Federal Aviation Administration

DOT/FAA/AFS400/2017/R/15
Flight Technologies and Procedures Division, AFS-400
Washington, DC 20591

Safety Study on the Selection of an Incorrect Established on Required Navigation Performance Instrument Approach Procedure

July 2017

Technical Report

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AFS400/2017/R/15		

4. Title and Subtitle	5. Report Date
Safety Study on the Selection of an Incorrect Established on Required Navigation Performance Instrument Approach Procedure	July 2017
6. Author(s)	**7. Performing Organization Code**
Cody Nichols, AFS-450; Jason Walls, AFS-450; Logan Branscum, AFS-450; Jeff Rawdon, AFS-420; Gary Foster, Clancy JG; Blair Dulli, DIGITALiBiz	AFS-450
8. Performing Organization Name and Address	**9. Type of Report and Period Covered**
Flight Systems Laboratory, AFS-450 6500 S MacArthur Blvd., STB Annex, RM 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 published a technical report on the safety of simultaneous independent Established on Required Navigation Performance (RNP) (EoR) operations using track-to-fix turns in July 2016. This study utilized parametric analysis that extended the results of the prior EoR analysis, including designs using radius-to-fix turns, to include airspaces that do not have airspace designs that allow for easy detection of incorrect approach selection. It identifies three distinct cases that characterize the risks associated with an incorrect approach selection. Based on these three cases, analysts developed collision risk models that leveraged widely accepted collision risk modeling techniques and data collected during human-in-the-loop experiments of the EoR concept. The collision risk of the three cases was evaluated, and the wake encounter risk was considered for those cases where an aircraft could violate the in-trail separation to another aircraft. In all three cases, controller intervention is critical to meeting the target level of safety for any procedure design that has a potential for incorrect flight path selection, as no dual or triple runway and approach geometry was identified that could achieve both collision risk and acceptable wake encounter risk without controller intervention. Air traffic intervention becomes sufficiently effective as a mitigation if the controller has at least 50 seconds to intervene after the error is observable and before an incorrect path selection would cross the path of another aircraft to any runway. There is no significant variation (more than one order of magnitude) in the risk as a function of runway spacing or turn radius while turning to the final approach course, regardless of the case analyzed. The rate of incorrect path selection is a significant factor, but insufficient information is available to determine a specific rate, and a range of rates was considered and found to be acceptable when controllers are provided adequate time to effectively intervene.

13. Key Words	14. Distribution Statement
Required Navigation Performance (RNP) Radius-to-fix (RF) Track-to-fix (TF) Established on RNP (EoR) Human-in-the-loop (HITL) Simultaneous Independent Approaches Closely Spaced Parallel Operations (CSPO) Multiple Runway Operations Performance Based Navigation (PBN) Collision Risk Modeling	Uncontrolled
15. Security Classification of This Report	**16. Security Classification of This Page**
Unclassified	Unclassified

DOT F1700.7

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Executive Summary

In July 2016, the Federal Aviation Administration (FAA) published DOT/FAA/AFS400/2016/R/01, *Safety Study on Simultaneous Independent Approaches Using Established on Required Navigation Performance Approach Procedures with Track-to-Fix Design*.[1] This safety study is referred to hereafter as the TF turn study. The TF turn study supports a separation standards change throughout the National Airspace System (NAS) utilizing the Established on Required Navigation Performance (RNP) (EoR) operational concept, which eliminates the requirement for 3 nautical mile (NM) lateral or 1000 ft vertical separation prior to becoming established on parallel final approach courses for multiple runway operations. In the TF turn study, we assumed that the airspace would be designed with unique flight paths to each landing runway to enable controllers to easily detect flight path deviations caused by an incorrect flight procedure selection. However, this assumption prevented application of the results to facilities with existing approach procedures that were not designed using unique flight paths. Furthermore, by making this assumption, we were not able to provide insight on how to design approaches using unique flight paths.

This study extends the results of prior EoR analysis, including designs using track-to-fix (TF) and radius-to-fix (RF) turns, to include terminal airspace procedures that are not designed to allow controllers to easily detect flight path deviations caused by an incorrect flight procedure selection.

This study utilized parametric analysis and identifies three distinct cases that characterize the risks associated with an incorrect flight procedure selection. The first case examines the collision risk of the deviating aircraft and an aircraft flying an approach to the runway that the deviating aircraft should have selected. In the second case, we examine the collision risk to an aircraft flying to the runway that the deviating aircraft incorrectly selected. The third case examines the collision risk as the deviating aircraft crosses the traffic to any runway between the intended runway and the incorrectly selected runway. Based on these three cases, analysts estimated collision risk leveraging widely accepted mathematical collision risk models and data collected during prior EoR human-in-the-loop (HITL) experiments.

The collision risk of the three cases was evaluated, and the wake encounter risk was considered for those cases where an aircraft could violate the in-trail separation to another aircraft. In all three cases, controller intervention is critical to meeting the target level of safety for any procedure design that has a potential for incorrect flight path selection, as no dual or triple runway and approach geometry was identified that could achieve both collision risk and acceptable wake encounter risk without controller intervention. Air traffic intervention becomes sufficiently effective as a mitigation if the controller has at least 50 seconds to intervene after the error is observable and before an incorrect path selection would cross the path of another aircraft to any runway. There is no significant variation (more than one order of magnitude) in the risk as a function of runway spacing or turn radius while turning to the final approach course, regardless of the case analyzed. The rate of incorrect path selection is a significant factor, but insufficient information is available to determine a specific rate, and a range of rates was considered and found to be acceptable when controllers are provided adequate