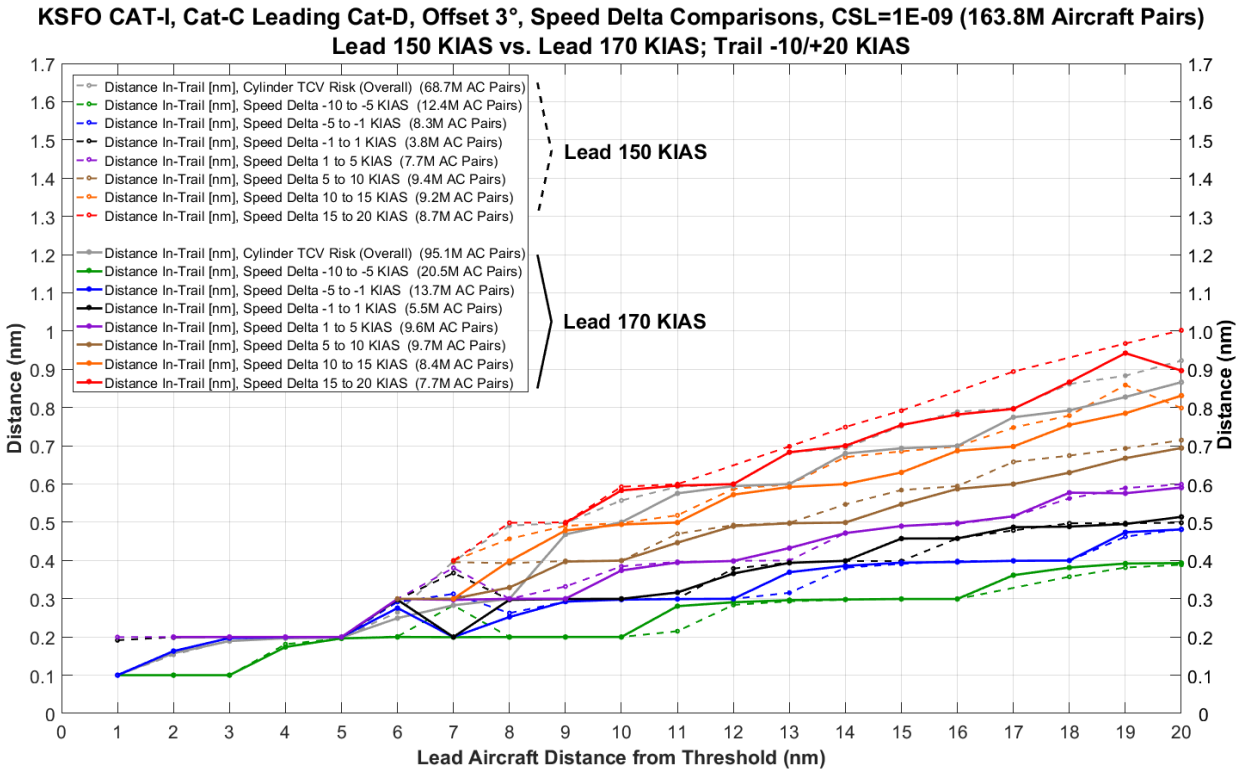

Figure 4-18: KSFO CSL Comparison (Initial 150 kts to FAS vs Initial 170 kts to FAS)

Table 4-10 identifies the trailing aircraft's overall CSL in-trail distance (in NM) behind the lead aircraft for CAT C leading CAT D for initial lead aircraft speeds of 150 kts vs 170 kts with a collision risk of 1×10^{-9}. The "Difference" column indicates a negligible change in the in-trail distance when comparing initial speeds of 150 kts and 170 kts.

Table 4-10: KSFO CSL IAS Comparison (Initial 150 kts vs Initial 170 kts Baseline)

	OFFSET		
Lead Aircraft Distance from TH (NM)	Initial 150 kts CAT C – D CSL (NM)	Initial 170 kts CAT C – D CSL (NM)	Difference (NM)
20	0.92	0.87	0.05
19	0.88	0.83	0.05
18	0.86	0.79	0.07
17	0.80	0.78	0.02
16	0.79	0.70	0.09
15	0.75	0.69	0.06
14	0.69	0.68	0.01
13	0.68	0.60	0.08
12	0.60	0.60	0.00
11	0.59	0.58	0.01
10	0.56	0.50	0.06
9	0.50	0.47	0.03
8	0.49	0.30	0.19
7	0.40	0.29	0.11
6	0.29	0.28	0.01
5	0.20	0.20	0.00
4	0.20	0.20	0.00
3	0.20	0.20	0.00
2	0.19	0.19	0.00
1	0.13	0.10	0.03

4.2.3.2 Constant IAS of 150 kts

Additional simulations were created in order to provide a control variable to the analysis. This was done by developing simulations to compare constant speed deltas with the parameters set forth in this study for the specific and generic airports. All aspects of this scenario remained consistent with previous configurations (e.g., wake category pairing, airport configuration, and lead aircraft constant speed). However, for this control setup, neither the lead nor the trailing aircraft decelerated from initial speeds. The lead aircraft maintained a constant speed of 150 kts (instead of 170 kts at initiation followed by a deceleration to a FAS) throughout the entire approach course, while the trailing aircraft was set at constant speeds of 140 kts to 170 kts in 5-knot increments. Each 5-knot increment was a new scenario and each scenario ran 75,000 simulation pairs. This ensured that speed bins were weighted evenly.

The CSL for offset approaches of 3° with constant IAS is depicted in Figure 4-19. The CSL maintained a linear gradient from 20 NM (from TH) throughout the approach course. The figure displays the trailing aircraft CSL for each of the individual speed bins for CAT C leading CAT D at KSFO.

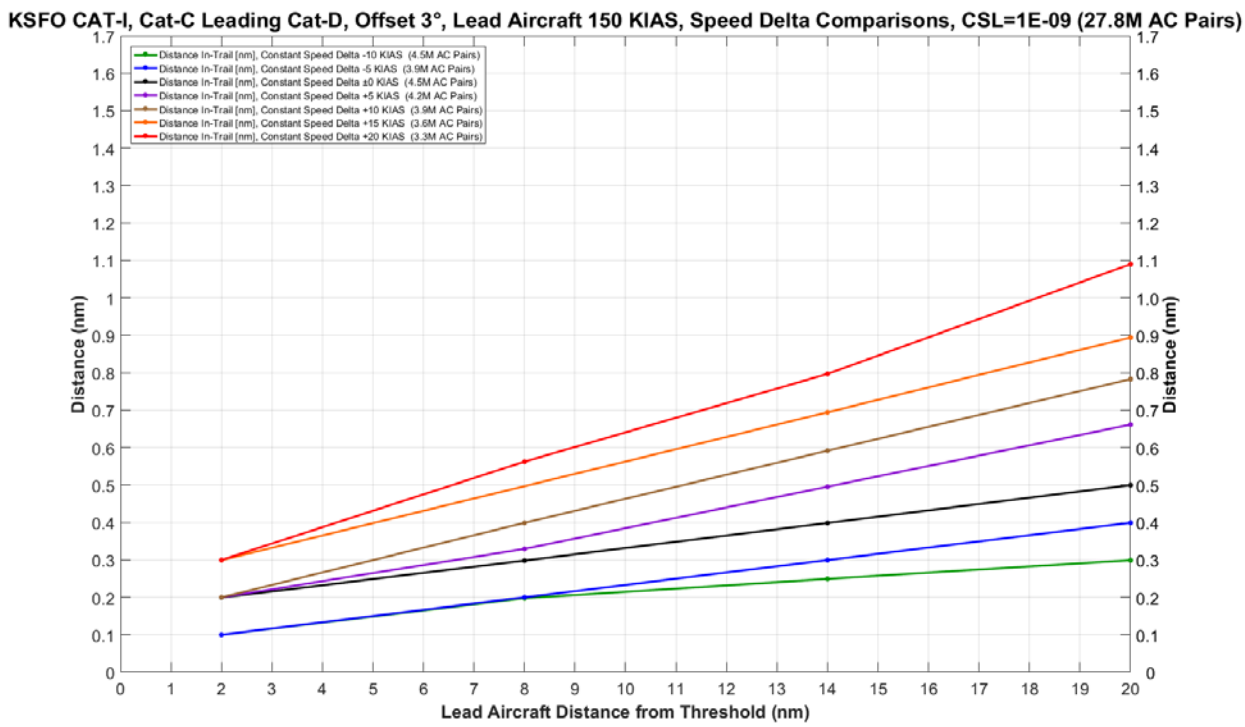

Figure 4-19: KSFO CSL for CAT C Leading CAT D (Special Case - Constant 150 kts)

Figure 4-20 depicts the CSL for offset approaches of 3° of a modified scenario with constant IAS of 150 kts (see Figure 4-19) overlaid on the KSFO scenario results with initial IAS of 150 kts transitioning to FAS (see Figure 4-17) for comparison. The figure displays the trailing aircraft CSL for each of the individual speed bins for CAT C leading CAT D at KSFO. Differences between the resultant safety limits were negligible. Thin lines represent results with constant IAS of 150 kts and thick lines represent results with initial IAS of 150 kts transitioning to FAS.

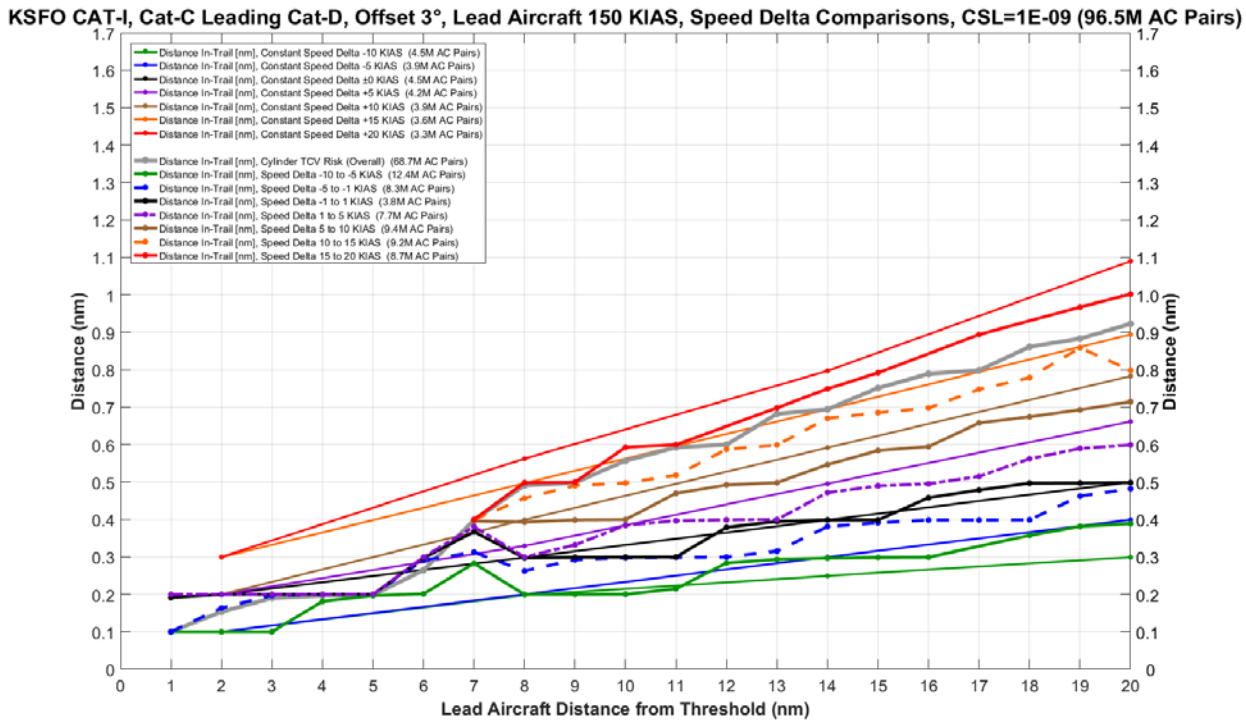

Figure 4-20: KSFO CSL Comparison (Constant 150 kts vs Initial 150 kts to FAS)

4.3 CSL Analysis Summary

The CSL continually changes during the approach. CSL collision risk is a function of many variables including runway approach alignment, runway spacing, runway stagger, airport elevation, fleet mix, navigation systems, speed variations between the aircraft, and the trailing aircraft's position relative to the lead aircraft.

For the evaluated airport configurations, the initial premise was that placement of the CSL was primarily dependent on airport approach configuration (e.g., RCLS, runway approach alignment, and runway stagger), aircraft pairing by wake category, and aircraft speed. Final analysis of data indicated that reduced CSL in-trail distances may be attained for airport configurations with smaller RCLS vs larger RCLS; and for straight-in approaches vs offset approaches. Results also determined that aircraft pairing by wake category has minimal impact on CSL in-trail spacing, as did results of both aircraft flying slower approach speeds vs faster approach speeds, as depicted in Figure 4-16. However, CSL placement was significantly influenced by speed differences between the lead and trailing aircraft (i.e., Δspeed).

Results were consistent across all airport approach configurations. The CSL exhibited smaller in-trail distances for:

- Closer RCLS vs more distant RCLS
- Straight-in approaches vs offset approaches
- Approach distances closer to runway threshold vs farther from runway threshold
- Speed bins of aircraft expansion vs aircraft compression

Airport configurations with a smaller RCLS tend to have smaller CSL in-trail distances. CSL in-trail distance increases as RCLS increases, as depicted in Figure 4-3. Given identical aircraft characteristics for a particular scenario, it will take the deviating lead aircraft a certain amount of time from initialization to the point where a CPA is recorded. This time is reduced as RCLS is reduced. With a smaller RCLS, the lead target aircraft may pass safely in front of the trailing IM aircraft, recording the CPA without penetrating the trailing aircraft's TCV volume. As RCLS is increased, the time it takes the deviating target aircraft to cross the flight path of the IM aircraft is increased; thus increasing the likelihood of a TCV as the aircraft trajectories converge. As the RCLS is further increased, the target aircraft may pass behind the IM aircraft, averting a TCV. All of these situations have the potential for a hazardous wake encounter. The effects of wake on an aircraft during a paired approach operation are being addressed separately in a Volpe Center study.

Straight-in approach configurations result in smaller CSL in-trail distances than offset approach configurations for a given RCLS. The diagonal separation of the aircraft pair remains relatively constant throughout a straight-in approach. With an offset approach, aircraft pair diagonal separation is larger farther from the runway threshold.

A combination of runway approach alignment, lateral error, and vertical error influence the CSL. Pairing the aircraft closer to the runway threshold contributes to a reduced CSL. Lateral (for ILS approaches) and vertical error (for ILS and RNAV/RNP approaches) are greater as the aircraft are paired farther from the runway threshold (see Appendix C).

Data analysis indicated that individual speed was a non-factor in CSL placement; rather, Δspeed was the principal contributor. In order to mimic possible dependent and independent relationships

at IAS of 150 kts and 170 kts between aircraft in PA operations, one set of scenarios were created with the lead aircraft maintaining a constant speed throughout the entire approach course, and the trailing aircraft maintaining a constant speed relative to the lead aircraft. Another set of scenarios were created with the lead aircraft maintaining a constant speed until a slowdown point predicated on the FAF location. The initial trailing aircraft speed differed from initial lead aircraft speed by -10 kts to +20 kts. Subsequently, the lead and trailing aircraft speeds changed independently in each simulation, as each aircraft began an independent deceleration phase at an appropriate time to attain a FAS at the FAF. Analysis of these scenarios concluded Δspeed between the lead and trailing aircraft impacted CSL placement. Aircraft expansion yielded smaller CSL values, as depicted in Figure 4-15.

Table 4-11 displays the results of the CSL determination (in NM) at select distances from runway threshold of 20 NM to 1 NM for bins representing Δspeeds from -1 kts to 1 kts. According to this study, this speed bin allows the trailing aircraft to maintain a safe position within the protection zone relative to the lead aircraft. Unless otherwise indicated, all values in this table represent trailing aircraft in-trail distances measured in nautical miles. Results for the other six speed bins are included in Appendix F.

Table 4-11: CSL at Threshold Distance Limits for Speed Bin from -1 kts to 1 kts

Airport	Generic Airport								Boston Logan International Airport							
Runway Approach Alignment	Straight-In 2,500 ft RCLS				3° Offset 2,500 ft RCLS				Straight-In 1,500 ft RCLS				2° Offset 1,500 ft RCLS			
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM
CAT B - A	0.38	0.32	0.30	0.25	0.66	0.50	0.39	0.25	0.36	0.29	0.21	0.20	0.49	0.40	0.30	0.20
CAT B - D	0.39	0.30	0.30	0.27	0.64	0.50	0.39	0.29	0.37	0.29	0.20	0.20	0.49	0.40	0.30	0.20
CAT C - D	0.38	0.30	0.30	0.20	0.60	0.49	0.38	0.20	0.34	0.29	0.20	0.20	0.49	0.39	0.30	0.20
CAT C - E	0.38	0.30	0.29	-	0.64	0.49	0.38	-	0.32	0.29	0.20	-	0.49	0.39	0.30	-
CAT D - E	0.39	0.32	0.30	0.26	0.60	0.50	0.39	0.29	0.37	0.29	0.20	0.20	0.51	0.40	0.30	0.20
CAT D - F	0.38	0.30	0.30	0.20	0.66	0.49	0.39	0.29	0.36	0.29	0.22	0.20	0.49	0.39	0.30	0.20

Airport	Seattle-Tacoma International Airport								San Francisco International Airport							
Runway Approach Alignment	Straight-In 800 ft RCLS				Straight-In 1,700 ft RCLS				3° Offset 750 ft RCLS							
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	15 NM	10 NM	8 NM	7 NM	5 NM	3 NM	1 NM
CAT B - A	0.29	0.20	0.20	0.20	0.36	0.30	0.20	0.20	0.50	0.40	0.30	0.30	0.29	0.20	0.20	0.20
CAT B - D	0.29	0.22	0.20	0.20	0.36	0.30	0.21	0.20	0.50	0.40	0.30	0.30	0.28	0.20	0.20	0.20
CAT C - D	0.29	0.24	0.20	-	0.36	0.30	0.23	0.20	0.51	0.46	0.30	0.30	0.20	0.20	0.20	-
CAT C - E	0.29	0.24	0.20	-	0.30	0.30	0.22	-	0.51	0.41	0.30	0.30	0.20	-	-	-
CAT D - E	0.29	0.21	0.20	0.20	0.36	0.30	0.27	0.20	0.54	0.46	0.31	0.30	0.29	0.20	0.20	0.20
CAT D - F	0.29	0.22	0.20	-	0.30	0.30	0.20	0.20	0.52	0.40	0.30	0.30	0.29	0.20	0.20	-

5 Conclusions

The PA concept endeavors to increase airport capacity by enabling properly equipped aircraft to fly simultaneous dependent approaches to parallel runways spaced at least 700 ft, but less than 2,500 ft apart. This report presents the results of an analysis identifying the CSL during PA operations for a generic airport and for KBOS, KSEA, and KSFO. Collision risk was assessed to determine the CSL as a function of aircraft wake category of the lead and trailing aircraft pair for a given airport. Lead aircraft utilized Category I ILS with flight director guidance on a 2.85° glideslope, while trailing aircraft flew an RNAV/RNP approach on a 3° glidepath. Straight-in approaches were analyzed for the generic case, KBOS, and KSEA. Offset approaches were analyzed for the generic case, KBOS, and KSFO.[33]

This study focused on the risk of a mid-air collision. Therefore, the report was limited to collision risk associated with the CSL due to a course deviation of the lead aircraft. No other potential hazards, such as wake turbulence avoidance, TCAS, ACAS-X, PA avionics, radar separation standards, or controlled flight into terrain were evaluated.

Final analysis of data indicated that the variance in CSL between differing aircraft pairs was insignificant, with no distinguishable trends. Additionally, data indicated that reduced CSL in-trail distances may be attained for airport configurations with:

- Aircraft pair expansion Δspeeds vs aircraft pair compression Δspeeds (see Figure 4-19)
- Straight-in approaches vs offset approaches (see Figure 4-7 vs Figure 4-8)
- Smaller RCLS vs larger RCLS (see Figure 4-3)

Analysis concluded that Δspeed between the lead and trailing aircraft was the principal contributor to CSL placement. Runway approach alignment was a secondary contributor, followed by RCLS as the tertiary contributor.

The CSL increases considerably as compression rates increase. For specific pairings, even a slight Δspeed compression rate of 5 kts to 10 kts requires a greater increase of in-trail spacing than either runway approach alignment or RCLS. Below are CSL values for CAT C leading CAT D with 5 kts to 10 kts compression vs -1 kts to 1 kts speed bins, when paired at 20 NM from runway threshold:

- 0.52 NM vs 0.38 NM for KGEN Straight-In
- 0.80 NM vs 0.60 NM for KGEN Offset
- 0.46 NM vs 0.34 NM for KBOS Straight-In
- 0.67 NM vs 0.49 NM for KBOS Offset
- 0.40 NM vs 0.29 NM for KSEA Straight-In (800 ft RCLS)
- 0.49 NM vs 0.36 NM for KSEA Straight-In (1,700 ft RCLS)
- 0.69 NM vs 0.51 NM for KSFO Offset

[33] Figures and tables of results for lead aircraft flying a CAT I ILS approach are included in Data Analysis (see Section 4) and in Appendix F.

When comparing runway approach alignment (offset vs straight-in), the change in in-trail separation increases with an increase in offset approach angle. Below are CSL values for CAT C leading CAT D with -1 kts to 1 kts compression, when paired at 20 NM from runway threshold:

- 0.60 NM (3° Offset) vs 0.38 NM (Straight-In) for KGEN
- 0.49 NM (2° Offset) vs 0.34 NM (Straight-In) for KBOS

When considering decreased RCLS as a mitigator for collision risk, the effect is minimal compared to the separation needed for Δspeed. Below are CSL values for CAT C leading CAT D with -1 kts to 1 kts compression, when paired at 20 NM from runway threshold:

- 0.36 NM (1,700 ft RCLS) for KSEA vs 0.29 NM (800 ft RCLS) for KSEA
- 0.60 NM (2,500 ft RCLS) for KGEN vs 0.51 NM (750 ft RCLS) for KSFO

For all evaluated combinations, results indicate that the closest reasonable in-trail spacing is achieved when the speed compression between the aircraft is 5 kts or less. Further improvements may be attained for airport configurations with smaller RCLS, and for straight-in approaches versus offset approaches. Results also determined that aircraft wake category pairing has minimal impact on CSL in-trail spacing.

While the PA concept continues to evolve prior to final PA implementation, further investigation of the effects of wake turbulence encounters on the trailing aircraft are suggested. Wake encounter risk caused by a non-deviating lead aircraft, a lead aircraft executing a missed approach, a deviating lead aircraft crossing the path of the trailing aircraft, or a deviating trailing aircraft encountering the wake of a lead aircraft have a potential impact on PA operations.

References

Air Traffic Organization. *Order JO 7110.65X, Air Traffic Control*. Federal Aviation Administration, October 12, 2017.

Air Traffic Organization. *Order JO 7110.123 CHG 1, Wake Turbulence Recategorization – Phase II*. Federal Aviation Administration, November 15, 2016.

Air Traffic Organization. *Order JO 7110.659C, Wake Turbulence Recategorization*. Federal Aviation Administration, February 29, 2016.

Air Traffic Organization. *Safety Management System Manual, Air Traffic Control*. Federal Aviation Administration, April 2019.

Air Traffic Organization. *Order JO 7360.1D, Aircraft Type Designators*. Federal Aviation Administration, May 24, 2018.

Flight Standards Service. *Order JO 8260.3D, United States Standards for Terminal Instrument Procedures (TERPS)*. Federal Aviation Administration, February 16, 2018.

Federal Aviation Administration, *NextGen Implementation Plan*, 2016.

Flight Systems Laboratory. *DOT-FAA-AFS-400-09, Flight Crew Performance Study for Paired Approach Operations.* Flight Technologies and Procedures Division, Federal Aviation Administration, January 2016.

Flight Systems Laboratory. *DOT-FAA-AFS-400-83, Reduction of Diagonal Separation from 1.5 Nautical Miles to 1.0 Nautical Mile for Parallel Dependent Approaches*. Flight Technologies and Procedures Division, Federal Aviation Administration, February 2014.

Flight Systems Laboratory. *DOT-FAA-AFS-450-63, Geometrical Models for Aircraft in Terminal Area Risk Analyses.* Flight Technologies and Procedures Division, Federal Aviation Administration, April 2011.

International Civil Aviation Organization (ICAO). *DOC 9274-AN/904, Manual on the Use of the Collision Risk Model (CRM) for ILS Operations.* ICAO, 1980.

MP090245, Frequency and Severity of Deviations during Simultaneous Independent Approaches to Parallel Runways – A 2009 Update. Massimini, S.V., G.C. McNeil, N. Tene. The MITRE Corporation Center for Advanced Aviation System Development, September 2009.

Acknowledgments

Thank you to the entire team supporting this effort. We appreciate the support received from the Office of NextGen. Thank you Paul Strande, Mark Palmer, and Chris Lawler for your guidance and patience.

- Finally, the project team assigned to support this work has been a pleasure to work with. Thank you for your insights and your time.

Name	Group	Role
Rany Azzi	Flight Research & Analysis	Project Manager
Tara George	Organizational Effectiveness (DIGITALiBiz)	Technical Editor
John Blair	Flight Operations	Reviewer
Paul VonHoene	Flight Operations	Reviewer
Joseph Lintzenich	Flight Operations (DIGITALiBiz)	Reviewer
George Steinmetz	Flight Procedures & Airspace	Reviewer
Logan Branscum	Flight Research & Analysis	Reviewer
Sherri Hubbard	Flight Research & Analysis	Reviewer
Dustin Lucas	Flight Research & Analysis	Reviewer
Larry Miller	Flight Research & Analysis	Reviewer
Cody Nichols	Flight Research & Analysis	Reviewer
Lane Ramirez	Flight Research & Analysis	Reviewer
Doug Rodzon	Flight Research & Analysis	Reviewer
Barry Thurman	Flight Research & Analysis	Reviewer
Jason Walls	Flight Research & Analysis	Reviewer
Gary Foster	Flight Research & Analysis (SAIC)	Reviewer
Mamuka Gomarteli	Flight Research & Analysis (DIGITALiBiz)	Reviewer
Taylor Bley	Flight Research & Analysis (DIGITALiBiz)	Administrative Support

Appendix A: Risk Analysis – Probability of a Collision

This appendix describes the analysis methodology used to determine the probability of collision. There were four mutually exclusive types of deviations in this study: a 20° level deviation, a 20° descending deviation, a 30° level deviation, and a 30° descending deviation. Several events must happen for a collision to occur during simultaneous instrument approaches. First, an aircraft must deviate from its approach course and continue deviating. Next, the pilots of the deviating aircraft must not respond to ATC instructions. Then, both aircraft must be aligned so that a TCV, which is considered a collision, will occur if the controllers and pilots fail to react in sufficient time to separate the deviating and the endangered aircraft. This is referred to as an at-risk deviation and is denoted in Equation 1 below.

A collision involves two aircraft on two separate approaches and results in two accidents, as defined by the National Transportation Safety Board. There are two approaches in each operation. Therefore, a TCV will result in two accidents per operation, but only one accident per approach. Hence, the results of Equation 1 yield the probability in terms of accidents per operation. Assuming that a TCV will result in a collision, the probability of a collision can be expressed in mathematical terms as a joint occurrence. The probability of a joint occurrence is the product of all independent events:

$$P(TCV[Deviation\ Type]) = P(TCV|D \cap NRD \cap ARD) \times P(NRD|D \cap ARD) \times P(ARD|D) \times P(D|\theta_{deviation}) \times P(D|V_{deviation}) \quad (1)$$

D stands for deviation, NRD stands for non-responding deviation, ARD stands for at-risk deviation, the symbol ∩ is read and, and the symbol | is read given that or given. A deviation for a specific angle, θ, refers to either a 20° or 30° deviation. V refers to a deviation for either a level or descending vertical profile. All of these events are independent.

Equation 1 would then be read: The probability of a collision [for a specific deviation event type] is equal to the probability of a TCV, given a deviation that is both non-responding and at risk, times the probability of a non-responding deviation, given a deviation that is at risk, times the probability of an at-risk deviation, given a deviation, times the probability of a deviation, given its angle, times the probability of a deviation, given its vertical profile.

Factor 1 determines the probability that a TCV occurs given that a non-responding, at-risk deviation has occurred. This was the TCV rate determined from the simulation. The probability of a TCV occurring for a given type is equal to the number of deviations resulting in a TCV divided by the total aircraft pairs simulated for that deviation type, as expressed in Equation 2.

$$P(TCV|D \cap NRD \cap ARD) = \frac{number\ deviations\ resulting\ in\ a\ TCV}{total\ aircraft\ pairs} \quad (2)$$

Factor 2 determines the probability that the deviating aircraft does not respond to air traffic controllers' instructions to return to course, given that a deviation has occurred which is also at risk. The value of this factor is 8.32×10^{-3}.[34] Factor 2 in Equation 1 is expressed as:

$$P(NRD|D\cap ARD)$$

Factor 3 is the probability that the deviation is an at-risk deviation given that a deviation has occurred. The value of this factor was estimated from simulation data using the TCV shape described in Section 3.2 of this report and was found to be 3.17×10^{-2}. This value represents the likelihood that another aircraft will be at risk with the deviating aircraft. It assumes that the deviation is occurring during peak traffic times where there are aircraft separated by 3 NM in-trail on the other approach. Factor 3 in Equation 1 is expressed as:

$$P(ARD|D)$$

Factor 4, as expressed in Equation 1, is the probability of a deviation of a specified angle. Deviation data was captured from actual simultaneous approaches conducted in less than visual conditions. The probability and frequency of the occurrence of various deviation angles has been determined from the data and binned at 10°, 20°, and 30° by 10° increments as indicated in Table A-1.[35] Only the 20° and 30° bins were used in this study.

$$P(D|\theta)$$

Table A-1: 99% Confidence Intervals for NTZ Penetration Rates

Deviation Degrees	High Confidence Limit
$5° \leq \theta < 15°$	4.58×10^{-5}
$15° \leq \theta < 25°$	2.55×10^{-5}
$25° \leq \theta < 35°$	1.18×10^{-5}

Factor 5, the probability of a deviation either occurring in a level or descending vertical profile was not determined. Equal probabilities for level deviations and descending deviations were used, as has been done in previous collision risk studies:

$$P(D|V_{level}) = 0.50$$
$$P(D|V_{descending}) = 0.50$$

[34] Flight Systems Laboratory, *DOT-FAA-AFS-400-83, Reduction of Diagonal Separation from 1.5 Nautical Miles to 1.0 Nautical Mile for Parallel Dependent Approaches*, Flight Technologies and Procedures Division, Federal Aviation Administration, February 2014.

[35] Massimini, S.V., G.C. McNeil, N. Tene, *MP090245, Frequency and Severity of Deviations during Simultaneous Independent Approaches to Parallel Runways – A 2009 Update*, The MITRE Corporation Center for Advanced Aviation System Development, September 2009.

Given four mutually exclusive types of deviation events possible, finding the probability of one of them occurring was accomplished by summing their probabilities. Therefore, the total probability of a collision can be expressed using Equation 3 with each of the two deviation angles considered and each of the two types of vertical profiles considered:

$$\begin{gathered}P(TCV) = P(TCV|D\cap NRD\cap ARD)\times P(NRD|D\cap ARD)\times P(ARD|D)\times P(D|\theta_{20^\circ})\times P(D|V_{level}) \\ + \\ P(TCV|D\cap NRD\cap ARD)\times P(NRD|D\cap ARD)\times P(ARD|D)\times P(D|\theta_{20^\circ})\times P(D|V_{descending}) \\ + \\ P(TCV|D\cap NRD\cap ARD)\times P(NRD|D\cap ARD)\times P(ARD|D)\times P(D|\theta_{30^\circ})\times P(D|V_{level}) \\ + \\ P(TCV|D\cap NRD\cap ARD)\times P(NRD|D\cap ARD)\times P(ARD|D)\times P(D|\theta_{30^\circ})\times P(D|V_{descending})\end{gathered} \tag{3}$$

The logic represented in the above equations provides the risk of collision for dual simultaneous independent approaches. This logic has been modified for use in this paired approach analysis. During the paired approach analysis, the aircraft were initially released simultaneously as an alternative to at-risk. This was done in order to define CSL locations based on the geometry of the aircraft in relation to one another. Additionally, there was no ATC involvement, thus the NRB element will also be eliminated. With these modifications, the total probability of a collision considering all deviation types modeled can be expressed as follows in Equation 4:

$$\begin{gathered}P(TCV) = P(TCV|D)\times P(D|\theta_{20^\circ})\times P(D|V_{level}) \\ + \\ P(TCV|D)\times P(D|\theta_{20^\circ})\times P(D|V_{descending}) \\ + \\ P(TCV|D)\times P(D|\theta_{30^\circ})\times P(D|V_{level}) \\ + \\ P(TCV|D)\times P(D|\theta_{30^\circ})\times P(D|V_{descending})\end{gathered} \tag{4}$$

Given there were four mutually exclusive types of deviation events possible, finding the probability of one of them occurring was accomplished by summing their probabilities. Therefore, the total probability of a collision can be expressed using the above equation with each of the two deviation angles considered and each of the two types of vertical profiles considered.

Appendix B: Aircraft IAS

This appendix describes PA aircraft IAS during simulation runs. Simulation aircraft speeds were dependent upon aircraft location with respect to the FAF as described in Table B-1. FAF distance from runway threshold was site-specific for lead and trailing aircraft.

Table B-1: Aircraft IAS during Simulations

Aircraft Distance from Threshold	Aircraft Speed Profile	Comments
20 NM – 15 NM	Constant Initial Speed	Lead Aircraft: Always 170 kts Trailing Aircraft: Between 160 kts and 190 kts
14 NM – FAF	Constant Initial Speed until Deceleration	Constant Initial IAS prior to ≈10kts/NM Deceleration to FAF. FAS Predicated on Aircraft Type.
FAF	Constant FAS	FAS Predicated on Aircraft Type.
FAF – 1 NM	Constant FAS	FAS Predicated on Aircraft Type.

Table B-2 shows the IAS distributions used for lead and trailing aircraft on the approach. Aircraft released at greater distances from the FAF (e.g., 19 NM from runway threshold) flew constant speeds with the lead aircraft speed always set at 170 kts and the trailing aircraft speed selected from a uniform distribution with lower and upper bounds of 160 kts and 190 kts, respectively. Aircraft released closer to the FAF (e.g., 8 NM from runway threshold) flew at speeds between 190 kts and a final approach speed. ASATng utilized an algorithm to determine the point along the flight path for deceleration to commence in order to achieve a final approach speed at the FAF. The deceleration rate during this phase of flight was approximately 10 kts/NM. Aircraft flying in the final approach segment (i.e., from the FAF to runway threshold) flew constant final approach speeds. The final approach speeds (ranging from 109.3 kts and 159.0 kts) were obtained from Johnson SB and Johnson SU distributions predicated on speeds commensurate with the aircraft modeled in the simulation, and were representative of other aircraft in the same wake category.

Table B-2: Aircraft IAS Distributions

Approach Segment	Wake CAT	Aircraft Type	Speed (kts)				Distribution Type	Distribution Parameters			
			Min	Max	μ	σ		γ	δ	λ	ξ
Initial	All	Lead	170.0	170.0	170.0	N/A	Uniform	N/A	N/A	N/A	N/A
Initial	All	Trailing	160.0	190.0	175.0	N/A	Uniform	N/A	N/A	N/A	N/A
Transition	All	All	109.3	190.0	N/A	N/A	Linear Mixed	N/A	N/A	N/A	N/A
Final	A	Airbus A380	129.3	148.6	N/A	N/A	Johnson SU	0.20967	0.91758	1.3462	137.4151
Final	B	Airbus A330-300	137.2	149.4	N/A	N/A	Johnson SU	-0.11379	0.88699	1.0594	142.0208
Final	B	Boeing 747-400	137.2	149.4	N/A	N/A	Johnson SU	-0.11379	0.88700	1.0594	142.0200
Final	C	Boeing 767-300	149.2	159.0	N/A	N/A	Johnson SB	-0.30850	0.63890	10.4140	148.7100
Final	D	Airbus A320	129.3	148.6	N/A	N/A	Johnson SU	0.20967	0.91758	1.3462	137.4151
Final	D	Boeing 737-800	135.0	154.0	N/A	N/A	Johnson SU	0.24900	0.97100	1.6900	146.0000
Final	E	Embraer RJ 145	117.8	141.8	N/A	N/A	Johnson SB	-2.63610	1.87662	53.0919	91.4145
Final	F	Saab 340	109.3	145.2	N/A	N/A	Johnson SU	0.66827	3.21004	17.2169	126.5200

Figure B-1 depicts an entire approach course for all scenarios. Scenarios consist of 3 phases: an initial phase (IAS_INIT), a deceleration phase (IAS_DECEL), and a final approach phase (IAS_FAS). Simulations start at discrete 1 NM points along the approach course; therefore, the aircraft can start within any phase of flight. An aircraft may start in one phase of flight and transition to the next phase prior to the completion of the simulation.

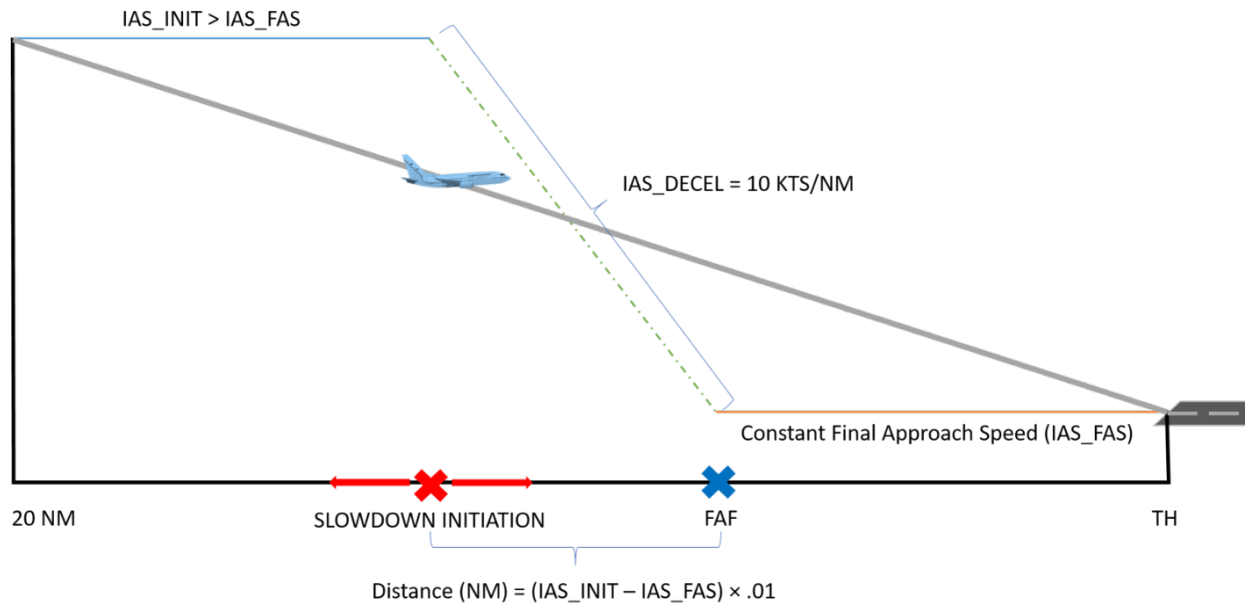

Figure B-1: Simulation Speeds

Table B-3 shows the runway threshold distance from the FAF for each of the airport configurations analyzed is this study. The FAF placement of parallel approaches in this study were predicated on distances from runway threshold at matching altitudes. Therefore, a FAF for an approach with a 3° glidepath was positioned closer to the runway threshold than a FAF for an approach with a 2.85° glidepath.

Table B-3: Airport Runway Configuration Information

	Lead Aircraft		Trailing Aircraft	
Airport	**Runway**	**Threshold Distance from FAF**	**Runway**	**Threshold Distance from FAF**
KBOS	4R	5.39 NM	4L	5.13 NM
KGEN	36R	5.00 NM	36L	4.76 NM
KSEA	16L	4.67 NM	16C	4.43 NM
KSEA	16C	4.68 NM	16R	4.48 NM
KSFO	28L	5.74 NM	28R	5.44 NM

Appendix C: Error Distributions

This appendix describes the impact of the components of total system error (TSE) on collision risk associated with approach operations analyzed in this study. Total system error is the difference between the true position and the desired position of the aircraft. The TSE is equal to the vector sum of the navigation system error (NSE), flight technical error (FTE), and path definition error (PDE).

Collision risk for the CSL in a PA operation was assessed for straight-in approaches and single offset approaches. ASATng fast-time simulations were configured and conducted to examine approaches utilizing Category I ILS with flight director guidance at a glideslope of 2.85° for the lead aircraft; and Global Positioning System (GPS)-equipped RNAV/RNP aircraft flying with flight director guidance and a glidepath of 3.00° for the trailing aircraft. RNAV aircraft that rely on distance measuring equipment (DME) and inertial reference unit (IRU) for DME/DME or DME/DME/IRU navigation were not considered for this study.

Tracking performance for the ILS aircraft was based on International Civil Aviation Organization (ICAO) collision risk model (CRM) distributions for both the lateral and vertical deviations from glidepath. For the RNAV/RNP aircraft considered in this study, the initial lateral deviation of the aircraft was based on an NSE defined by a Gaussian (normal) distribution with zero mean and 50-meter standard deviation, the FTE distribution with zero mean and 50-meter standard deviation, and the PDE a 20-meter standard deviation. The RNAV/RNP aircraft utilized the same Category I ILS CRM vertical deviation distributions that were used for the ILS approaches.

Table C-1 shows a comparison of the cumulative lateral deviation distribution percentages bounded within a given standard deviation. The CRM distribution (for ILS aircraft) has a more compact distribution near the mean than the Gaussian distribution (for RNAV/RNP aircraft). The opposite is true at the edges of the distributions, where the CRM distribution (for ILS aircraft) flattens out and has much thicker tails than the Gaussian distribution (for RNAV/RNP aircraft). Restated, the CRM distribution (for ILS aircraft) is the tighter distribution at lower standard deviations and the Gaussian distribution (for RNAV/RNP aircraft) becomes the tighter distribution at approximately 1.7 standard deviation and beyond.

Table C-1: Lateral Distribution Cumulative Probabilities (CRM vs Gaussian)

Standard Deviation	Normal Distribution	CRM for Category I at 1,200 m	CRM for Category I at 4,200 m	CRM for Category I at 7,800 m
0.4	31.08%	35.12%	35.26%	35.42%
1.0	68.27%	72.14%	72.50%	72.58%
1.4	83.85%	85.49%	85.65%	85.61%
1.6	89.04%	89.68%	89.74%	89.67%
1.8	92.81%	92.68%	92.68%	92.61%
2.0	95.45%	94.83%	94.79%	94.72%
2.4	98.36%	97.43%	97.36%	97.32%
3.0	99.73%	99.10%	99.05%	99.08%
3.4	99.93%	99.55%	99.52%	99.58%

Table C-2 displays the displacement in meters of one standard deviation laterally and vertically for the ILS and RNAV/RNP approaches used in this study. For ILS approaches, the lateral displacement increases as a function of range from runway threshold. For RNAV/RNP approaches, the lateral displacement remains constant.

Table C-2: Standard Deviations of Aircraft Displacement during Approach[36]

Aircraft & Approach Type	Range (meters)	Lateral Displacement (meters)		Vertical Displacement (meters)	
		Lead Aircraft ILS	Trailing Aircraft RNAV/RNP	Lead Aircraft 2.85° Glideslope	Trailing Aircraft 3.0° Glidepath
Lead Aircraft: Category I ILS Trailing Aircraft: RNAV/RNP	1,200	16.4	74.1	5.5	5.8
	4,200	35.9	74.1	12.9	13.6
	7,800	67.5	74.1	26.0	27.4

Note: Root-sum-squaring the NSE, FTE, and PDE values translates to a lateral 1σ TSE displacement of 0.04 NM (i.e., 74.1 meters) for flight director-guided RNAV/RNP approaches.

[36] ICAO, *DOC 9274-AN/904, Manual on the Use of the Collision Risk Model (CRM) for ILS Operations*, International Civil Aviation Organization, 1980.

Appendix D: Scenario Creation and Simulation Runs

This appendix describes scenario creation and simulation runs. The primary analysis tool for this evaluation was ASATng, a Monte Carlo simulation tool for aviation related safety assessments. Monte Carlo simulations run millions of simulations for a scenario by repeatedly sampling values from probability distributions for input variables.

A key emphasis of this safety study centered on analysis of seven runway configurations spread across four airports: KGEN, KBOS, KSEA, and KSFO. CSL determination for a runway configuration required the creation of multiple scenarios. Scenarios were differentiated from one another by consisting of unique lead aircraft distances from runway threshold coupled with unique in-trail distances of the trailing aircraft. Lead aircraft release positions were initially placed at 20 NM from runway threshold, followed by release positions at select locations to 1 NM from runway threshold. Trailing aircraft release positions were established with respect to the lead aircraft, typically starting roughly abeam of the lead aircraft and continuing at 0.1 NM increments until the point where the collision risk met or exceeded a desired probability of collision risk. Each of these lead/trailing aircraft starting positions is referred to as a "node." Aircraft release positions (i.e., nodes) in a scenario were positioned at various locations as depicted in Figure D-1. The location and number of nodes varied per scenario based on the data needed to determine and satisfactorily graph the CSL. The example in the figure below depicts 60 nodes. The red and green lines signify the upper and lower bounds for speed bins.

Figure D-1: Nodes for an Airport Runway Configuration (Example)

Scenarios were created for nodes associated with each airport runway configuration, aircraft pairing, and deviation type. Table D-1 provides information on the composition and number of scenarios required.

Table D-1: Scenario Composition

Item #	Variable	Number of Values	Comments
1	Airport Runway Configuration	7	KGEN (Straight-in, 2,500 ft RCLS), KGEN (Offset, 2,500 ft RCLS), KBOS (Straight-in, 1,500 ft RCLS), KBOS (Offset, 1,500 ft RCLS), KSEA (Straight-in, 800 ft RCLS), KSEA (Offset, 1,700 ft RCLS) KSFO (Offset, 750 ft RCLS)
2	Aircraft Pairing	6	CAT B leading CAT A, CAT B leading CAT D, CAT C leading CAT D, CAT C leading CAT E, CAT D leading CAT E, CAT D leading CAT F
3	Deviation Type	4	20° Level, 20° Descending 30° Level, 30° Descending
4	Node	80 (Nominal)	The number of nodes required for a given airport runway configuration and aircraft pairing may vary widely. The number is typically between 26 and 200, with a nominal value around 80. Each node has a specific lead aircraft distance from runway threshold coupled with an in-trail distance of the trailing aircraft.
Total			Total scenarios in this example: 7 x 6 x 4 x 80 = 13,440

A Scenario serves as the basic framework for ASATng Monte Carlo analysis. Once scenarios were created, multiple simulation runs (where input variable values were modified for each run) were conducted for each scenario to establish the CSL at locations along the approach course. A Simulation run is a single instance of an ASATng Monte Carlo simulation. Each input variable is assigned a value for the fast-time simulation run. For each scenario, 150,000 simulation runs[37] were conducted for each of the 13,440 scenarios. Values for input variables were randomly selected for each simulation as indicated in Table D-2. The results of the Monte Carlo simulations were analyzed to identify the location of the CSL for the desired probability of collision.

Table D-2: Simulation Input Variables Associated with a Scenario

Item #	Variable	Number of Values Selected for Each Simulation	Comments on Variable Values
1	Lead Aircraft Initial IAS	1	If TH distance is 20 NM to 14 NM, then IAS is a constant 170 kts. If TH distance is 14 NM to FAF, then IAS is a transition speed. If TH distance is FAF to 1 NM, then IAS is a FAS.
2	Trailing Aircraft Initial IAS	1	If TH distance is 20 NM to 14 NM, then IAS is selected from a range of 160 kts to 190 kts. If TH distance is 14 NM to FAF, then IAS is a transition speed. If TH distance is FAF to 1 NM, then IAS is a FAS.
3	Lead Aircraft FAS	1	From FAS distributions ranging from 129.3 kts to 159.0 kts.
4	Trailing Aircraft FAS	1	From FAS distributions ranging from 109.3 kts to 154.0 kts.
5	Lead Aircraft Starting Displacement	1	Lateral displacement selected from CRM distribution. Vertical displacement selected from CRM distribution.
6	Trailing Aircraft Starting Displacement	1	Lateral displacement selected from Gaussian distribution. Vertical displacement selected from CRM distribution.
Total			A value is selected for each item for each simulation run. 150,000 simulations are run for each scenario. Total simulations: 150,000 sims/scenario x 13,440 scenarios = 2,016,000,000

[37] Typically, 150,000 simulation runs were conducted. This number varied for some of the modified special cases.

Appendix E: Aircraft Count

In Monte Carlo simulations, the Law of Large Numbers applies. This states that as the number of identically distributed, randomly generated variables increases, their sample mean (average) approaches their theoretical mean. In other words, the more runs simulated, the closer the results will get to the actual risk value. Multiple simulations of the same scenario were performed during this analysis to examine the relationship between risk and number of aircraft pairs (simulation runs). Figure E-1 shows the comparison of 50,000, 100,000, 150,000, and 200,000 pairs of aircraft for a 3° offset scenario at KSFO. There was a slight difference between the 50,000, 100,000, and 150,000 aircraft simulation pairs, but there was no significant difference between a scenario with 150,000 pairs and a scenario with 200,000 pairs of aircraft. In this way, it was determined that 150,000 pairs were adequate to provide a reasonable risk value without adding to the total amount of simulation time required to run 400,000 pairs.

The analysis in this report was performed in such a way, that for each airport configuration, the results of the analysis were broken down into speed bins. This provides valuable insight to the risk at a given location with relation to the Δspeed of the aircraft. However, the simulations were performed depending on aircraft type, using different types of distributions for the Final Approach Speeds. For this reason and because the speeds of the aircraft were captured at the CPA, it is impossible to force the simulation to uniformly distribute the Δspeeds from the deceleration phase to the runway threshold. This forces calculation of risk with an asymmetrical amount of aircraft pairs per speed bin. For example, a speed bin may only record 25,000 pairs and 0 TCVs, resulting in an acceptable collision risk value. If that number of aircraft pairs is increased to 100,000, there is the potential for a dramatic increase in collision risk. It is concluded that a low number of aircraft pairs can adequately describe the risk of a particular scenario, but cannot determine safety due to an insufficient sample size.

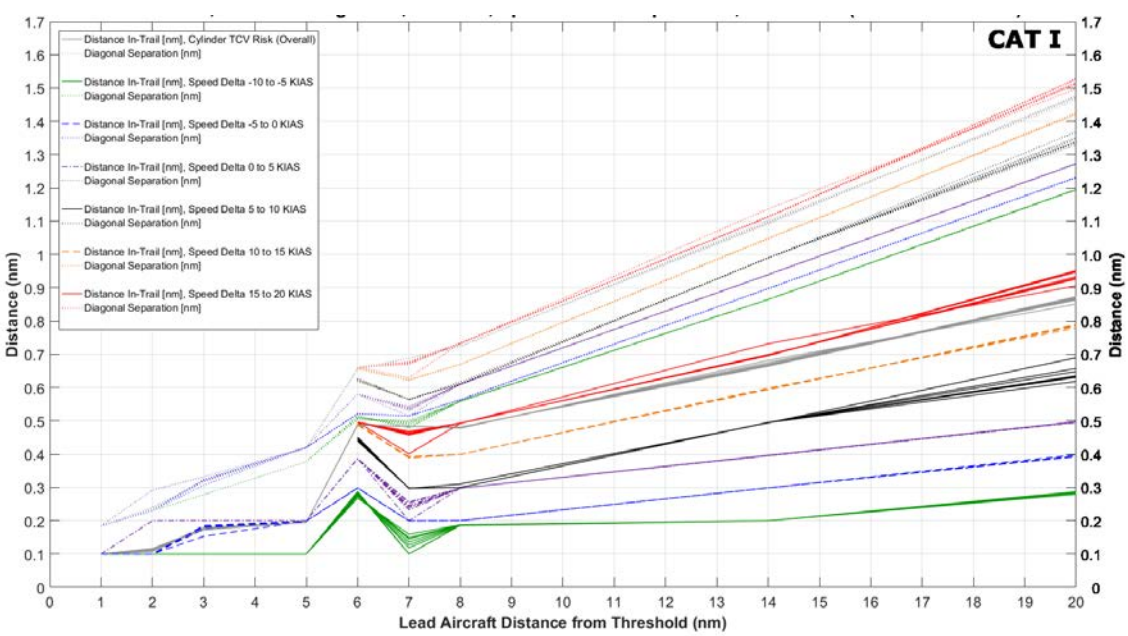

Figure E-1: Comparison of Number of Aircraft Pairs

Appendix F: Generic and Specific Approach Supplemental Graphs & Tables

This appendix contains additional figures and tables of data analyzed for Generic and Specific Airport approach configurations at KGEN, KBOS, KSEA, and KSFO referenced in the Methodology and Data Analysis sections of this safety study. Lead aircraft were flown using Category I ILS at a glideslope of 2.85°; while trailing aircraft flew an RNAV/RNP approach with flight director at a glidepath of 3°. Figure F-1 through Figure F-35 and Table F-1 through Table F-6 present the results for the approach configurations identified below:

- KGEN straight-in approaches (see Figure F-1 through Figure F-5)
- KGEN offset approaches (see Figure F-6 through Figure F-10)
- KBOS straight-in approaches (see Figure F-11 through Figure F-15)
- KBOS offset approaches (see Figure F-16 through Figure F-20)
- KSEA straight-in approaches with an RCLS of 800 ft
  (see Figure F-21 through Figure F-25)
- KSEA straight-in approaches with an RCLS of 1,700 ft
  (see Figure F-26 through Figure F-30)
- KSFO offset approaches (see Figure F-31 through Figure F-35)
- CSL at Threshold Distance Limits for Speed Bins (see Table F-1 through Table F-6)

Figure F-1 depicts the CSL for an aircraft pair of CAT B leading CAT A with a straight-in approach at KGEN.

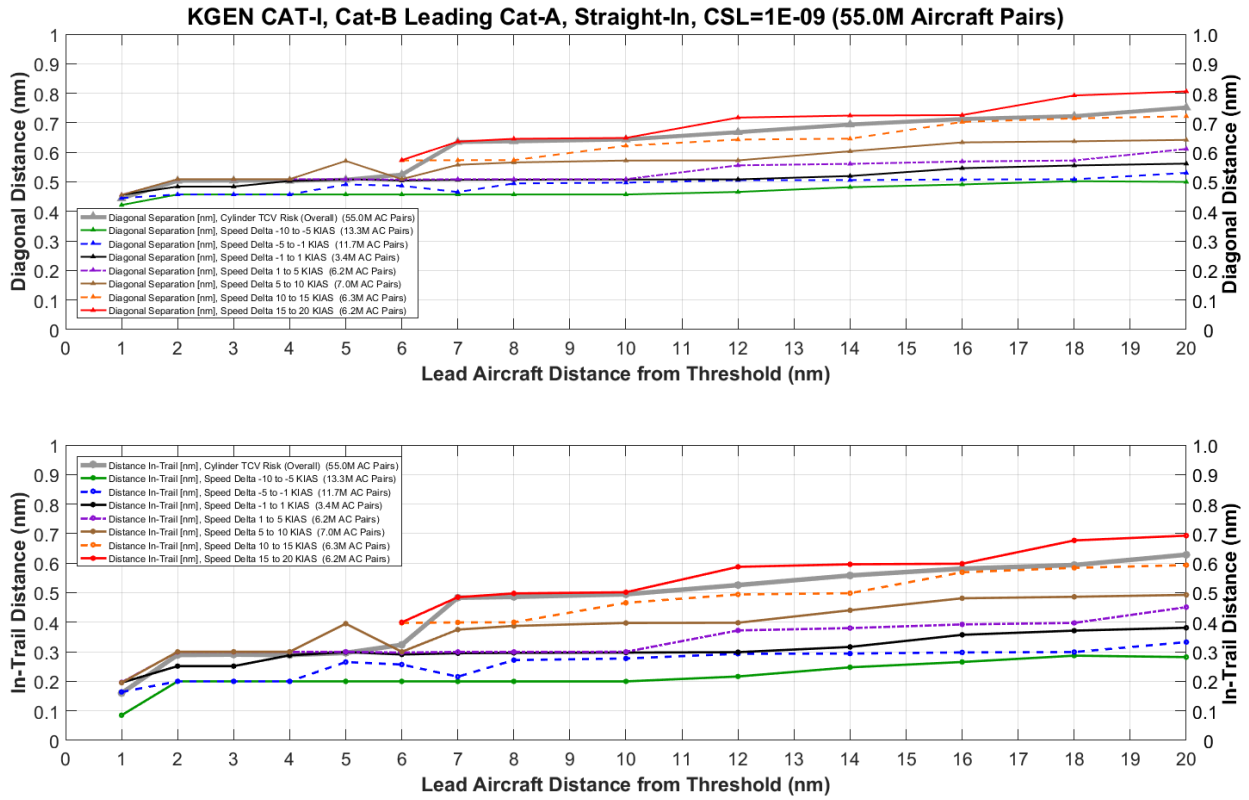

Figure F-1: KGEN CSL for CAT B Leading CAT A (Straight-In with 2,500 ft RCLS)

Figure F-2 depicts the CSL for an aircraft pair of CAT B leading CAT D with a straight-in approach at KGEN.

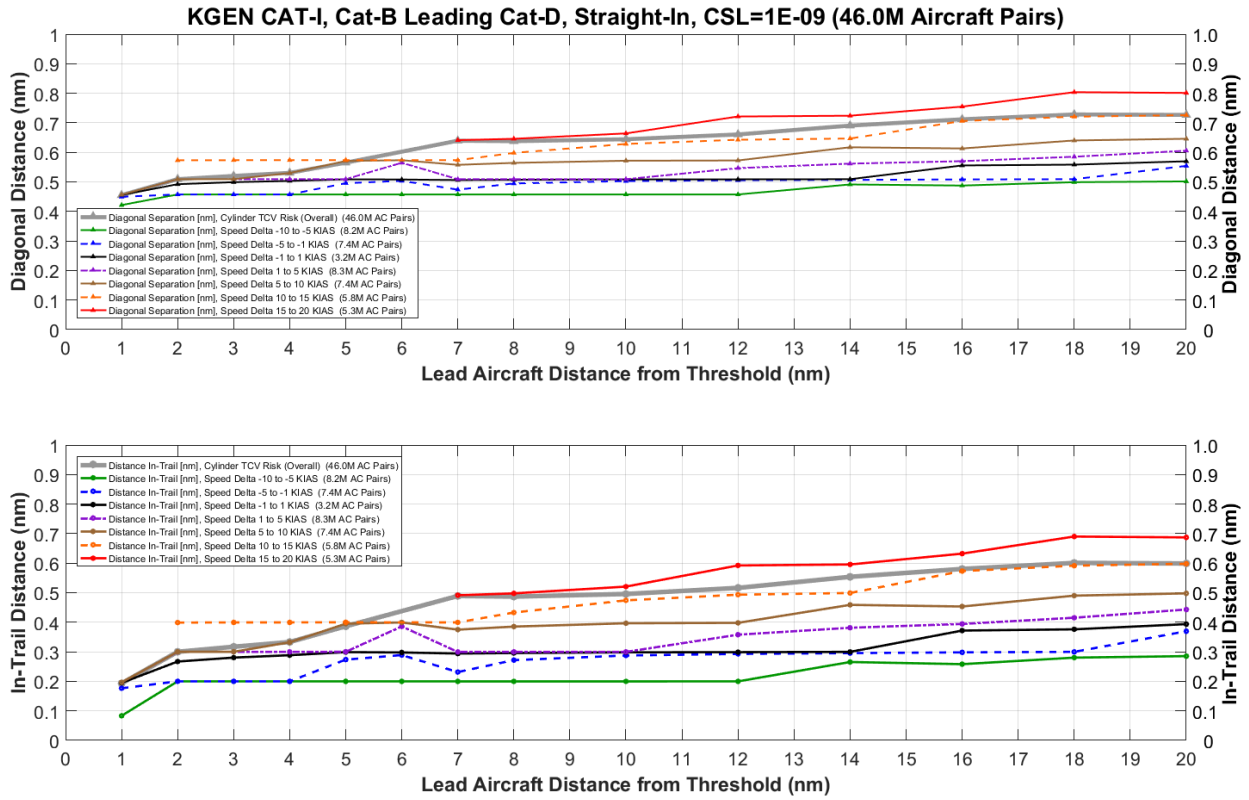

Figure F-2: KGEN CSL for CAT B Leading CAT D (Straight-In with 2,500 ft RCLS)

Figure F-3 depicts the CSL for an aircraft pair of CAT C leading CAT E with a straight-in approach at KGEN.

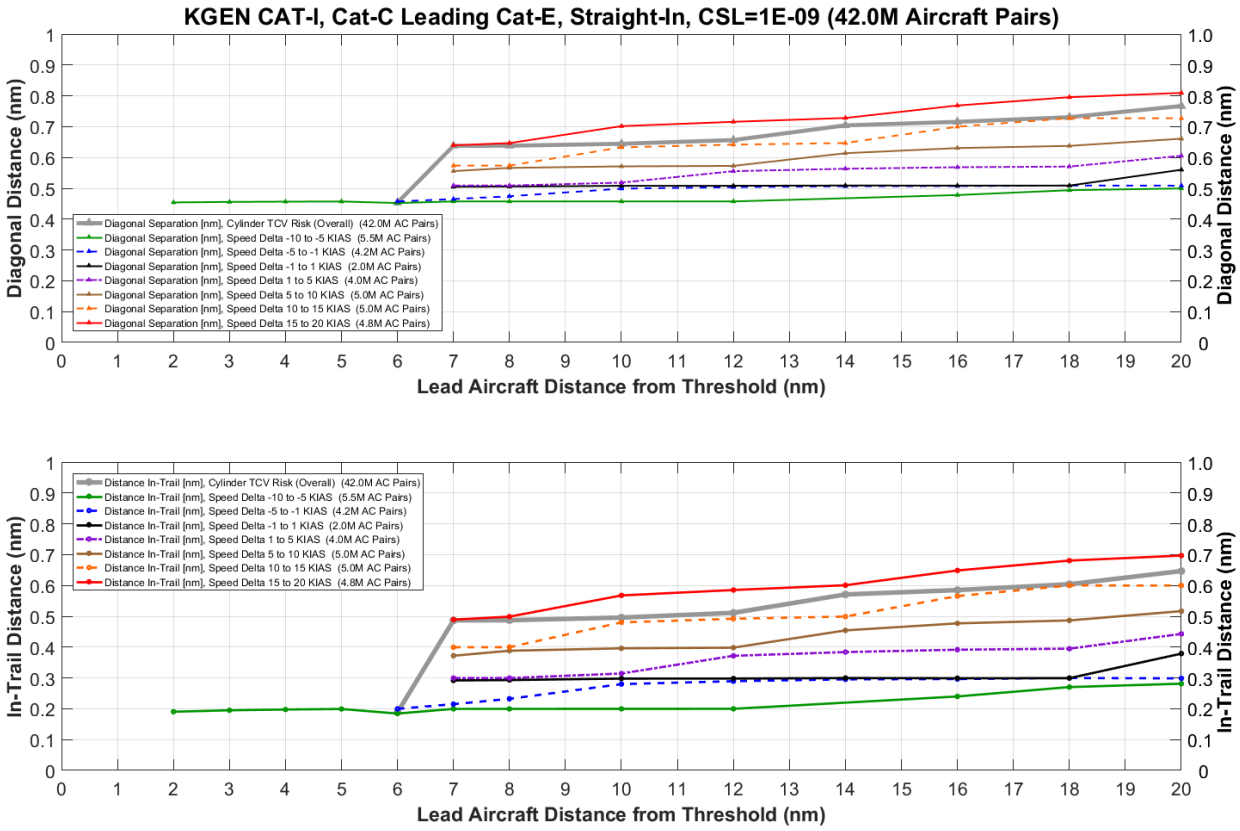

Figure F-3: KGEN CSL for CAT C Leading CAT E (Straight-In with 2,500 ft RCLS)

Figure F-4 depicts the CSL for an aircraft pair of CAT D leading CAT E with a straight-in approach at KGEN.

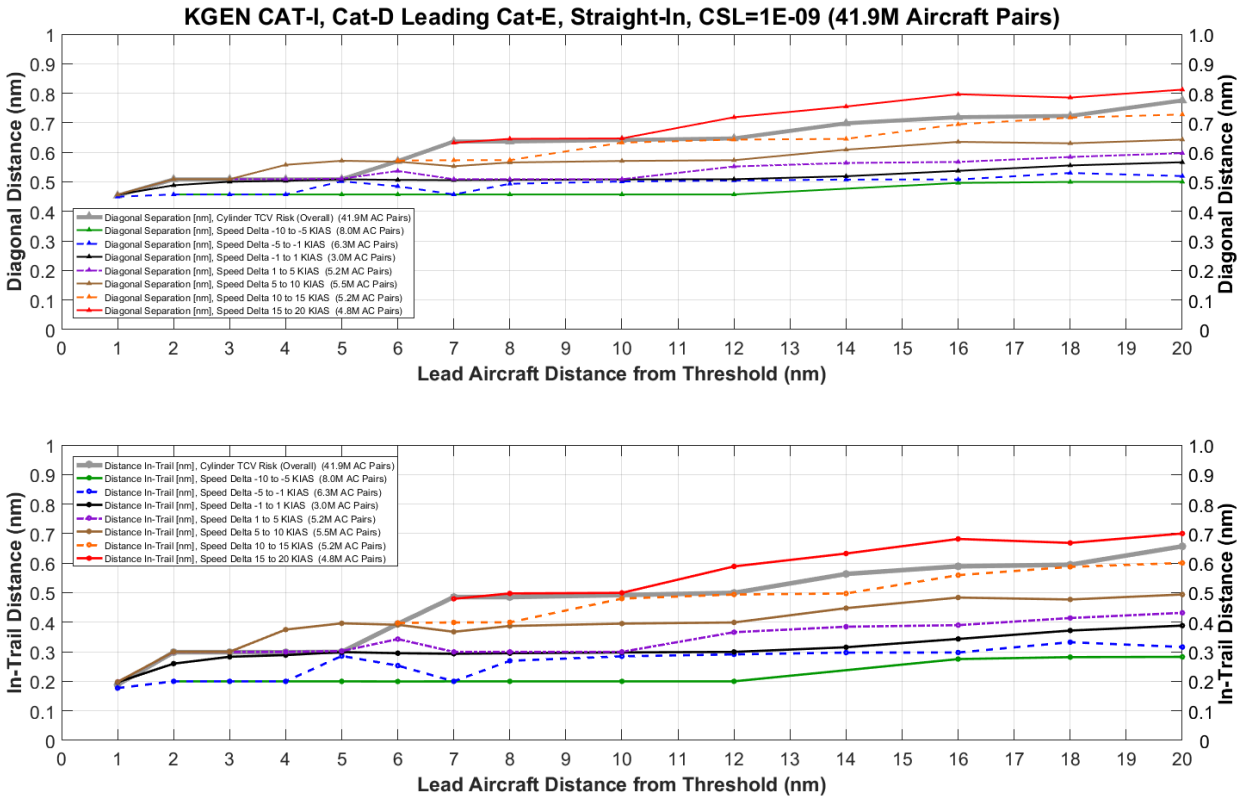

Figure F-4: KGEN CSL for CAT D Leading CAT E (Straight-In with 2,500 ft RCLS)

Figure F-5 depicts the CSL for an aircraft pair of CAT D leading CAT F with a straight-in approach at KGEN.

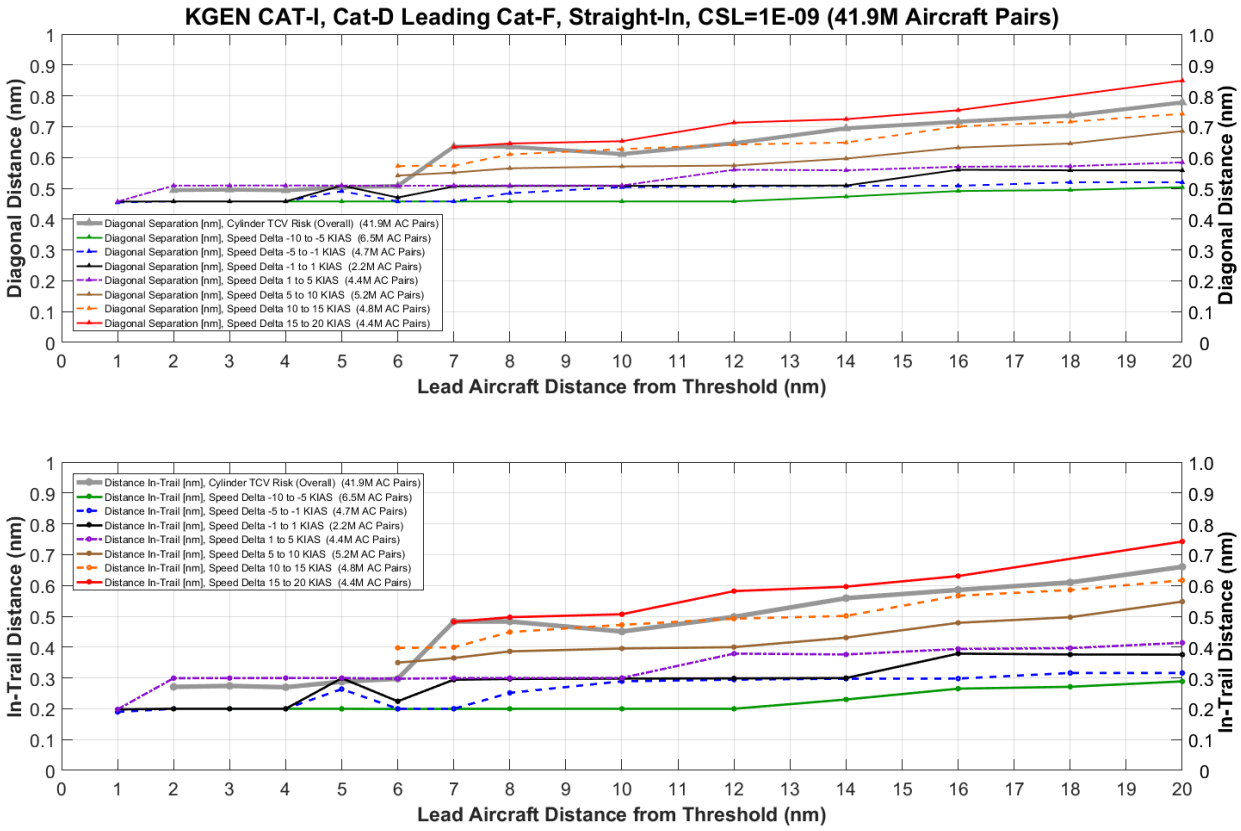

Figure F-5: KGEN CSL for CAT D Leading CAT F (Straight-In with 2,500 ft RCLS)

Figure F-6 depicts the CSL for an aircraft pair of CAT B leading CAT A with a 3° offset approach at KGEN.

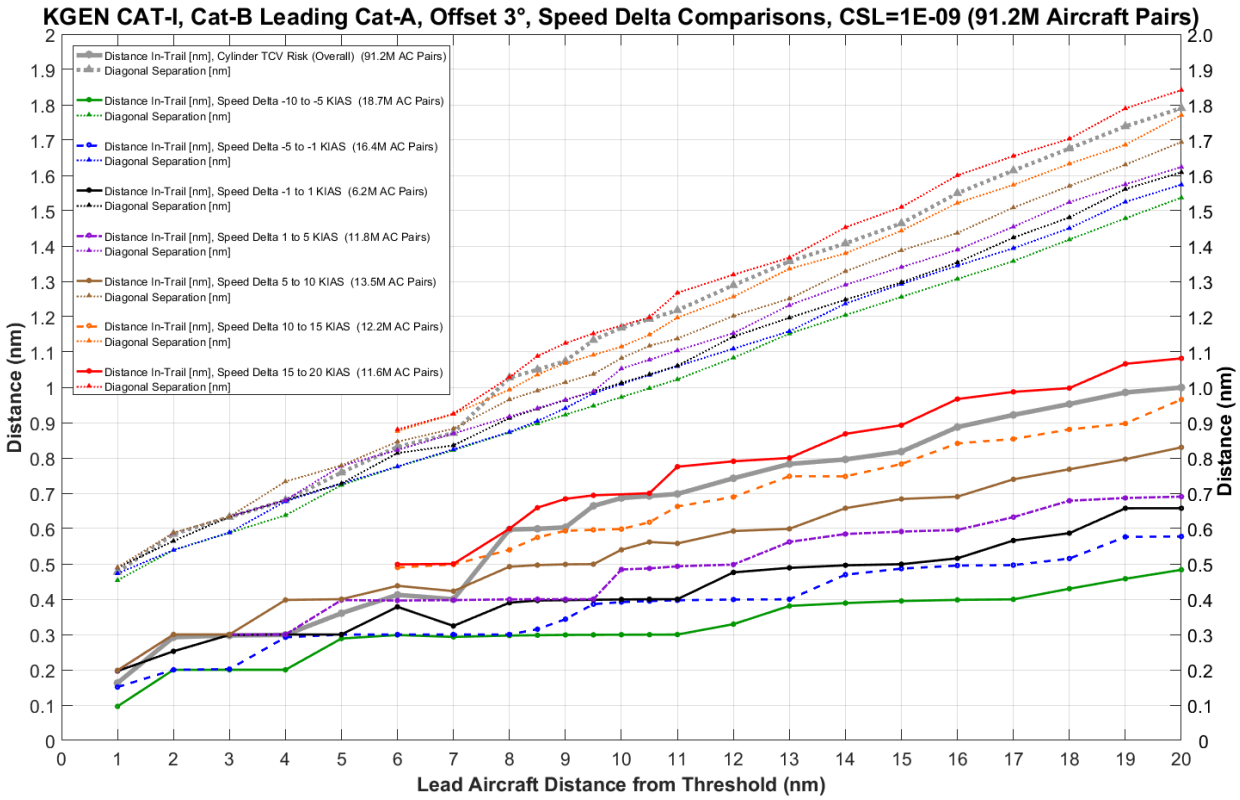

Figure F-6: KGEN CSL for CAT B Leading CAT A (3° Offset with 2,500 ft RCLS)

Figure F-7 depicts the CSL for an aircraft pair of CAT B leading CAT D with a 3° offset approach at KGEN.

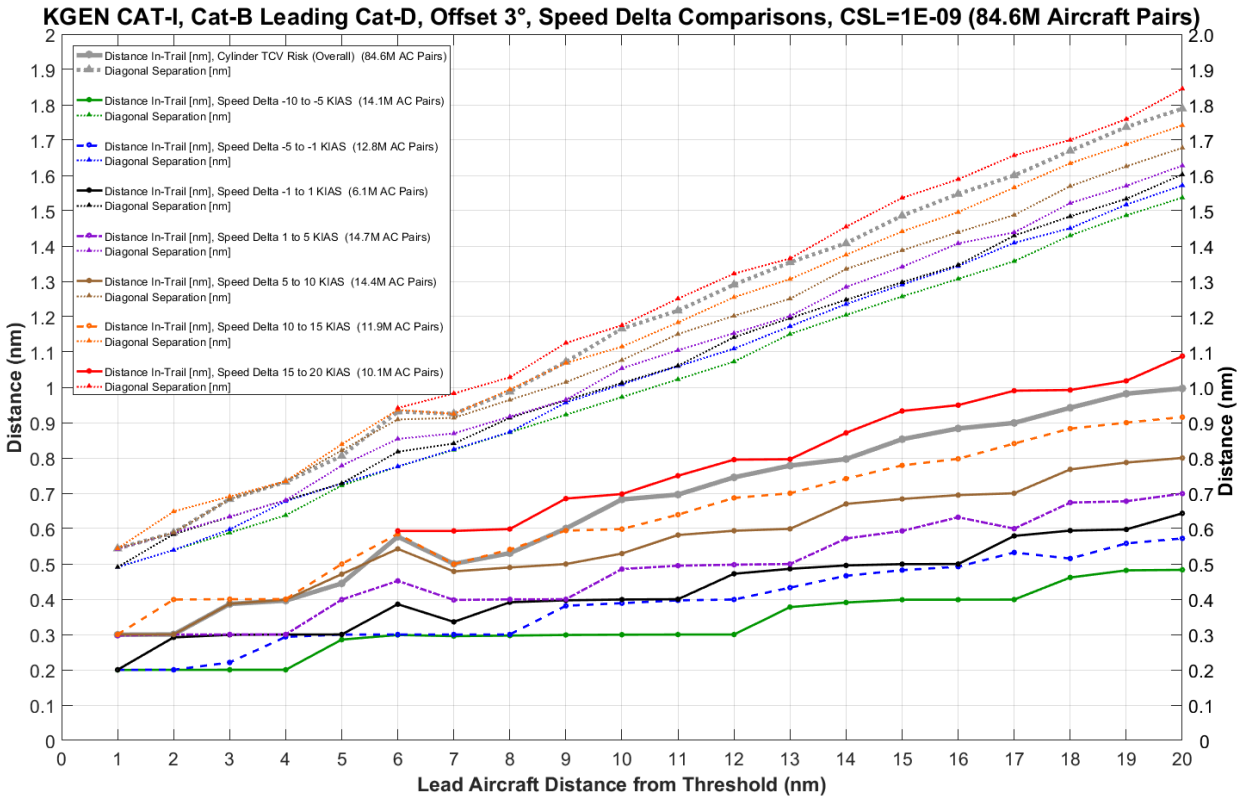

Figure F-7: KGEN CSL for CAT B Leading CAT D (3° Offset with 2,500 ft RCLS)

Figure F-8 depicts the CSL for an aircraft pair of CAT C leading CAT E with a 3° offset approach at KGEN.

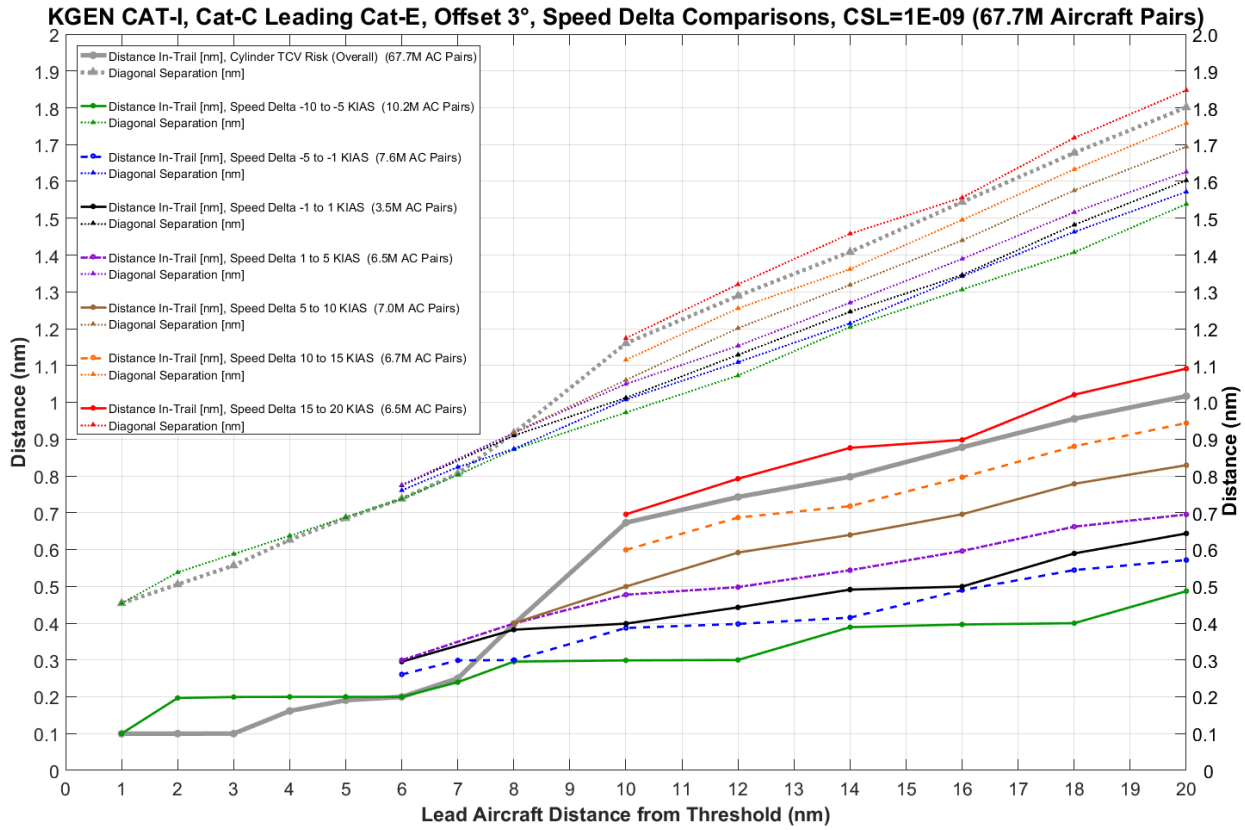

Figure F-8: KGEN CSL for CAT C Leading CAT E (3° Offset with 2,500 ft RCLS)

Figure F-9 depicts the CSL for an aircraft pair of CAT D leading CAT E with a 3° offset approach at KGEN.

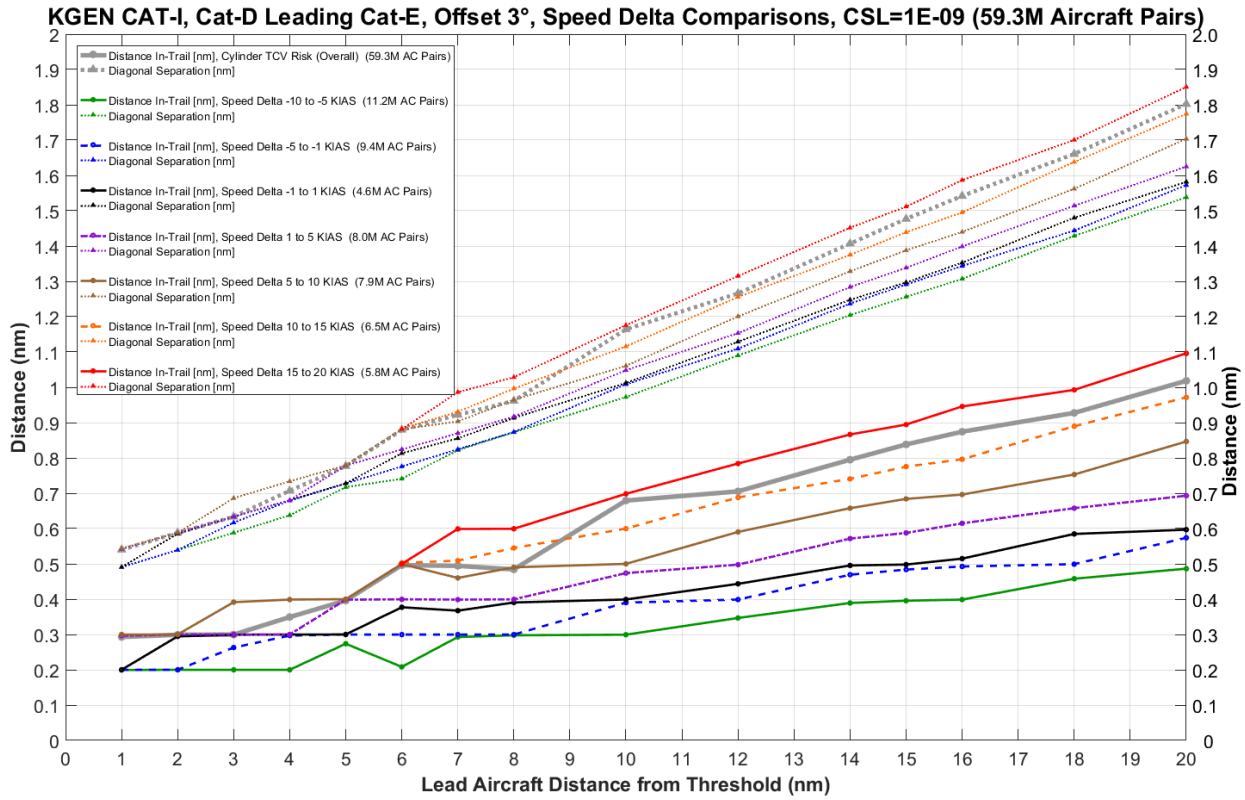

Figure F-9: KGEN CSL for CAT D Leading CAT E (3° Offset with 2,500 ft RCLS)

Figure F-10 depicts the CSL for an aircraft pair of CAT D leading CAT F with a 3° offset approach at KGEN.

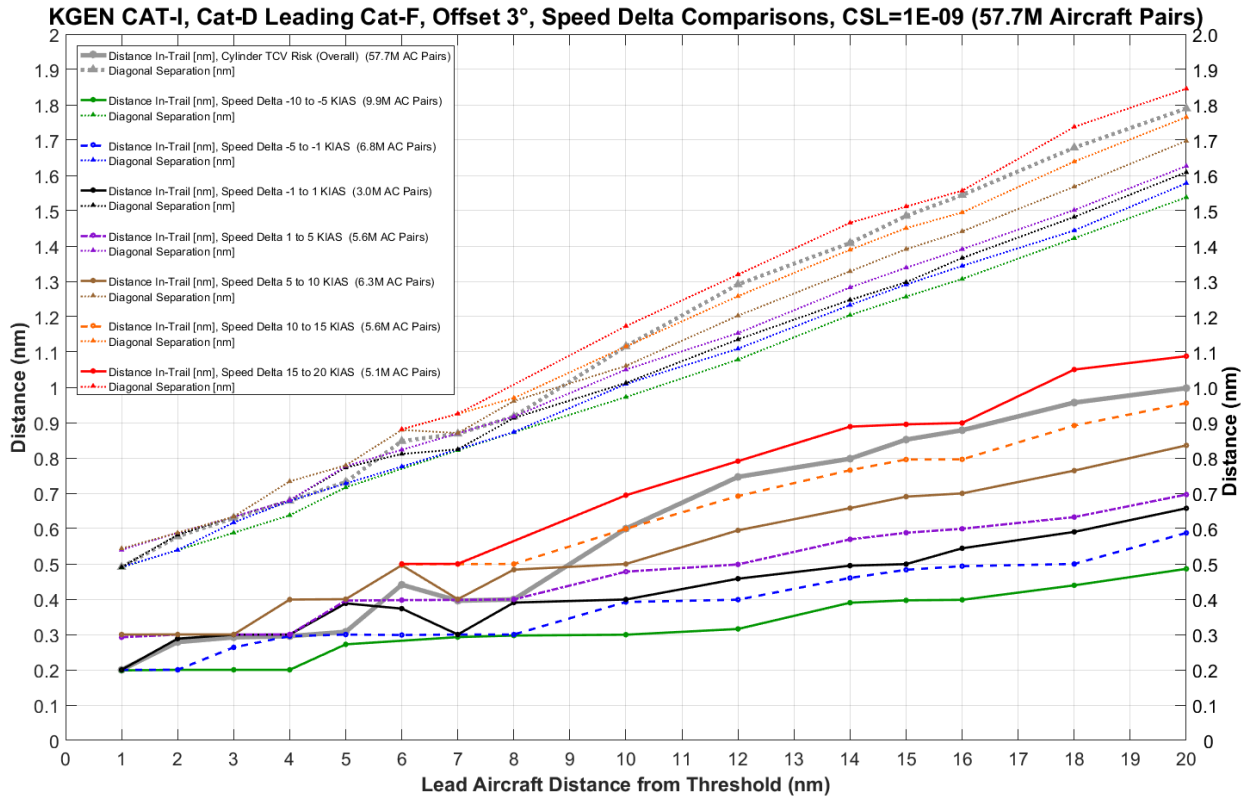

Figure F-10: KGEN CSL for CAT D Leading CAT F (3° Offset with 2,500 ft RCLS)

Figure F-11 depicts the CSL for an aircraft pair of CAT B leading CAT A with a straight-in approach at KBOS.

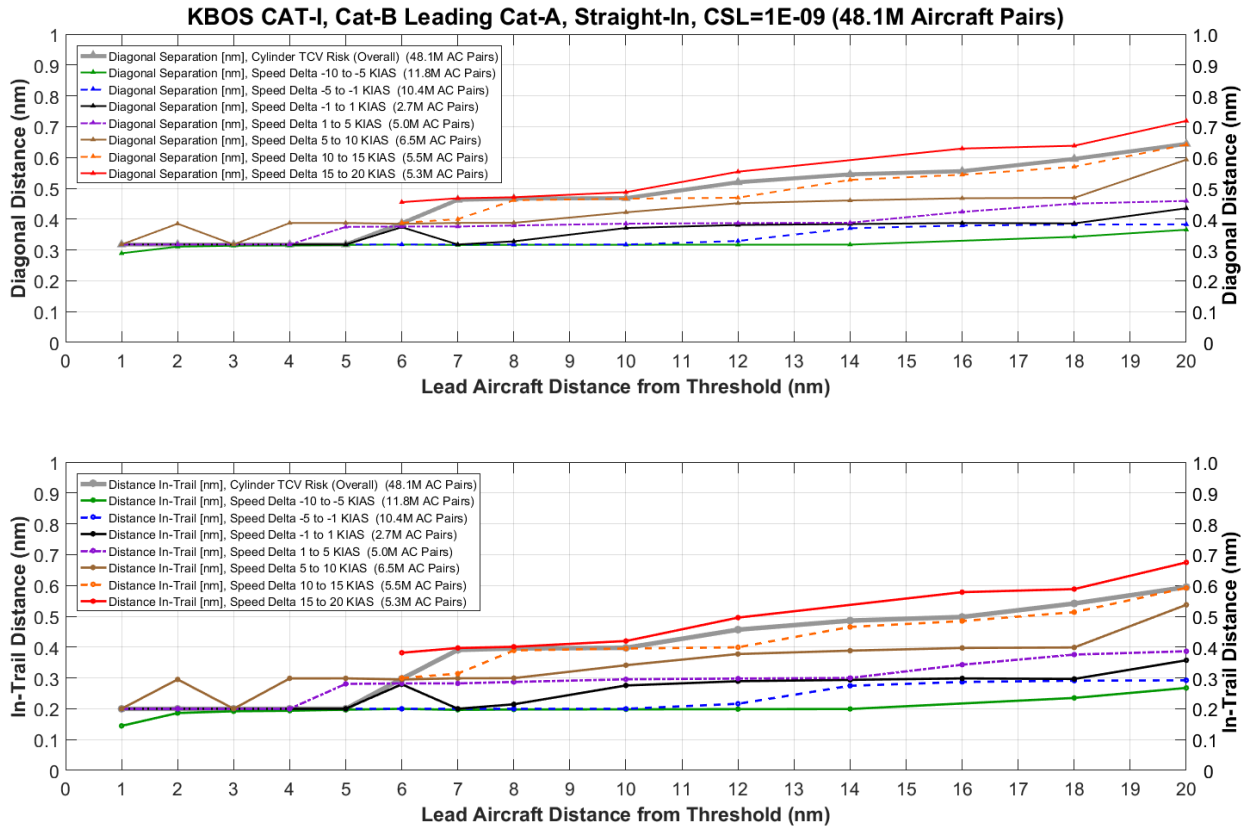

Figure F-11: KBOS CSL for CAT B Leading CAT A (Straight-In with 1,500 ft RCLS)

Figure F-12 depicts the CSL for an aircraft pair of CAT B leading CAT D with a straight-in approach at KBOS.

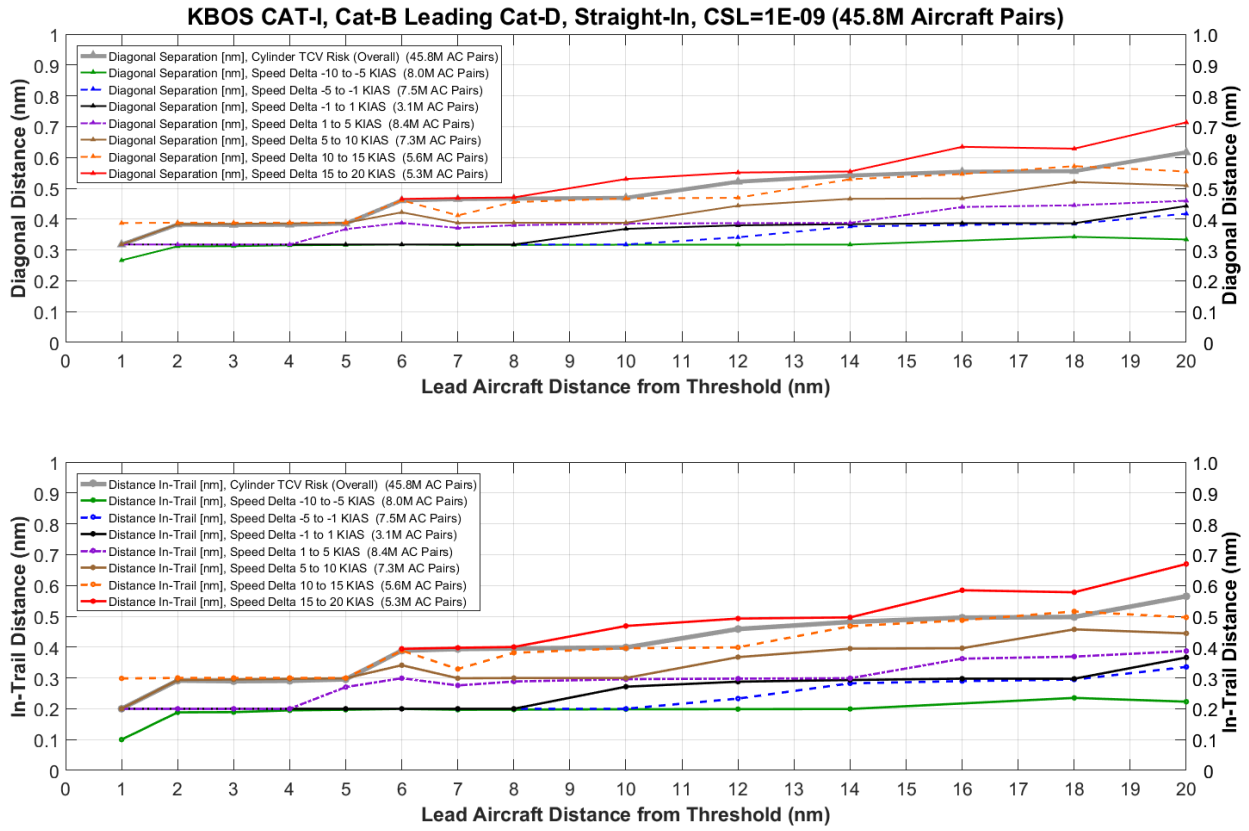

Figure F-12: KBOS CSL for CAT B Leading CAT D (Straight-In with 1,500 ft RCLS)

Figure F-13 depicts the CSL for an aircraft pair of CAT C leading CAT E with a straight-in approach at KBOS.

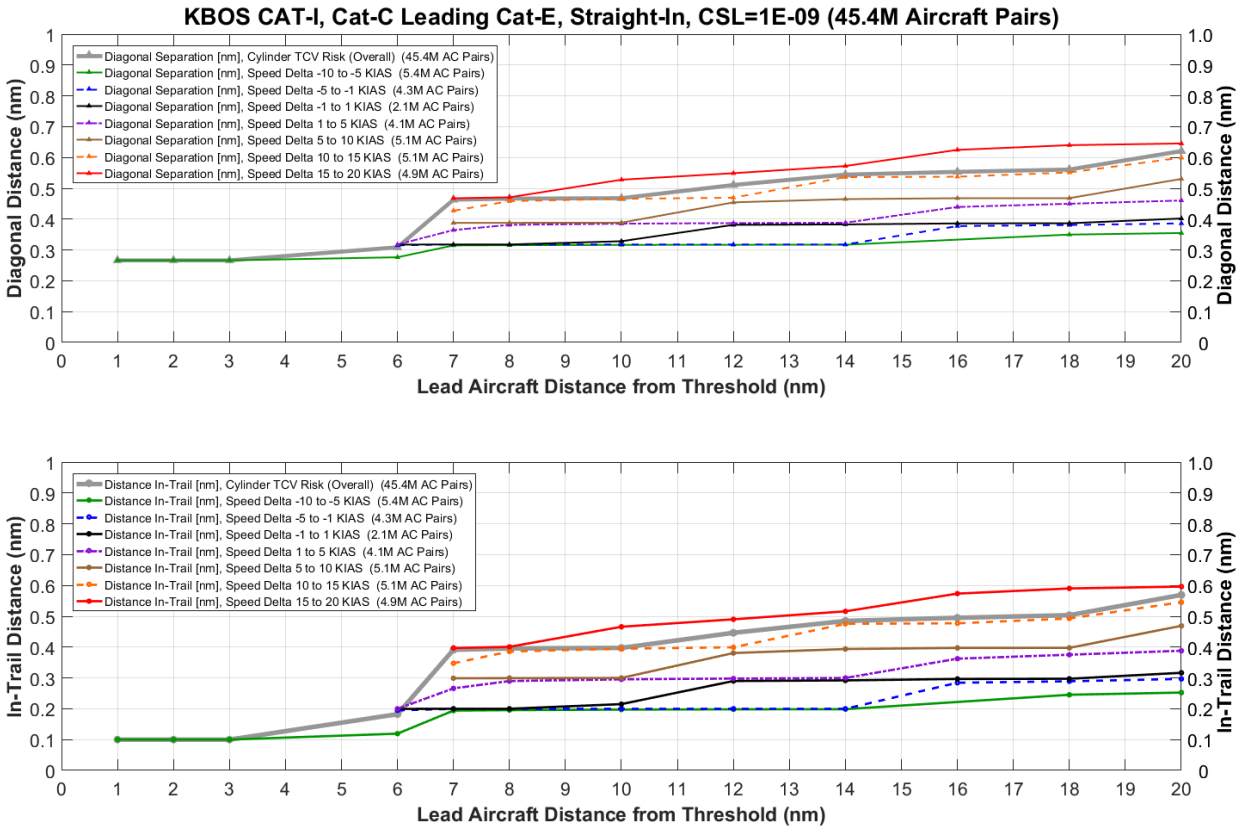

Figure F-13: KBOS CSL for CAT C Leading CAT E (Straight-In with 1,500 ft RCLS)

Figure F-14 depicts the CSL for an aircraft pair of CAT D leading CAT E with a straight-in approach at KBOS.

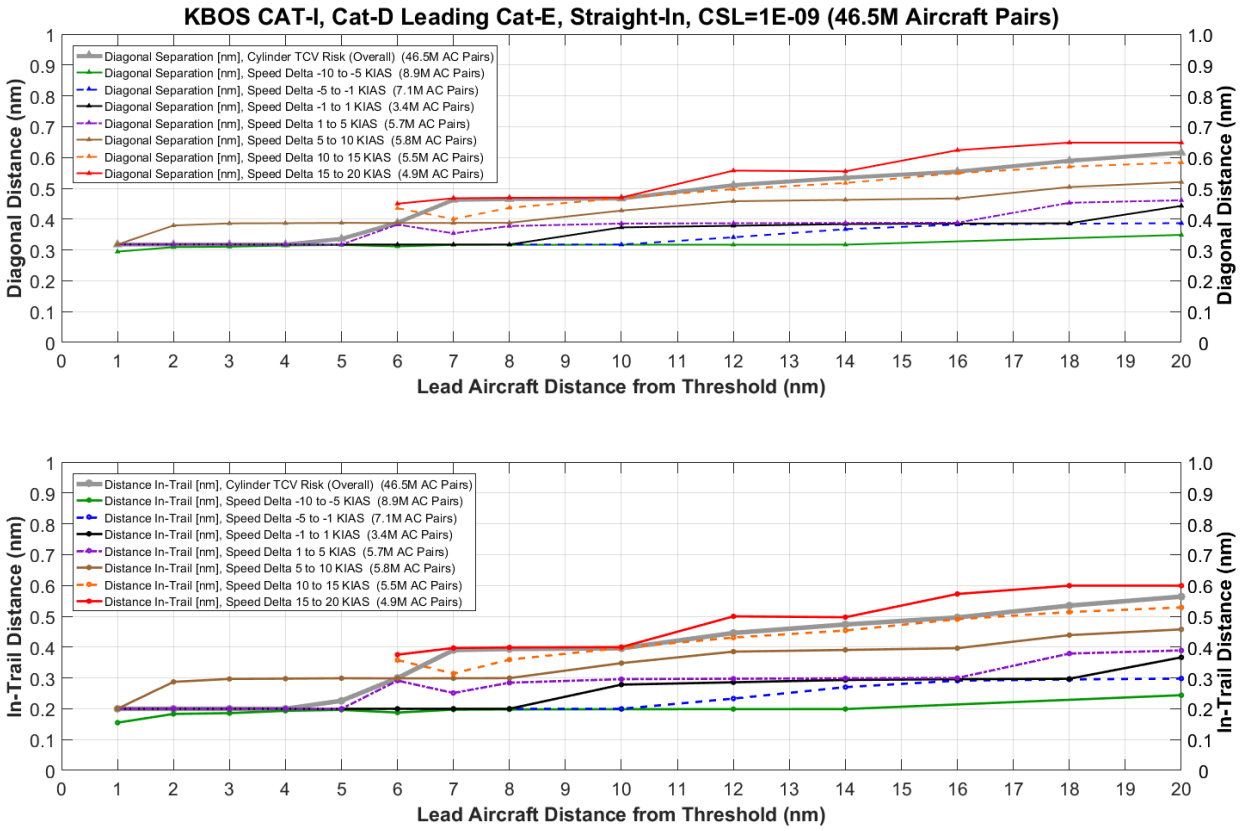

Figure F-14: KBOS CSL for CAT D Leading CAT E (Straight-In with 1,500 ft RCLS)

Figure F-15 depicts the CSL for an aircraft pair of CAT D leading CAT F with a straight-in approach at KBOS.

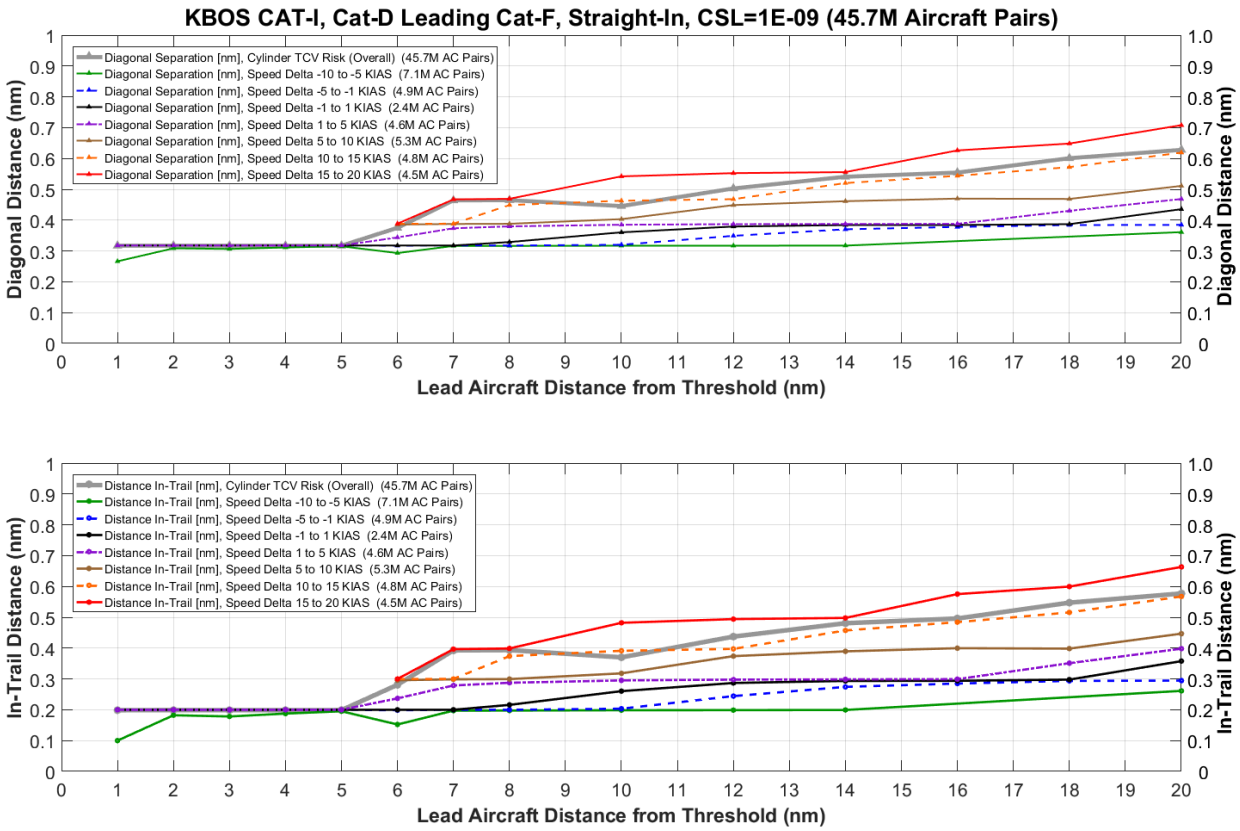

Figure F-15: KBOS CSL for CAT D Leading CAT F (Straight-In with 1,500 ft RCLS)

Figure F-16 depicts the CSL for an aircraft pair of CAT B leading CAT A with a 2° offset approach at KBOS.

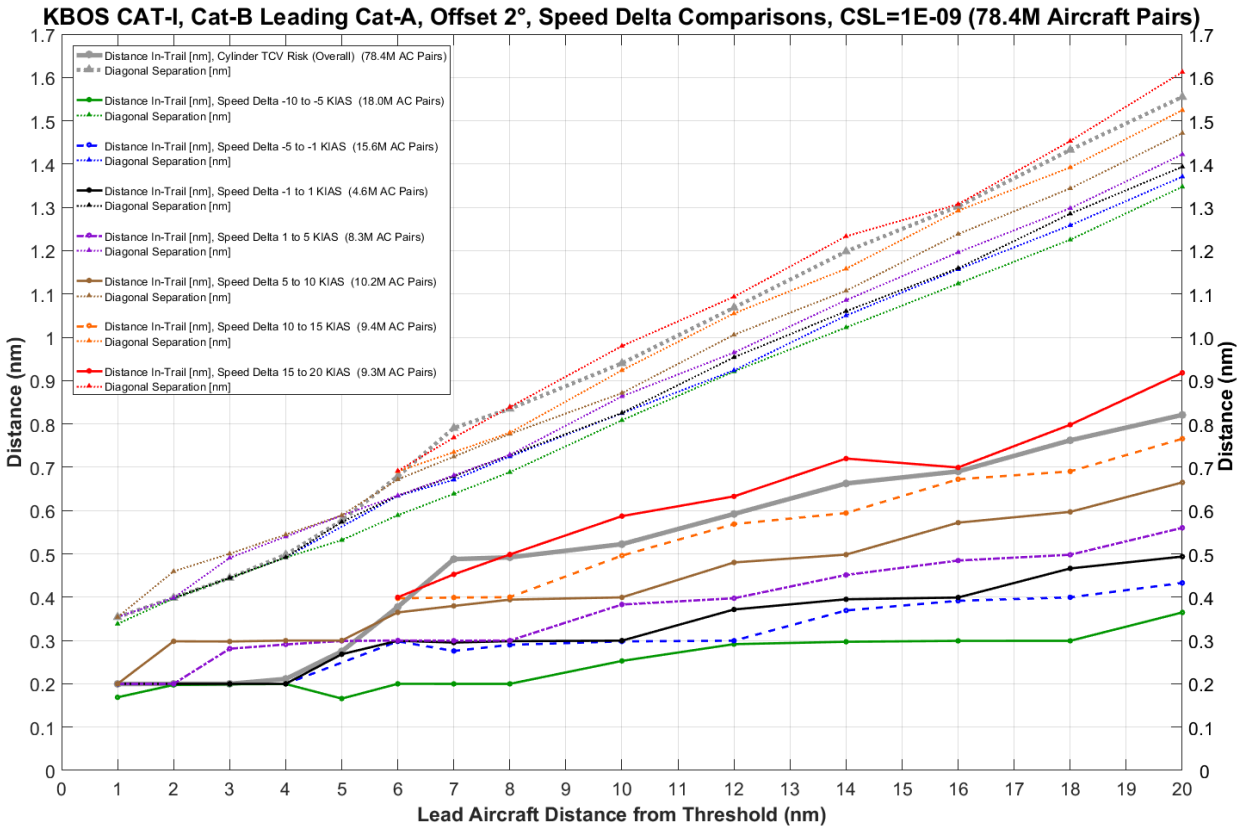

Figure F-16: KBOS CSL for CAT B Leading CAT A (2° Offset with 1,500 ft RCLS)

Figure F-17 depicts the CSL for an aircraft pair of CAT B leading CAT D with a 2° offset approach at KBOS.

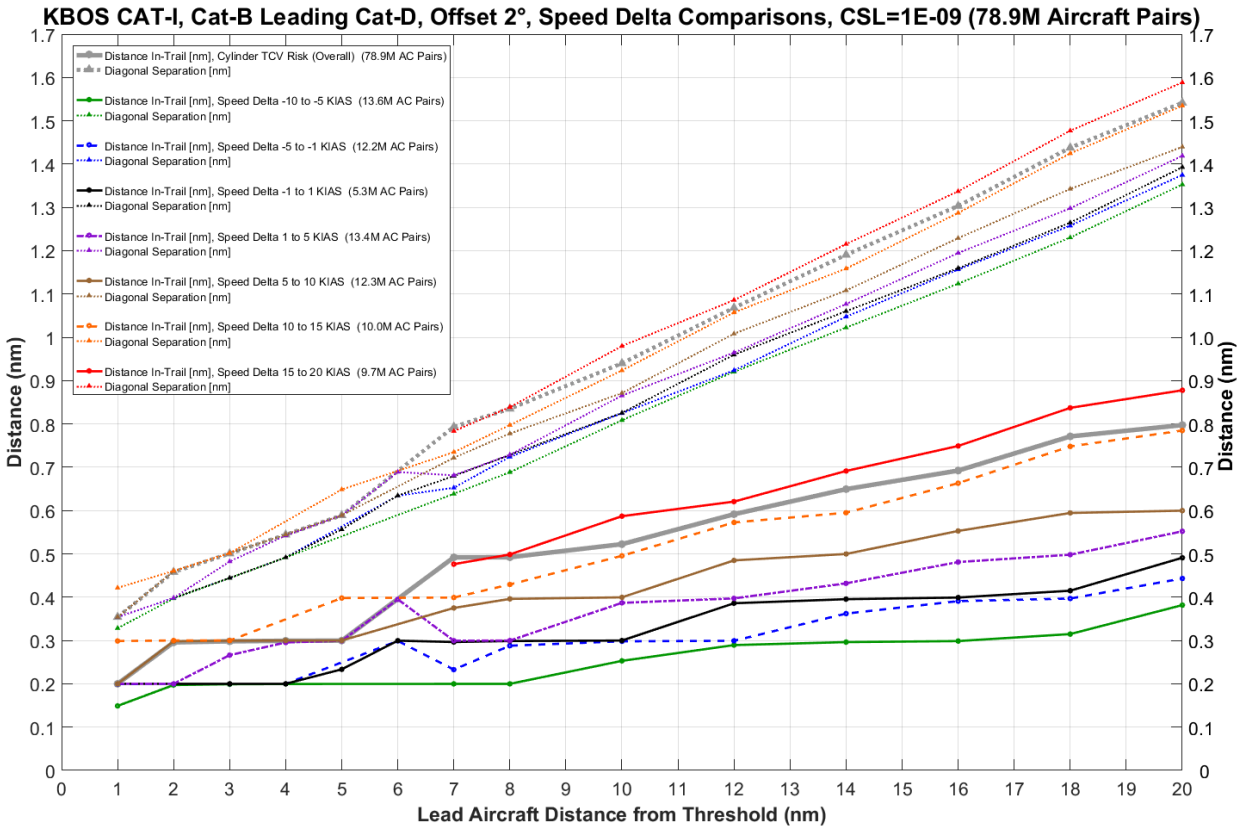

Figure F-17: KBOS CSL for CAT B Leading CAT D (2° Offset with 1,500 ft RCLS)

Figure F-18 depicts the CSL for an aircraft pair of CAT C leading CAT E with a 2° offset approach at KBOS.

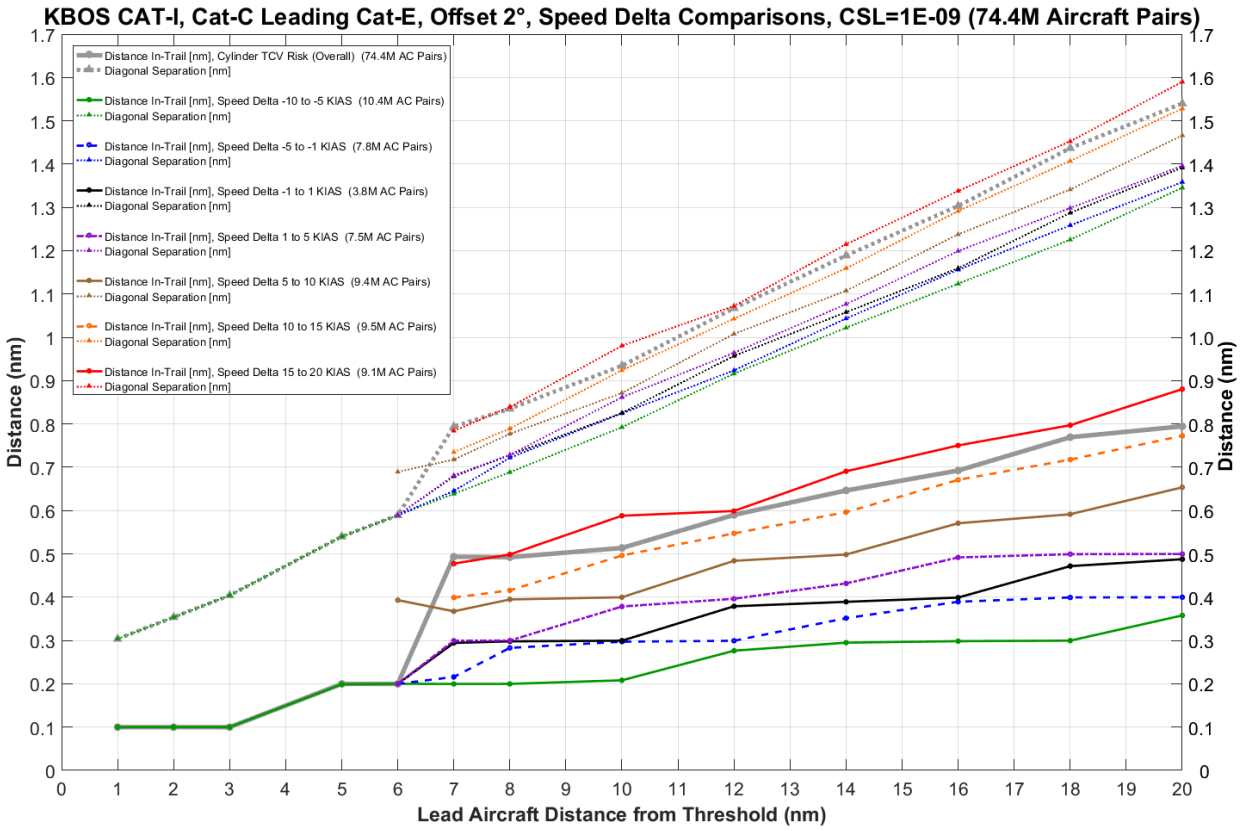

Figure F-18: KBOS CSL for CAT C Leading CAT E (2° Offset with 1,500 ft RCLS)

Figure F-19 depicts the CSL for an aircraft pair of CAT D leading CAT E with a 2° offset approach at KBOS.

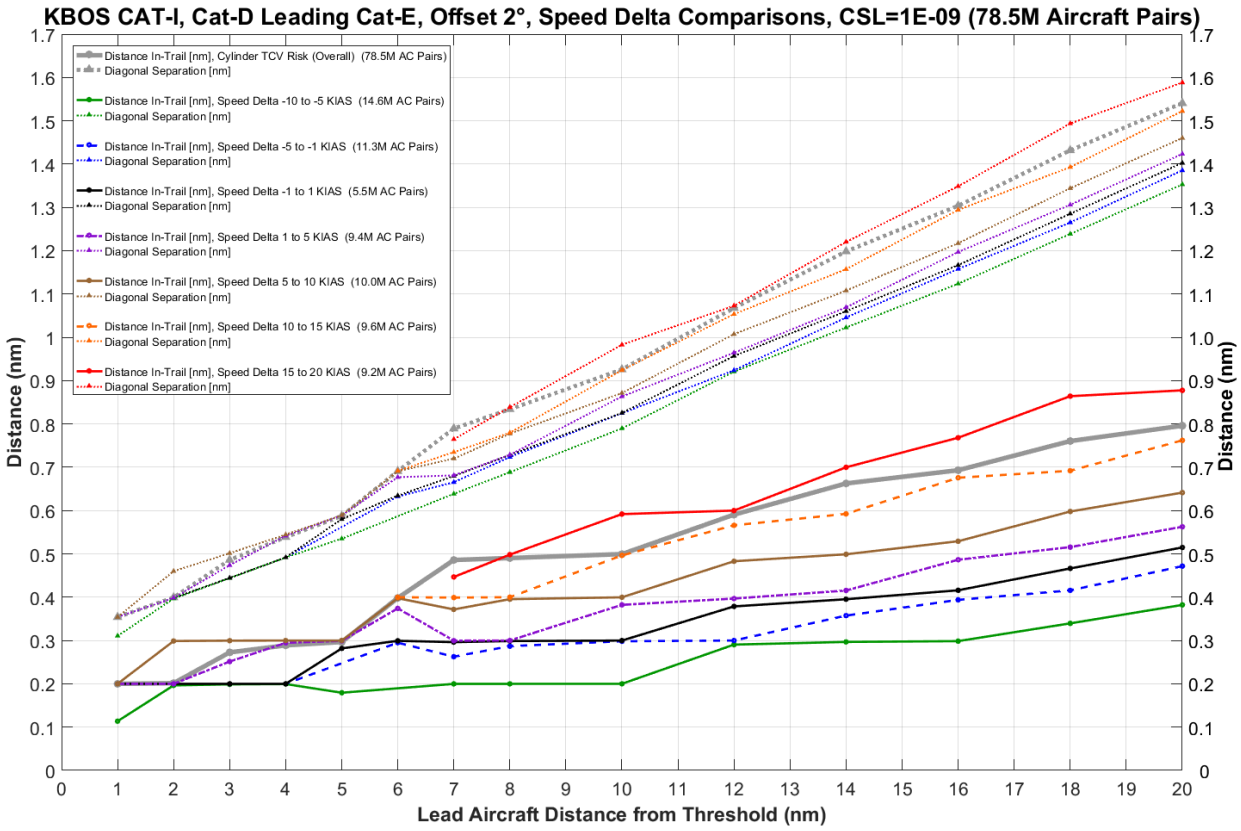

Figure F-19: KBOS CSL for CAT D Leading CAT E (2° Offset with 1,500 ft RCLS)

Figure F-20 depicts the CSL for an aircraft pair of CAT D leading CAT F with a 2° offset approach at KBOS.

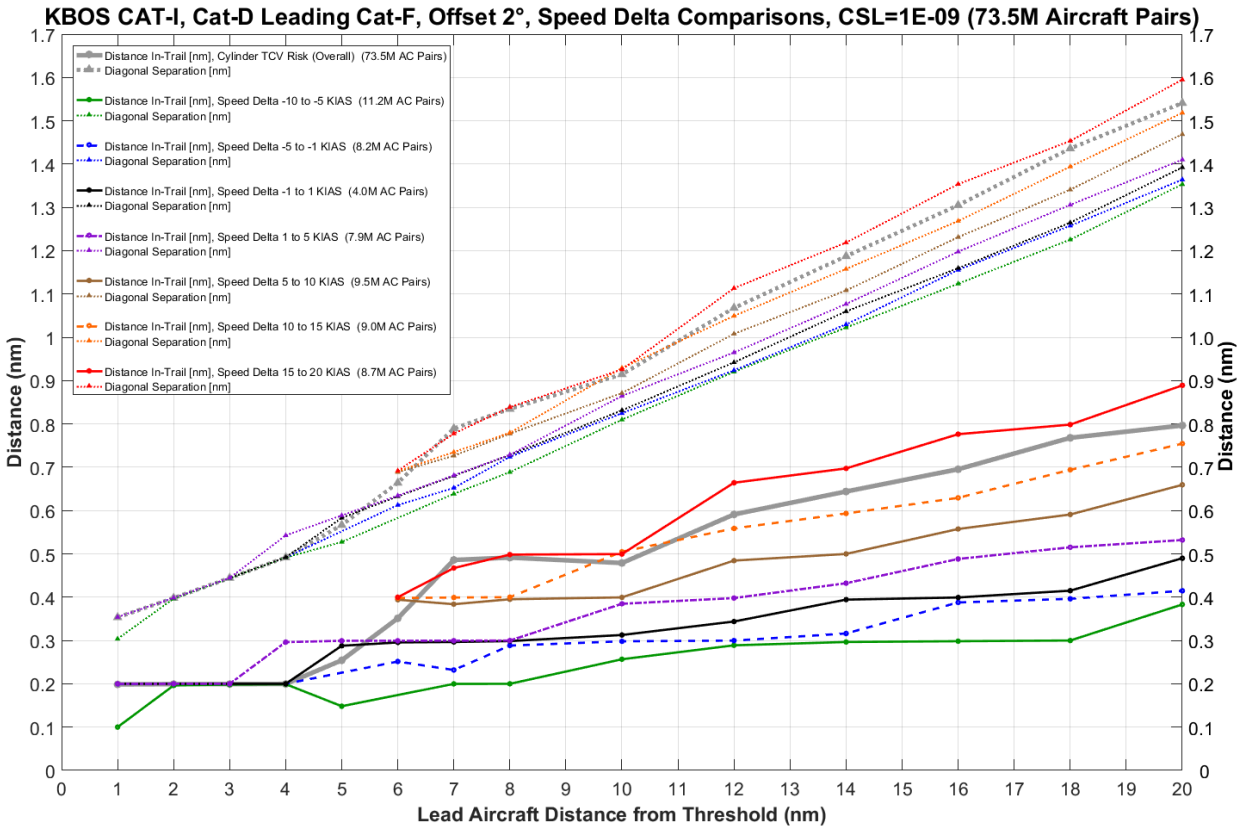

Figure F-20: KBOS CSL for CAT D Leading CAT F (2° Offset with 1,500 ft RCLS)

Figure F-21 depicts the CSL for an aircraft pair of CAT B leading CAT A with a straight-in approach at KSEA with RCLS of 800.

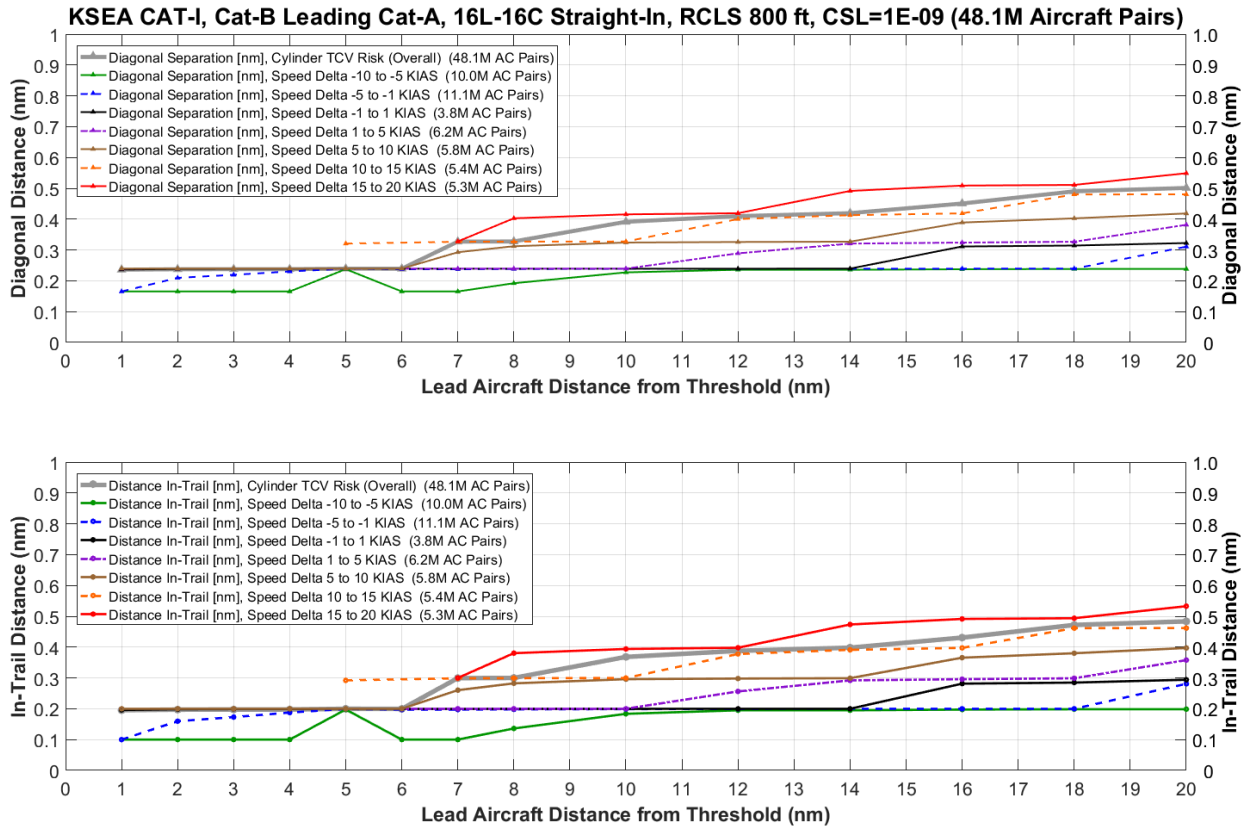

Figure F-21: KSEA CSL for CAT B Leading CAT A (Straight-In with 800 ft RCLS)

Figure F-22 depicts the CSL for an aircraft pair of CAT B leading CAT D with a straight-in approach at KSEA with RCLS of 800.

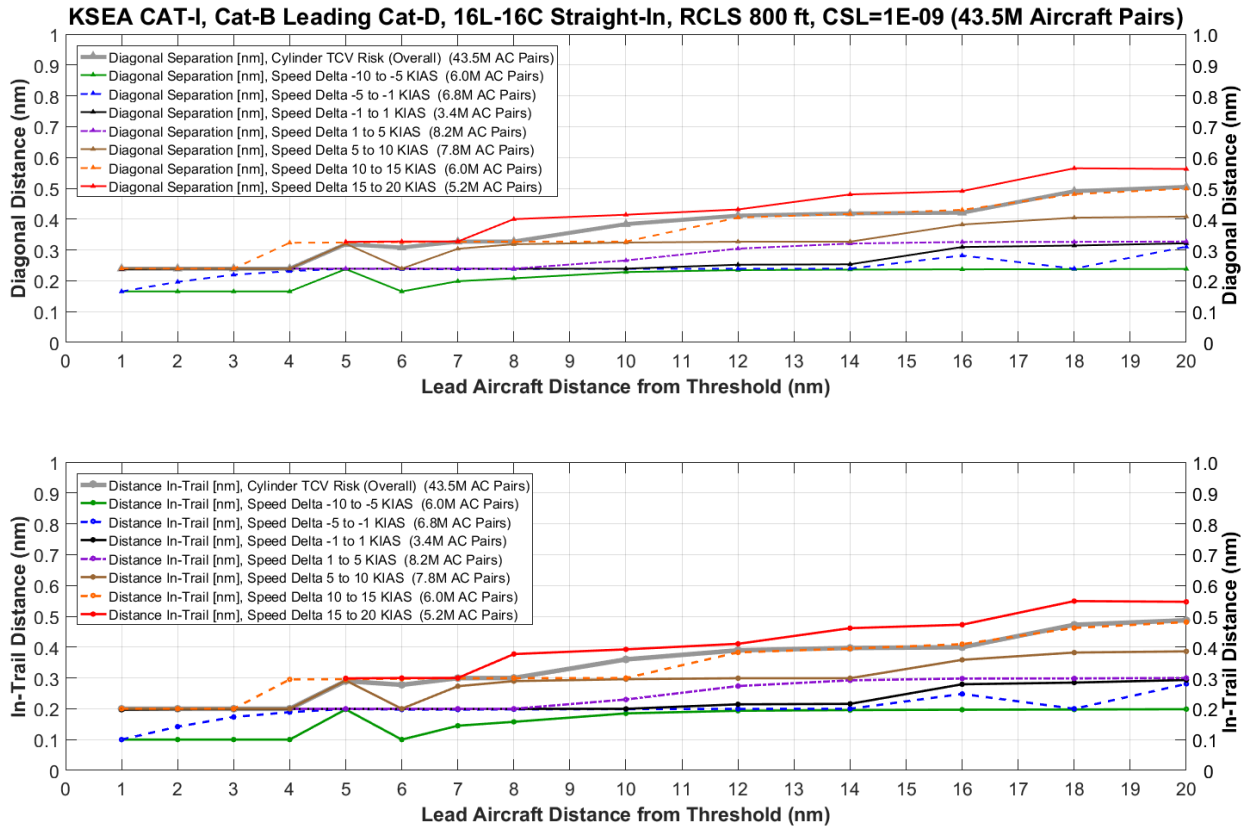

Figure F-22: KSEA CSL for CAT B Leading CAT D (Straight-In with 800 ft RCLS)

Figure F-23 depicts the CSL for an aircraft pair of CAT C leading CAT E with a straight-in approach at KSEA with RCLS of 800.

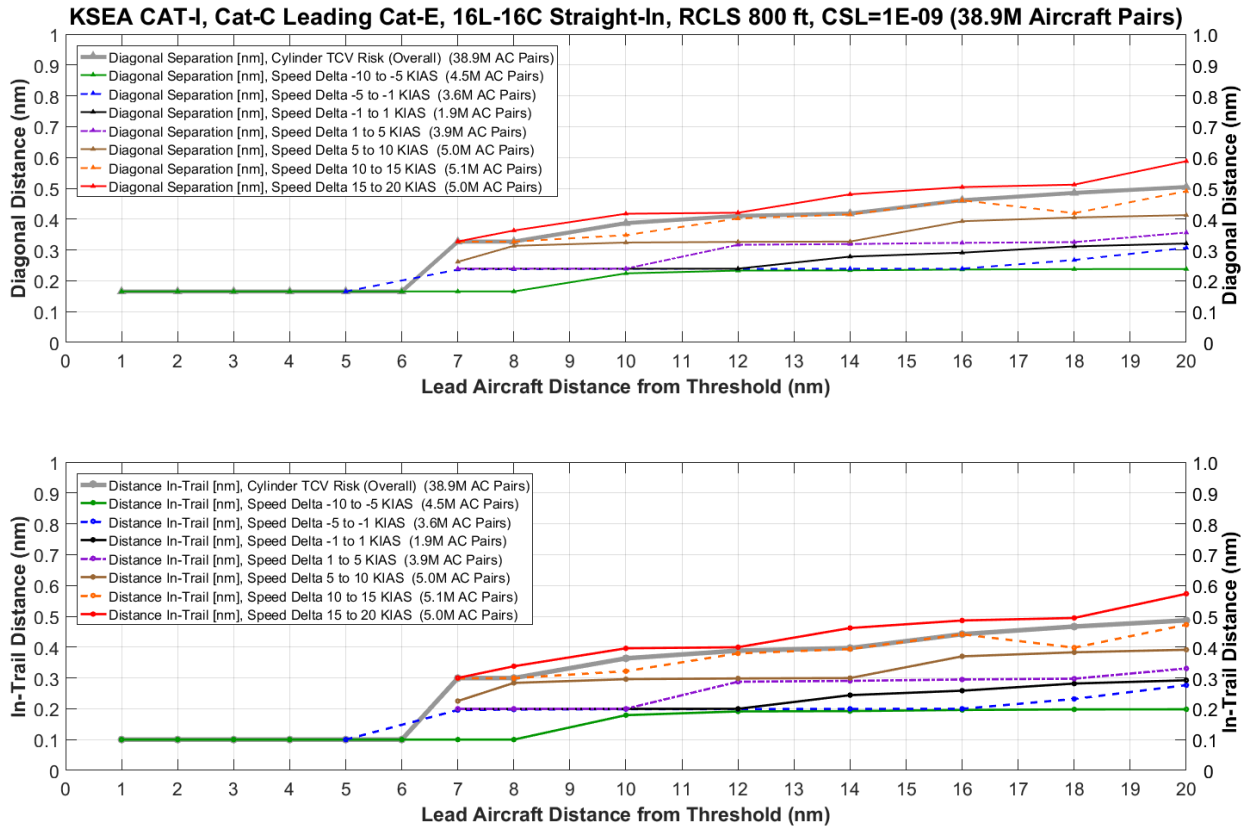

Figure F-23: KSEA CSL for CAT C Leading CAT E (Straight-In with 800 ft RCLS)

Figure F-24 depicts the CSL for an aircraft pair of CAT D leading CAT E with a straight-in approach at KSEA with RCLS of 800.

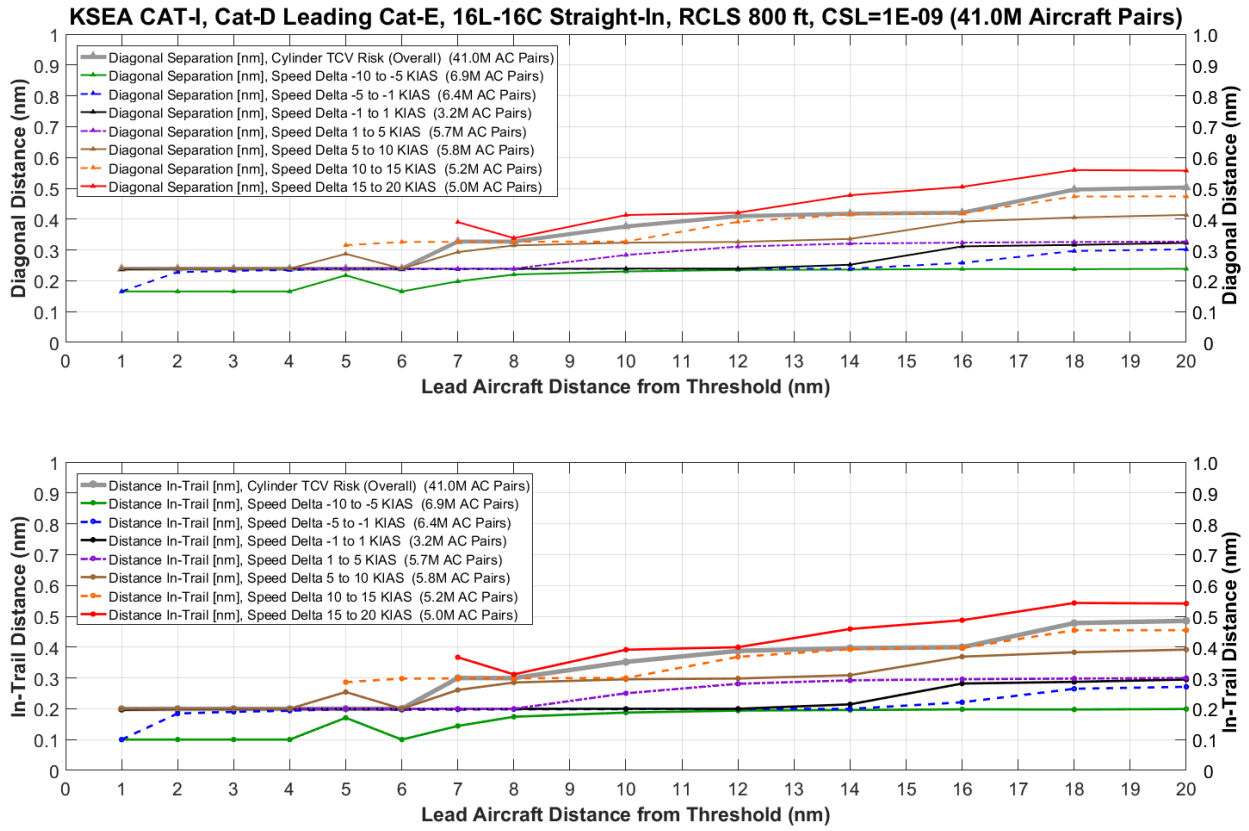

Figure F-24: KSEA CSL for CAT D Leading CAT E (Straight-In with 800 ft RCLS)

Figure F-25 depicts the CSL for an aircraft pair of CAT D leading CAT F with a straight-in approach at KSEA with RCLS of 800.

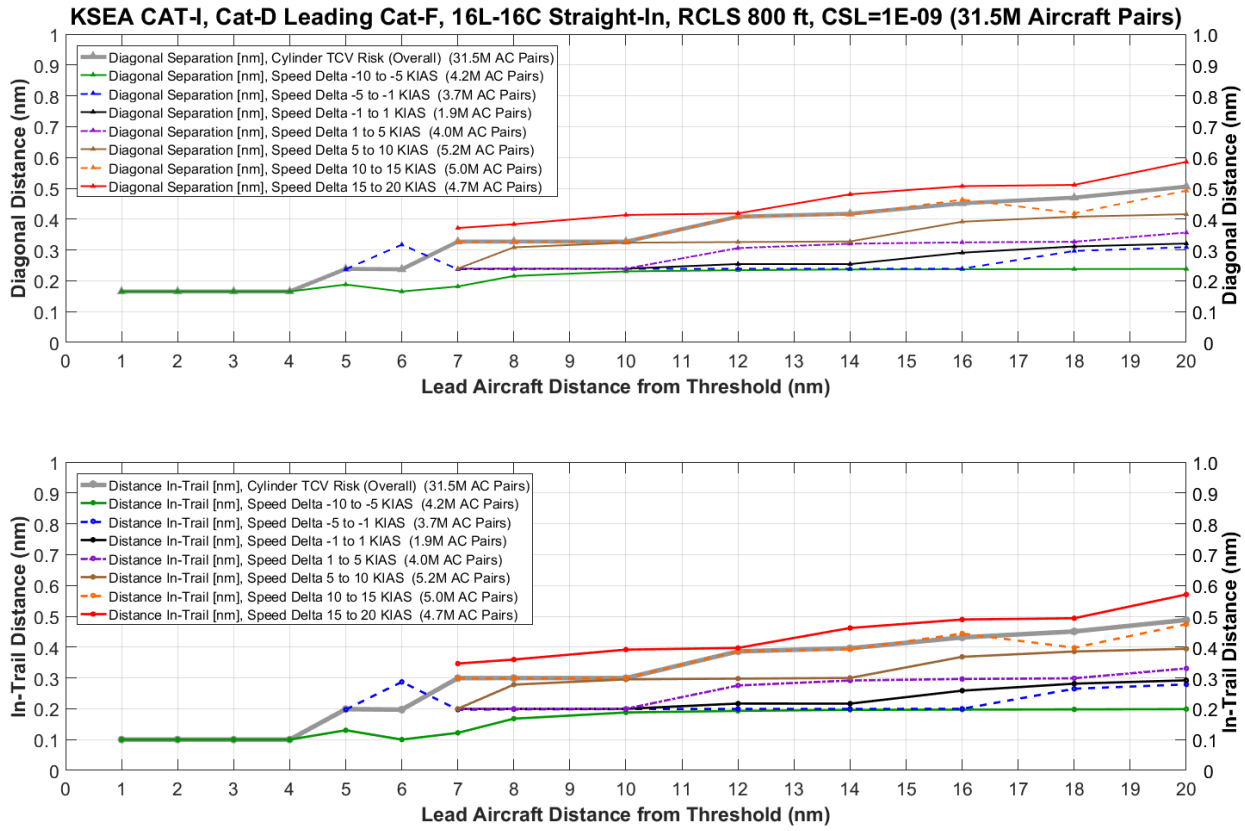

Figure F-25: KSEA CSL for CAT D Leading CAT F (Straight-In with 800 ft RCLS)

Figure F-26 depicts the CSL for an aircraft pair of CAT B leading CAT A with a straight-in approach at KSEA with RCLS of 1,700.

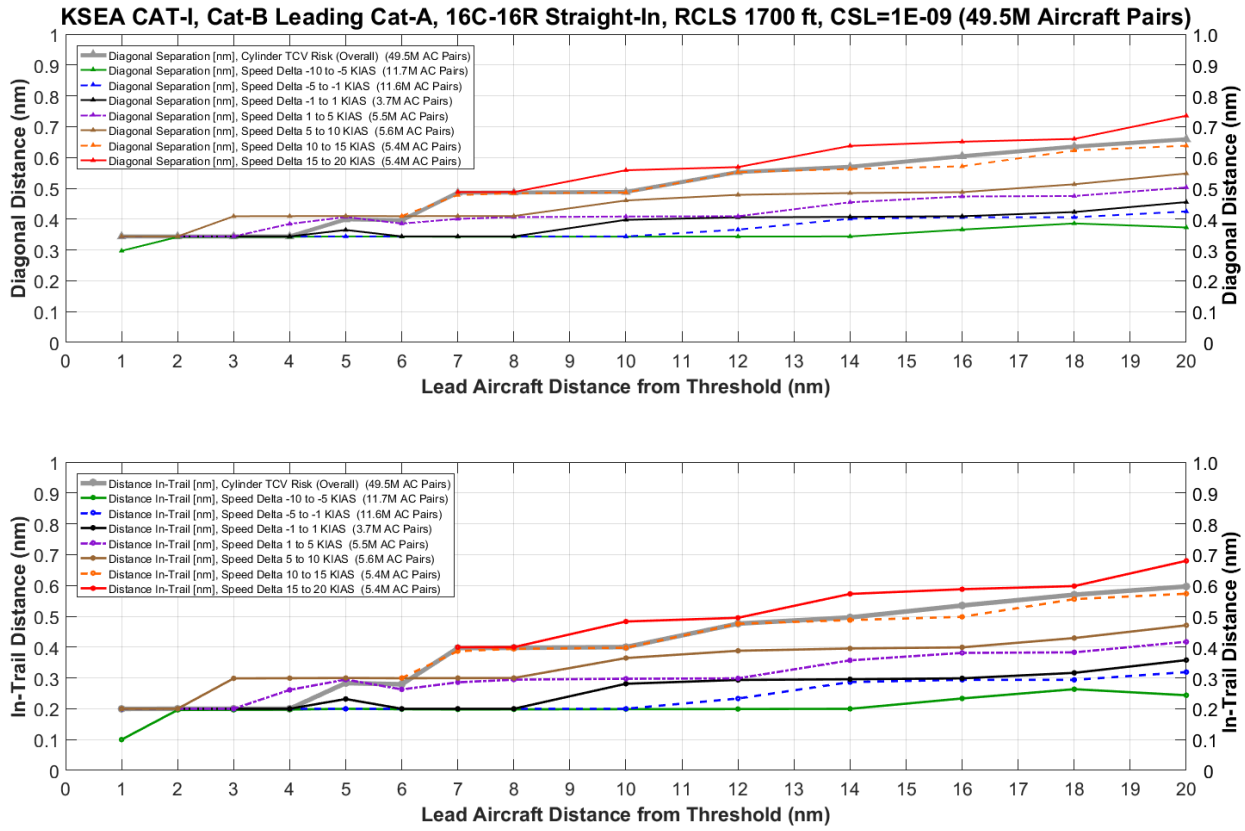

Figure F-26: KSEA CSL for CAT B Leading CAT A (Straight-In with 1,700 ft RCLS)

Figure F-27 depicts the CSL for an aircraft pair of CAT B leading CAT D with a straight-in approach at KSEA with RCLS of 1,700.

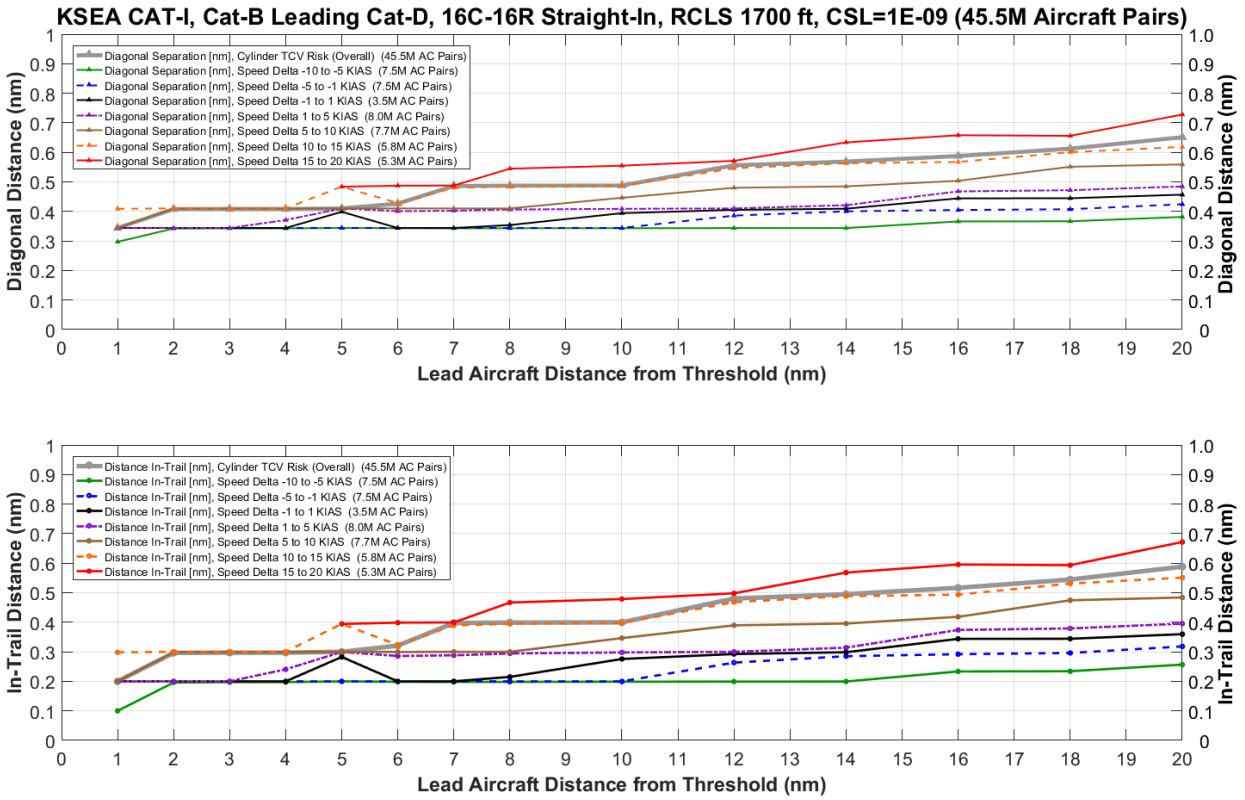

Figure F-27: KSEA CSL for CAT B Leading CAT D (Straight-In with 1,700 ft RCLS)

Figure F-28 depicts the CSL for an aircraft pair of CAT C leading CAT E with a straight-in approach at KSEA with RCLS of 1,700.

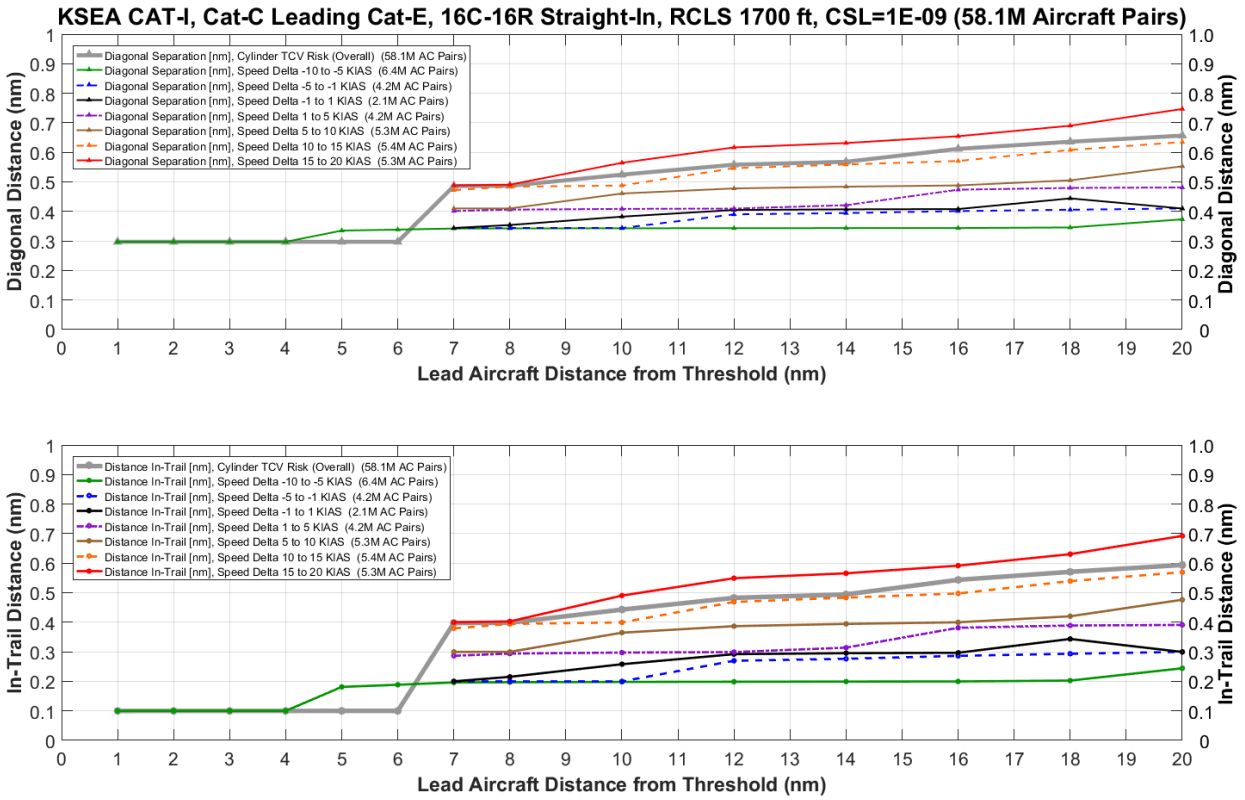

Figure F-28: KSEA CSL for CAT C Leading CAT E (Straight-In with 1,700 ft RCLS)

Figure F-29 depicts the CSL for an aircraft pair of CAT D leading CAT E with a straight-in approach at KSEA with RCLS of 1,700.

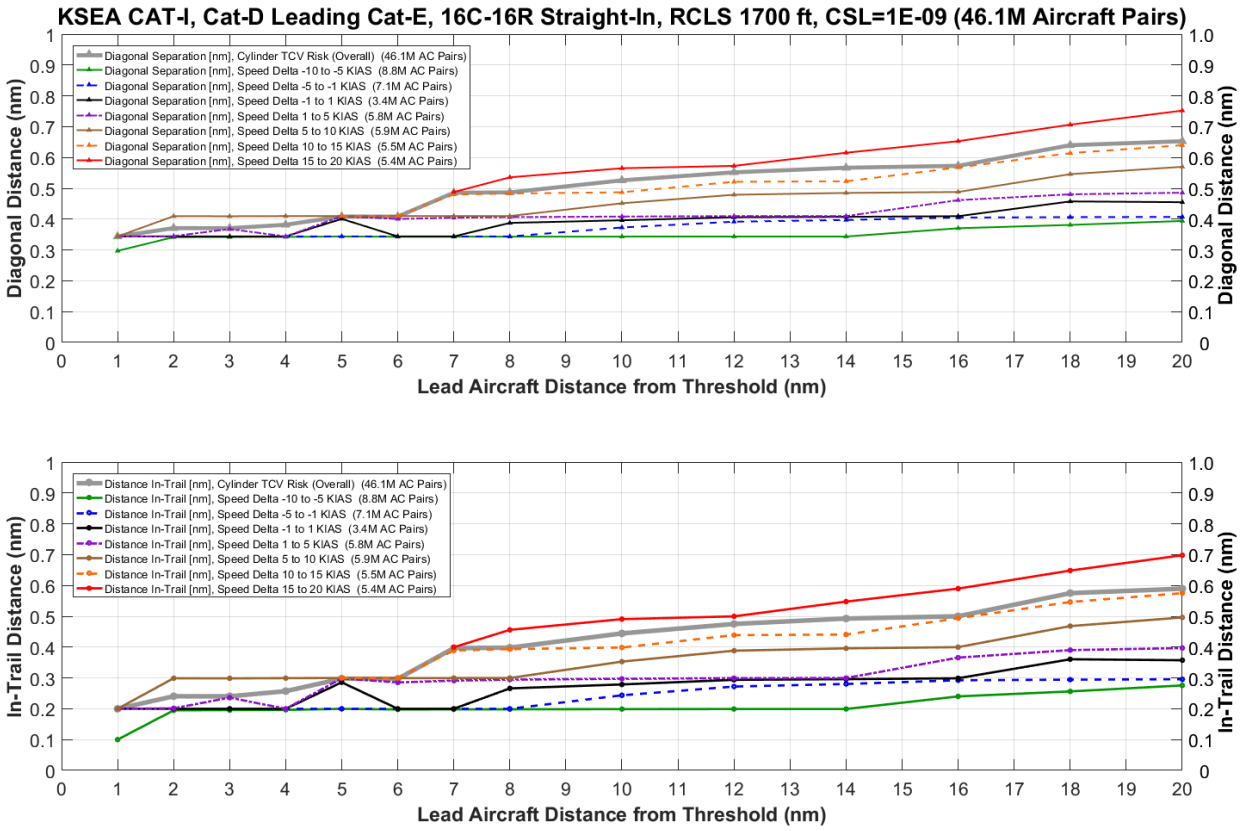

Figure F-29: KSEA CSL for CAT D Leading CAT E (Straight-In with 1,700 ft RCLS)

Figure F-30 depicts the CSL for an aircraft pair of CAT D leading CAT F with a straight-in approach at KSEA with RCLS of 1,700.

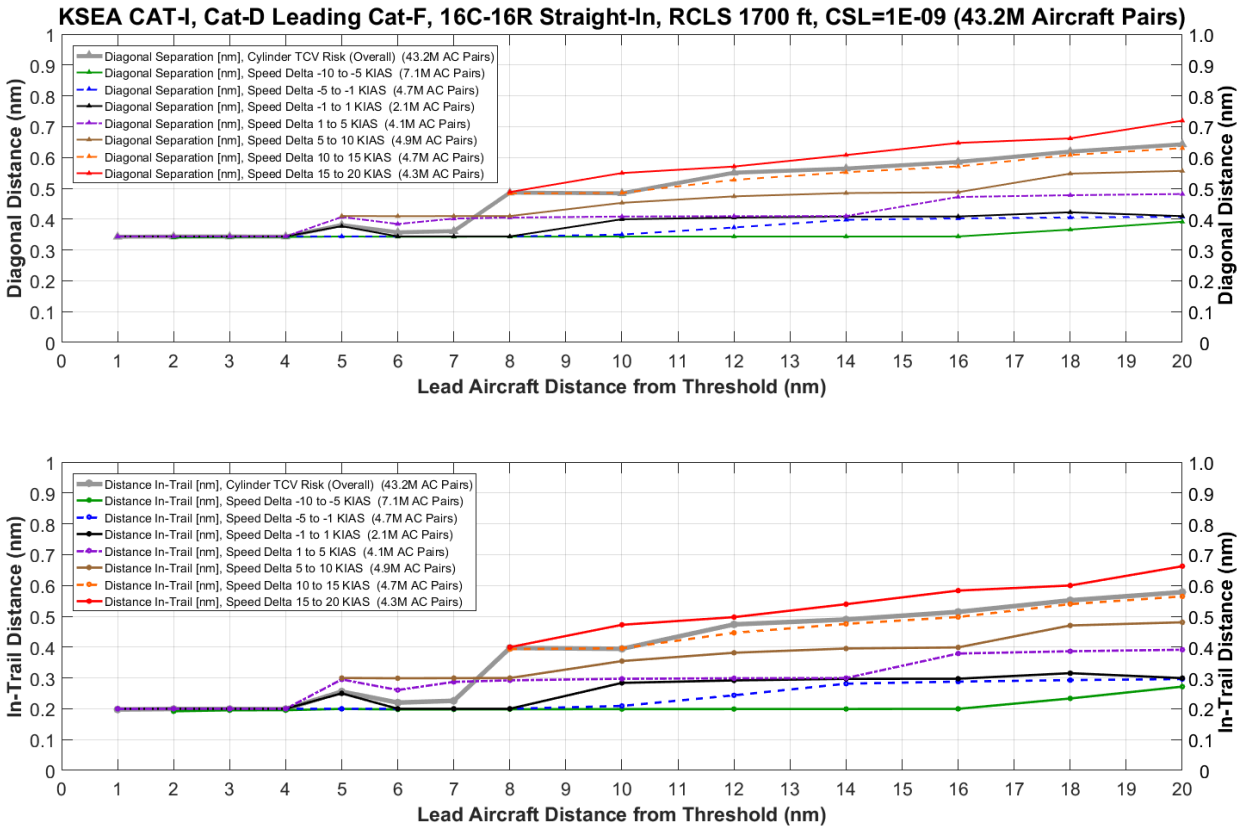

Figure F-30: KSEA CSL for CAT D Leading CAT F (Straight-In with 1,700 ft RCLS)

Figure F-31 depicts the CSL for an aircraft pair of CAT B leading CAT A with a 3° offset approach at KSFO.

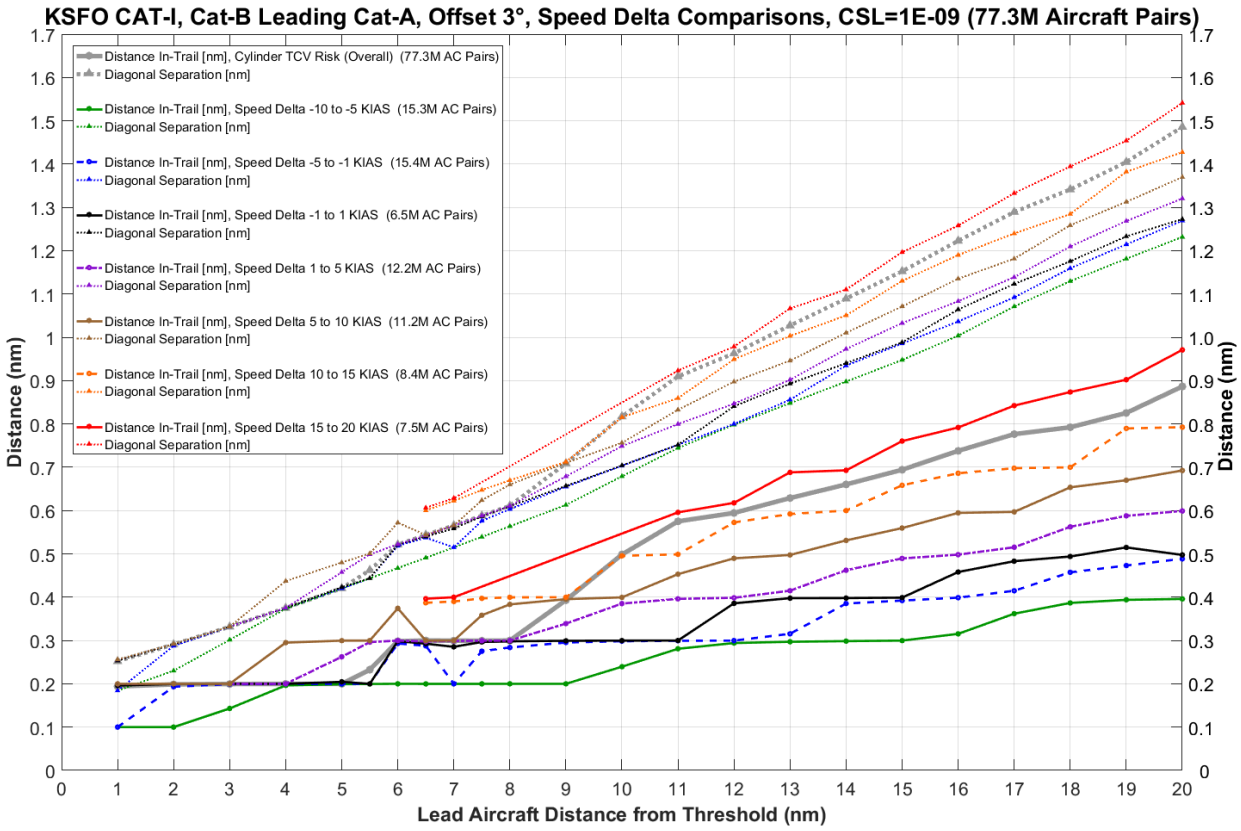

Figure F-31: KSFO CSL for CAT B Leading CAT A (3° Offset with 750 ft RCLS)

Figure F-32 depicts the CSL for an aircraft pair of CAT B leading CAT D with a 3° offset approach at KSFO.

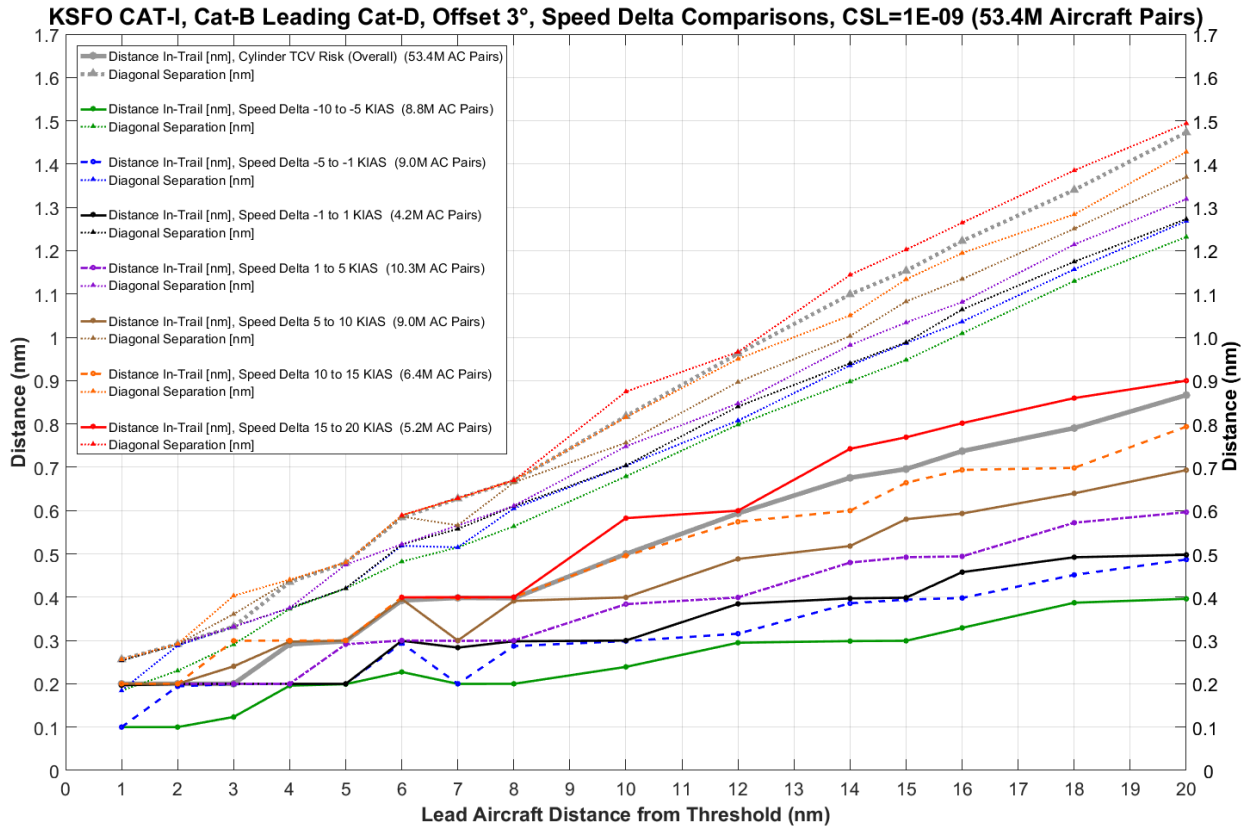

Figure F-32: KSFO CSL for CAT B Leading CAT D (3° Offset with 750 ft RCLS)

Figure F-33 depicts the CSL for an aircraft pair of CAT C leading CAT E with a 3° offset approach at KSFO.

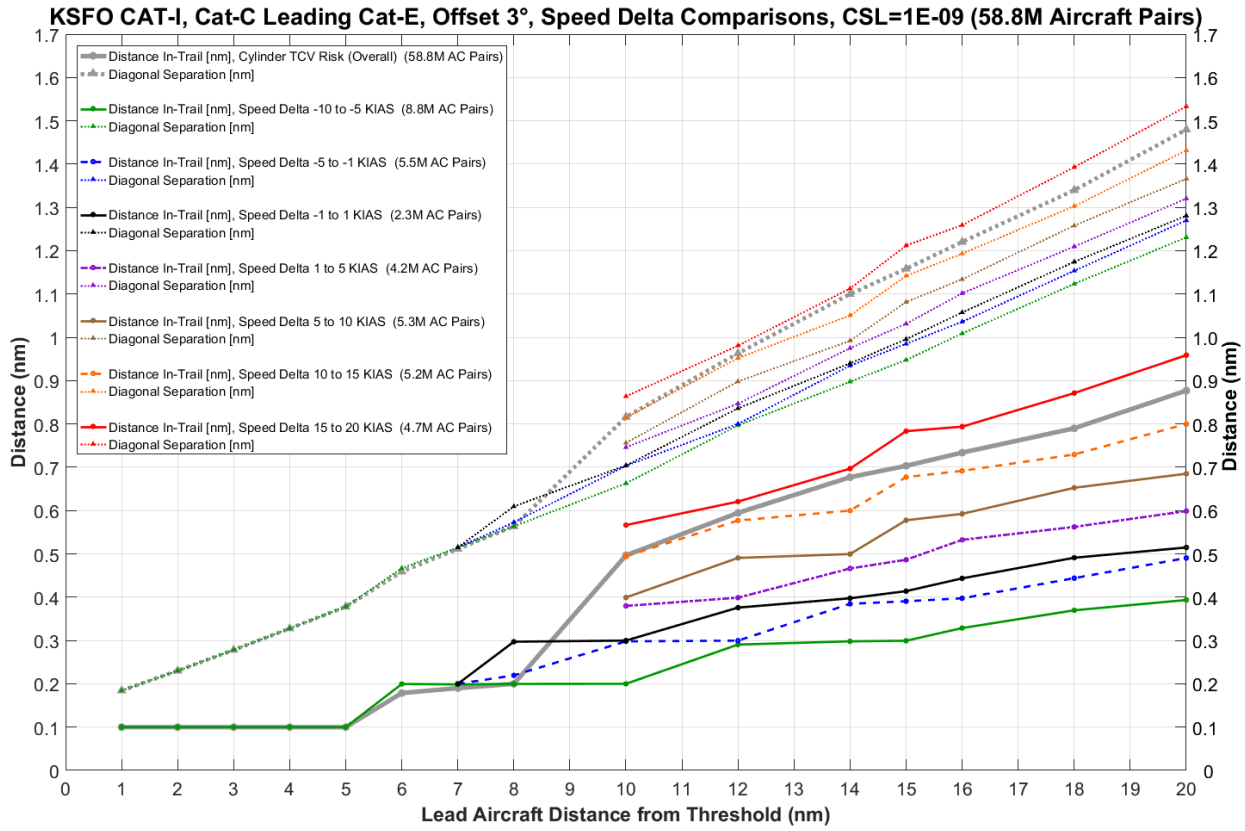

Figure F-33: KSFO CSL for CAT C Leading CAT E (3° Offset with 750 ft RCLS)

Figure F-34 depicts the CSL for an aircraft pair of CAT D leading CAT E with a 3° offset approach at KSFO.

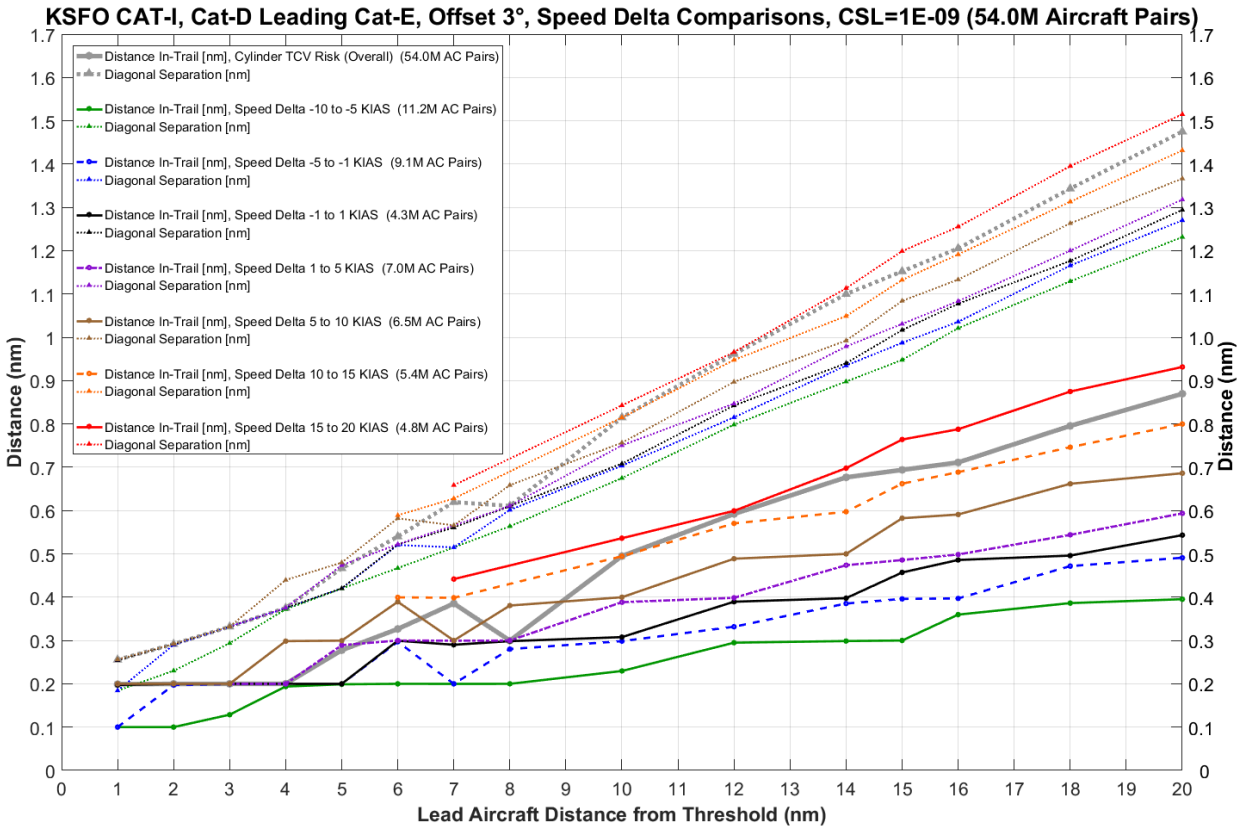

Figure F-34: KSFO CSL for CAT D Leading CAT E (3° Offset with 750 ft RCLS)

Figure F-35 depicts the CSL for an aircraft pair of CAT D leading CAT F with a 3° offset approach at KSFO.

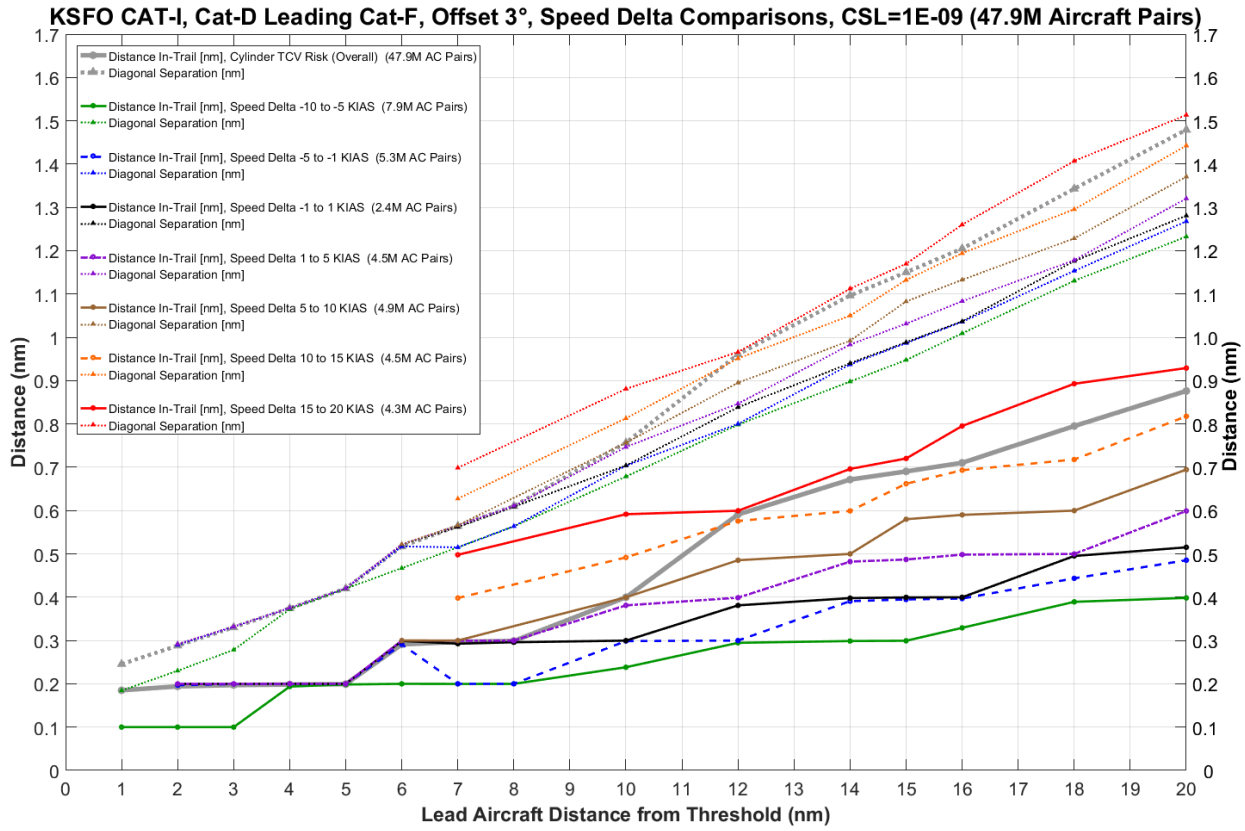

Figure F-35: KSFO CSL for CAT D Leading CAT F (3° Offset with 750 ft RCLS)

Table F-1 lists the CSL for the -10 kts to -5 kts speed bin for the six aircraft pairs at the seven runway configurations analyzed in this study.

Table F-1: CSL at Threshold Distance Limits for Speed Bin from -10 kts to -5 kts

Airport	Generic Airport								Boston Logan International Airport							
Runway Approach Alignment	Straight-In 2,500 ft RCLS				3° Offset 2,500 ft RCLS				Straight-In 1,500 ft RCLS				2° Offset 1,500 ft RCLS			
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM
CAT B - A	0.28	0.25	0.20	0.20	0.48	0.39	0.30	0.20	0.27	0.20	0.20	0.19	0.36	0.30	0.20	0.20
CAT B - D	0.29	0.27	0.20	0.20	0.48	0.39	0.30	0.20	0.22	0.20	0.20	0.19	0.38	0.30	0.20	0.20
CAT C - D	0.27	0.23	0.20	0.20	0.48	0.38	0.30	0.20	0.25	0.20	0.20	-	0.37	0.30	0.20	0.18
CAT C - E	0.28	-	0.20	0.19	0.49	0.39	0.30	0.20	0.25	0.20	0.20	0.10	0.36	0.29	0.20	0.10
CAT D - E	0.28		0.20	0.20	0.49	0.39	0.30	0.20	0.24	0.20	0.20	0.18	0.38	0.30	0.20	0.20
CAT D - F	0.29	0.23	0.20	0.20	0.49	0.39	0.30	0.20	0.26	0.20	0.20	0.18	0.38	0.30	0.20	0.20

Airport	Seattle-Tacoma International Airport								San Francisco International Airport							
Runway Approach Alignment	Straight-In 800 ft RCLS				Straight-In 1,700 ft RCLS				3° Offset 750 ft RCLS							
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	15 NM	10 NM	8 NM	7 NM	5 NM	3 NM	1 NM
CAT B - A	0.20	0.19	0.14	0.10	0.24	0.20	0.20	0.20	0.40	0.30	0.24	0.20	0.20	0.20	0.14	0.10
CAT B - D	0.20	0.20	0.16	0.10	0.26	0.20	0.20	0.20	0.40	0.30	0.24	0.20	0.20	0.20	0.12	0.10
CAT C - D	0.20	0.19	0.13	0.10	0.28	0.20	0.20	0.18	0.39	0.30	0.20	0.20	0.20	0.20	0.10	0.10
CAT C - E	0.20	0.19	0.10	0.10	0.24	0.20	0.20	0.10	0.39	0.30	0.20	0.20	0.20	0.10	0.10	0.10
CAT D - E	0.20	0.20	0.17	0.10	0.28	0.20	0.20	0.19	0.40	0.30	0.23	0.20	0.20	0.20	0.13	0.10
CAT D - F	0.20	0.20	0.17	0.10	0.27	0.20	0.20	0.19	0.40	0.30	0.24	0.20	0.20	0.20	0.10	0.10

Table F-2 lists the CSL for the -5 kts to -1 kts speed bin for the six aircraft pairs at the seven runway configurations analyzed in this study.

Table F-2: CSL at Threshold Distance Limits for Speed Bin from -5 kts to -1 kts

Airport	Generic Airport								Boston Logan International Airport							
Runway Approach Alignment	Straight-In 2,500 ft RCLS				3° Offset 2,500 ft RCLS				Straight-In 1,500 ft RCLS				2° Offset 1,500 ft RCLS			
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM
CAT B - A	0.33	0.29	0.27	0.20	0.58	0.47	0.30	0.20	0.29	0.27	0.20	0.20	0.43	0.37	0.29	0.20
CAT B - D	0.37	0.30	0.27	0.20	0.57	0.47	0.30	0.20	0.34	0.28	0.20	0.20	0.44	0.36	0.29	0.20
CAT C - D	0.33	0.30	0.24	0.20	0.56	0.46	0.30	0.20	0.29	0.26	0.20	0.20	0.40	0.33	0.29	0.20
CAT C - E	0.30	0.30	0.23	-	0.57	0.42	0.30	-	0.30	0.20	0.20	-	0.40	0.35	0.28	-
CAT D - E	0.32	0.30	0.27	0.20	0.57	0.47	0.30	0.20	0.30	0.27	0.20	0.20	0.47	0.36	0.29	0.20
CAT D - F	0.32	0.30	0.25	0.20	0.59	0.46	0.30	0.20	0.29	0.27	0.20	0.20	0.41	0.32	0.29	0.20

Airport	Seattle-Tacoma International Airport								San Francisco International Airport							
Runway Approach Alignment	Straight-In 800 ft RCLS				Straight-In 1,700 ft RCLS				3° Offset 750 ft RCLS							
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	15 NM	10 NM	8 NM	7 NM	5 NM	3 NM	1 NM
CAT B - A	0.28	0.20	0.20	0.16	0.32	0.29	0.20	0.20	0.49	0.39	0.30	0.28	0.20	0.20	0.20	0.10
CAT B - D	0.28	0.20	0.20	0.14	0.32	0.29	0.20	0.20	0.49	0.39	0.30	0.29	0.20	0.20	0.20	0.10
CAT C - D	0.27	0.20	0.20	0.10	0.30	0.27	0.20	0.20	0.48	0.39	0.30	0.25	0.20	0.20	0.20	0.10
CAT C - E	0.28	0.20	0.20	-	0.30	0.28	0.20	-	0.49	0.39	0.30	0.22	0.20	-	-	-
CAT D - E	0.27	0.20	0.20	0.18	0.30	0.28	0.20	0.20	0.49	0.40	0.30	0.28	0.20	0.20	0.20	0.10
CAT D - F	0.28	0.20	0.20	-	0.30	0.28	0.20	0.20	0.49	0.39	0.30	0.20	0.20	0.20	0.20	-

Table F-3 lists the CSL for the 1 kts to 5 kts speed bin for the six aircraft pairs at the seven runway configurations analyzed in this study.

Table F-3: CSL at Threshold Distance Limits for Speed Bin from 1 kts to 5 kts

Airport	Generic Airport								Boston Logan International Airport							
Runway Approach Alignment	Straight-In 2,500 ft RCLS				3° Offset 2,500 ft RCLS				Straight-In 1,500 ft RCLS				2° Offset 1,500 ft RCLS			
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM
CAT B - A	0.45	0.38	0.30	0.30	0.69	0.58	0.40	0.30	0.39	0.30	0.29	0.20	0.56	0.45	0.30	0.20
CAT B - D	0.44	0.38	0.30	0.30	0.70	0.57	0.40	0.30	0.39	0.30	0.29	0.20	0.55	0.43	0.30	0.20
CAT C - D	0.44	0.38	0.30	0.30	0.69	0.56	0.40	0.30	0.39	0.30	0.28	0.20	0.57	0.40	0.30	0.20
CAT C - E	0.44	0.38	0.30	-	0.70	0.54	0.40	-	0.39	0.30	0.29	-	0.50	0.43	0.30	-
CAT D - E	0.43	0.38	0.30	0.30	0.69	0.57	0.40	0.30	0.39	0.30	0.28	0.20	0.56	0.42	0.30	0.20
CAT D - F	0.41	0.38	0.30	0.30	0.70	0.57	0.40	0.30	0.40	0.30	0.29	0.20	0.53	0.43	0.30	0.20

Airport	Seattle-Tacoma International Airport								San Francisco International Airport							
Runway Approach Alignment	Straight-In 800 ft RCLS				Straight-In 1,700 ft RCLS				3° Offset 750 ft RCLS							
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	15 NM	10 NM	8 NM	7 NM	5 NM	3 NM	1 NM
CAT B - A	0.36	0.29	0.20	0.20	0.42	0.36	0.29	0.20	0.60	0.49	0.39	0.30	0.30	0.26	0.20	0.20
CAT B - D	0.30	0.29	0.20	0.20	0.40	0.31	0.29	0.20	0.60	0.49	0.38	0.30	0.30	0.29	0.20	0.20
CAT C - D	0.33	0.29	0.20	-	0.40	0.36	0.30	0.20	0.59	0.49	0.37	0.30	0.30	0.20	0.20	-
CAT C - E	0.33	0.29	0.20	-	0.39	0.31	0.29	-	0.60	0.49	0.38	-	-	-	-	-
CAT D - E	0.30	0.29	0.20	0.20	0.40	0.30	0.29	0.20	0.59	0.49	0.39	0.30	0.30	0.29	0.20	0.20
CAT D - F	0.33	0.29	0.20	-	0.39	0.30	0.29	0.20	0.60	0.49	0.38	0.30	0.30	0.20	0.20	-

Table F-4 lists the CSL for the 5 kts to 10 kts speed bin for the six aircraft pairs at the seven runway configurations analyzed in this study.

Table F-4: CSL at Threshold Distance Limits for Speed Bin from 5 kts to 10 kts

Airport	Generic Airport								Boston Logan International Airport							
Runway Approach Alignment	Straight-In 2,500 ft RCLS				3° Offset 2,500 ft RCLS				Straight-In 1,500 ft RCLS				2° Offset 1,500 ft RCLS			
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM
CAT B - A	0.49	0.44	0.39	0.30	0.83	0.66	0.49	0.30	0.54	0.39	0.30	0.30	0.66	0.50	0.39	0.30
CAT B - D	0.50	0.46	0.39	0.30	0.80	0.67	0.49	0.30	0.44	0.39	0.30	0.29	0.60	0.50	0.40	0.30
CAT C - D	0.52	0.44	0.39	-	0.80	0.64	0.49	-	0.46	0.39	0.30	-	0.67	0.50	0.40	-
CAT C - E	0.52	0.45	0.39	-	0.83	0.64	0.40	-	0.47	0.39	0.30	-	0.65	0.50	0.39	-
CAT D - E	0.49	0.45	0.39	0.30	0.85	0.66	0.49	0.30	0.46	0.39	0.30	0.29	0.64	0.50	0.40	0.30
CAT D - F	0.55	0.43	0.39	-	0.84	0.66	0.48	0.30	0.45	0.39	0.30	-	0.66	0.50	0.40	-

Airport	Seattle-Tacoma International Airport								San Francisco International Airport							
Runway Approach Alignment	Straight-In 800 ft RCLS				Straight-In 1,700 ft RCLS				3° Offset 750 ft RCLS							
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	15 NM	10 NM	8 NM	7 NM	5 NM	3 NM	1 NM
CAT B - A	0.40	0.30	0.28	0.20	0.47	0.40	0.30	0.20	0.69	0.56	0.40	0.38	0.30	0.30	0.20	0.20
CAT B - D	0.39	0.30	0.29	0.20	0.48	0.40	0.30	0.30	0.69	0.58	0.40	0.39	0.30	0.30	0.24	0.20
CAT C - D	0.40	0.30	0.27	-	0.49	0.40	0.30	-	0.69	0.55	0.40	0.33	0.30	-	-	-
CAT C - E	0.39	0.30	0.28	-	0.48	0.39	0.30	-	0.69	0.58	0.40	-	-	-	-	-
CAT D - E	0.39	0.31	0.29	0.20	0.50	0.40	0.30	0.30	0.69	0.58	0.40	0.38	0.30	0.30	0.20	0.20
CAT D - F	0.39	0.30	0.28	-	0.48	0.40	0.30	-	0.69	0.58	0.40	-	0.30	-	-	-

Table F-5 lists the CSL for the 10 kts to 15 kts speed bin for the six aircraft pairs at the seven runway configurations analyzed in this study.

Table F-5: CSL at Threshold Distance Limits for Speed Bin from 10 kts to 15 kts

Airport	Generic Airport								Boston Logan International Airport							
Runway Approach Alignment	Straight-In 2,500 ft RCLS				3° Offset 2,500 ft RCLS				Straight-In 1,500 ft RCLS				2° Offset 1,500 ft RCLS			
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM
CAT B - A	0.59	0.50	0.40	-	0.97	0.75	0.54		0.59	0.47	0.39	-	0.77	0.59	0.40	-
CAT B - D	0.60	0.50	0.43	0.40	0.92	0.74	0.54	0.40	0.50	0.47	0.38	0.30	0.78	0.60	0.43	0.30
CAT C - D	0.63	0.50	0.40	-	0.98	0.72	0.56	-	0.55	0.46	0.35	-	0.78	0.60	0.40	-
CAT C - E	0.60	0.50	0.40	-	0.94	0.72	-	-	0.55	0.48	0.39	-	0.77	0.60	0.42	-
CAT D - E	0.60	0.50	0.40	-	0.97	0.74	0.54	-	0.53	0.45	0.36	-	0.76	0.59	0.40	-
CAT D - F	0.62	0.50	0.45	-	0.96	0.77	0.50	-	0.57	0.46	0.37	-	0.75	0.59	0.40	-

Airport	Seattle-Tacoma International Airport								San Francisco International Airport							
Runway Approach Alignment	Straight-In 800 ft RCLS				Straight-In 1,700 ft RCLS				3° Offset 750 ft RCLS							
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	15 NM	10 NM	8 NM	7 NM	5 NM	3 NM	1 NM
CAT B - A	0.46	0.39	0.30	-	0.57	0.49	0.39	-	0.79	0.66	0.50	0.40	0.39	-	-	-
CAT B - D	0.48	0.40	0.30	0.20	0.55	0.49	0.39	0.30	0.79	0.66	0.50	0.40	0.40	0.30	0.30	0.20
CAT C - D	0.48	0.40	0.30	-	0.59	0.49	0.39	-	0.83	0.63	0.49	0.40	0.30	-	-	-
CAT C - E	0.47	0.39	0.30	-	0.57	0.48	0.39	-	0.80	0.68	0.49	-	-	-	-	-
CAT D - E	0.45	0.39	0.30	-	0.58	0.44	0.39	-	0.80	0.66	0.49	-	0.40	-	-	-
CAT D - F	0.47	0.39	0.30	-	0.56	0.48	0.39	-	0.82	0.66	0.49	-	0.40	-	-	-

Table F-6 lists the CSL for the 15 kts to 20 kts speed bin for the six aircraft pairs at the seven runway configurations analyzed in this study.

Table F-6: CSL at Threshold Distance Limits for Speed Bin from 15 kts to 20 kts

Airport	Generic Airport								Boston Logan International Airport							
Runway Approach Alignment	Straight-In 2,500 ft RCLS				3° Offset 2,500 ft RCLS				Straight-In 1,500 ft RCLS				2° Offset 1,500 ft RCLS			
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM
CAT B - A	0.69	0.60	0.50	-	1.08	0.87	0.60	-	0.67	-	0.40	-	0.92	0.72	0.50	-
CAT B - D	0.69	0.60	0.50	-	1.09	0.87	0.60	-	0.67	0.50	0.40	-	0.88	0.69	0.50	-
CAT C - D	0.73	0.60	0.50	-	1.10	0.88	0.60	-	0.68	0.54	0.30	-	0.89	0.69	0.50	-
CAT C - E	0.70	0.60	0.50	-	1.09	0.88	-	-	0.60	0.52	0.40	-	0.88	0.69	0.50	-
CAT D - E	0.70	0.63	0.50	-	1.10	0.87	0.60	-	0.60	0.50	0.40	-	0.88	0.70	0.50	-
CAT D - F	0.74	0.60	0.50	-	1.09	0.89	-	-	0.66	0.50	0.40	-	0.89	0.70	0.50	-

Airport	Seattle-Tacoma International Airport								San Francisco International Airport							
Runway Approach Alignment	Straight-In 800 ft RCLS				Straight-In 1,700 ft RCLS				3° Offset 750 ft RCLS							
CSL at / Pair	20 NM	14 NM	8 NM	2 NM	20 NM	14 NM	8 NM	2 NM	20 NM	15 NM	10 NM	8 NM	7 NM	5 NM	3 NM	1 NM
CAT B - A	0.53	0.47	0.38	-	0.68	0.57	0.40	-	0.97	0.76	-	-	0.40	-	-	-
CAT B - D	0.55	0.46	0.38	-	0.67	0.57	0.47	-	0.90	0.77	0.58	0.40	0.40	-	-	-
CAT C - D	0.50	0.47	0.38	-	0.67	0.56	0.40	-	0.90	0.75	0.58	-	-	-	-	-
CAT C - E	0.57	0.46	0.34	-	0.69	0.57	0.40	-	0.96	0.78	0.57	-	-	-	-	-
CAT D - E	0.54	0.46	0.31	-	0.70	0.55	0.46	-	0.93	0.76	0.54	-	0.44	-	-	-
CAT D - F	0.57	0.46	0.36	-	0.66	0.54	0.40	-	0.93	0.72	0.59	-	0.50	0.93	0.72	0.59

Appendix G: Example of Simulation Output File

Example of an abbreviated output file used to determine collision risk during paired approach operations.

Scenario Type	Distance from Threshold (NM)	Distance In Trail (NM)	Diagonal Distance (NM)	Deviation Type	Deviation Angle	Number of Aircraft Pairs	Cylinder TCVs	Percent Cylinder TCVs	Percent Theta	Percent Value	Individual Cylinder TCV Risk	Cylinder TCV Risk
CAT C leading CAT D	6	0.0	0.412	Level	20	100,000	1,198	0.01198	0.0000255	5.00E-01	1.52745E-07	1.81E-06
CAT C leading CAT D	6	0.0	0.412	Descending	20	100,000	8,482	0.08482	0.0000255	5.00E-01	1.08146E-06	
CAT C leading CAT D	6	0.0	0.412	Level	30	100,000	1,162	0.01162	0.0000118	5.00E-01	6.85580E-08	
CAT C leading CAT D	6	0.0	0.412	Descending	30	100,000	8,527	0.08527	0.0000118	5.00E-01	5.03093E-07	
CAT C leading CAT D	6	0.1	0.429	Level	20	100,000	2,354	0.02354	0.0000255	5.00E-01	3.00135E-07	3.10E-06
CAT C leading CAT D	6	0.1	0.429	Descending	20	100,000	14,328	0.14328	0.0000255	5.00E-01	1.82682E-06	
CAT C leading CAT D	6	0.1	0.429	Level	30	100,000	2,263	0.02263	0.0000118	5.00E-01	1.33517E-07	
CAT C leading CAT D	6	0.1	0.429	Descending	30	100,000	14,310	0.1431	0.0000118	5.00E-01	8.44290E-07	
CAT C leading CAT D	6	0.2	0.467	Level	20	100,000	1,941	0.01941	0.0000255	5.00E-01	2.47478E-07	2.83E-06
CAT C leading CAT D	6	0.2	0.467	Descending	20	100,000	13,130	0.1313	0.0000255	5.00E-01	1.67408E-06	
CAT C leading CAT D	6	0.2	0.467	Level	30	100,000	1,925	0.01925	0.0000118	5.00E-01	1.13575E-07	
CAT C leading CAT D	6	0.2	0.467	Descending	30	100,000	13,398	0.13398	0.0000118	5.00E-01	7.90482E-07	
CAT C leading CAT D	6	0.3	0.522	Level	20	100,000	322	0.00322	0.0000255	5.00E-01	4.10550E-08	6.76E-07
CAT C leading CAT D	6	0.3	0.522	Descending	20	100,000	3,300	0.033	0.0000255	5.00E-01	4.20750E-07	
CAT C leading CAT D	6	0.3	0.522	Level	30	100,000	332	0.00332	0.0000118	5.00E-01	1.95880E-08	
CAT C leading CAT D	6	0.3	0.522	Descending	30	100,000	3,290	0.0329	0.0000118	5.00E-01	1.94110E-07	
CAT C leading CAT D	6	0.4	0.589	Level	20	100,000	1	0.00001	0.0000255	5.00E-01	1.27500E-10	9.47E-09
CAT C leading CAT D	6	0.4	0.589	Descending	20	100,000	46	0.00046	0.0000255	5.00E-01	5.86500E-09	
CAT C leading CAT D	6	0.4	0.589	Level	30	100,000	4	0.00004	0.0000118	5.00E-01	2.36000E-10	
CAT C leading CAT D	6	0.4	0.589	Descending	30	100,000	55	0.00055	0.0000118	5.00E-01	3.24500E-09	

Appendix H: Definitions

This appendix redefines terms utilized in this safety study where definitions may differ slightly from common usage. These definitions should supplant dictionary definitions if a discrepancy exists.

ADS-B Guidance Display	-	The ADS-B Guidance Display (AGD) is installed in the trailing aircraft to provide IM speed information to assist the trailing aircraft cockpit in maintaining a safe position with respect to the lead aircraft.
Airport Approach Configuration	-	An Airport Approach Configuration consists of a unique parallel runway configuration (e.g., runway threshold stagger and RCLS) coupled with a unique runway approach alignment (i.e., straight-in or offset). This safety study analyzed seven runway configurations spread across four airports: KGEN, KBOS, KSEA, and KSFO.
ASATng	-	The Airspace Simulation and Analysis Tool – Next Generation (ASATng) is a Monte Carlo simulation tool developed by Air Traffic Simulation (ATSI), Incorporated for use in conducting aviation related safety assessments.
Assigned Spacing Goal	-	The Assigned Spacing Goal (ASG) is the desired time or distance-based spacing interval relative to a specified target.
Closely Spaced Parallel Operations	-	Closely Spaced Parallel Operations (CSPO) are utilized to increase capacity at busy airports when visual approaches cannot be conducted. The operations may be simultaneous dependent or simultaneous independent in nature, and are conducted at airports with parallel runways whose extended runway centerline spacing is less than 4,300 ft.
Closest Point of Approach	-	The Closest Point of Approach (CPA) is the minimum three-dimensional distance between aircraft pair. It is utilized to determine if a test criterion violation (TCV) has occurred during a simulation run.
Cockpit Display of Traffic Information	-	The Cockpit Display of Traffic Information (CDTI) is installed in the trailing aircraft and serves as a situational awareness display during the PA operations.
Collision Safety Limit	-	The Collision Safety Limit (CSL) is the in-trail distance of the trailing IM aircraft with respect to the lead target aircraft at a given location along the approach course. It signifies the closest in-trail distance to ensure collision risk remains within a specified safety limit. The CSL continually changes as the aircraft pair proceed along the approach course. The CSL may also be referred to as the front-gate CSL in-trail distance, the front-gate CSL, or the CSL in-trail distance.

Current	-	Current as of the date this safety study was published.
Diagonal Distance	-	The Diagonal Distance is the two-dimensional lateral measurement between the centers of gravity of an aircraft pair using the Cartesian coordinate system. The axes are referred to as abscissa and ordinate (i.e., the X and Y planes).
Effect (of a Hazard)	-	An Effect refers to the real or credible harmful outcome that can be expected if a hazard occurs. A credible outcome is one that is reasonable to expect within the operational lifetime of a typical ATC system.
Final Approach Speed	-	The Final Approach Speed (FAS) is the indicated air speed flown during the final approach. It should be attained at or before reaching the final approach fix.
Flight Deck Based Interval Management Equipment	-	The Flight Deck Based Interval Management (FIM) Equipment is an ADS-B based suite of avionics which provide speed commands to the flight crew which enables them to manage an ASG.
Hazard	-	A Hazard is a condition that could foreseeably cause or contribute to an aircraft accident.
Interval Management	-	Interval Management (IM) is a component of trajectory based operations. It uses ADS-B In capabilities to manage aircraft spacing. In PA operations, IM allows air traffic controllers to precisely manage the spacing interval between lead and trailing aircraft.
Interval Management Aircraft	-	The Interval Management (IM) aircraft is the trailing aircraft in a paired approach operation.
KGEN	-	The fictitious four-letter ICAO airport code signifying the Generic Airport (KGEN) and associated runway configuration with a runway centerline spacing of 2,500 ft.
Likelihood	-	Likelihood is the estimated probability of an outcome associated with a hazard. It is a rate of how often a given effect is expected to occur.
Monte Carlo Method	-	The Monte Carlo Method is a fast-time simulation technique that relies on the repeated sampling of random variables from probability distributions to obtain results.
Overall	-	Overall, when referring to CSL, is the risk calculated from the total number of TCV's in relation to the total number of simulation pairs at a given location.

Paired Approach	-	Paired Approach operations enable a lead and trailing aircraft to fly simultaneous dependent approaches to parallel runways spaced at least 700 ft, but less than 2,500 ft apart, in low visibility conditions. The trailing aircraft must maintain a position within a protection zone behind a forward CSL, such that it is protected from collision in the event of a deviation by the lead aircraft; and in front of an aft WSL, such that it is protected against wake encounters associated with a non-deviating lead aircraft.
Probability Density Functions	-	Probability Density Functions are functions of random variables. When integrated across an interval, these functions provide the probability that the variable lies within that same interval.
Protection Zone	-	The Protection Zone is the area between the forward CSL and aft WSL. In a PA operation, the trailing aircraft is to stay within the protection zone. The protection zone is intended to protect the trailing aircraft from possible collision and wake encounters from the lead aircraft.
Risk	-	Risk is the composite of predicted severity and likelihood of the potential effect of a hazard. While the worst credible effect may produce the highest risk, the likelihood of the worst credible effect is often very low.
Runway Centerline Spacing	-	Runway Centerline Spacing (RCLS) is the distance between centerlines of two parallel runways.
Scenario	-	A Scenario serves as the basic framework for ASATng Monte Carlo analysis. A scenario is composed of airport runway configuration, aircraft pairing, unique lead aircraft distances from runway threshold coupled with unique in-trail distances of the trailing aircraft, deviation type, and other aspects of an ATC environment. Once created, multiple simulation runs (where input variable values are modified for each run) are conducted for each scenario to establish the CSL at locations along the approach course.
Severity	-	Severity is the potential consequence of a hazard in terms of degree of loss or harm. It is a prediction of how dire the outcome of a hazard can be.
Simulation Run	-	A Simulation run (a.k.a., simulation) is a single instance of an ASATng Monte Carlo simulation. Each input variable is assigned a value for the fast-time simulation run.
Speed Differential	-	A Speed Differential is the difference in speed between the lead aircraft and the trailing aircraft, sometimes referred to as Δspeed.

Target Aircraft	-	The target aircraft is the lead aircraft in a paired approach operation.
Test Criterion Violation	-	A Test Criterion Violation (TCV) is considered a collision. It occurs when the center of gravity of the deviating lead aircraft penetrates a defined volume of airspace encompassing the trailing aircraft. Typically, the volume of airspace assessed is a cylinder with a radius of 265 ft and height of ±80 ft. A TCV for this volume is referred to as an extremely improbable catastrophic event.
Three-Dimensional Distance	-	The Three-Dimensional Distance is a measurement between the centers of gravity of an aircraft pair using the Cartesian coordinate system. The axes are referred to as abscissa, ordinate and applicate (i.e., the X, Y, and Z planes).
Wake Turbulence Recategorization	-	Wake Turbulence Recategorization (RECAT) was intended to update the U.S. current aircraft classification for wake turbulence purposes from a categorization based on certified takeoff weight to a classification standard based on multiple criteria, such as wingspan, the aircraft's ability to withstand a wake encounter, and certified takeoff weight. This new classification resulted in six different categories of aircraft for wake turbulence separation purposes. This safety study concentrated on Wake RECAT Phase 1.5.
Wake Safety Limit	-	The Wake Safety Limit (WSL) is the in-trail distance of the trailing IM aircraft with respect to the lead target aircraft at a given location along the approach course. It signifies the farthest in-trail distance allowed to protect against wake encounters associated with a non-deviating lead aircraft. The WSL continually changes as the aircraft pair proceed along the approach course at an in-trail distance ahead of the wake hazard area. The WSL may also be referred to as the rear-gate WSL in-trail distance, the rear-gate WSL, or the WSL in-trail distance.

Appendix I: Acronyms

This appendix includes a list of acronyms associated with this study.

ACAS-X	-	Airborne Collision Avoidance System X
ADS-B	-	Automatic Dependent Surveillance – Broadcast
AGD	-	ADS-B Guidance Display
ASATng	-	Airspace Simulation and Analysis Tool – Next Generation
ASG	-	Assigned Spacing Goal
ATSI	-	Air Traffic Simulation, Incorporated
ATC	-	Air Traffic Control
CAT	-	Category
CDTI	-	Cockpit Display of Traffic Information
CPA	-	Closest Point of Approach
CRM	-	Collision Risk Model
CSL	-	Collision Safety Limit
CSPO	-	Closely Spaced Parallel Operations
DME	-	Distance Measuring Equipment
FAA	-	Federal Aviation Administration
FAF	-	Final Approach Fix
FAS	-	Final Approach Speed
FIM	-	Flight Deck Based Interval Management
FTE	-	Flight Technical Error
GPS	-	Global Positioning System
HUR	-	High Update Rate
KBOS	-	Boston Logan International Airport
KGEN	-	Generic Airport
KSEA	-	Seattle-Tacoma International Airport
KSFO	-	San Francisco International Airport
IAS	-	Indicated Air Speed
ICAO	-	International Civil Aviation Organization
ILS	-	Instrument Landing System
IM	-	Interval Management

IMC	-	Instrument Meteorological Conditions
IRU	-	Inertial Reference Unit
LOC	-	Localizer
LOC-TH	-	Localizer to Threshold
MTOW	-	Maximum Takeoff Weight
NM	-	Nautical Miles
NSE	-	Navigation System Error
PA	-	Paired Approach
PDE	-	Path Definition Error
RCLS	-	Runway Centerline Spacing
RA	-	TCAS Resolution Advisory
RECAT	-	Wake Turbulence Recategorization
RNAV	-	Area Navigation
RNP	-	Required Navigation Performance
SOIA	-	Simultaneous Offset Instrument Approach
TA	-	TCAS Traffic Advisory
TCAS	-	Traffic Collision Avoidance System
TCV	-	Test Criterion Violation
TH	-	Threshold
TLS	-	Target Level of Safety
TSE	-	Total System Error
WSL	-	Wake Safety Limit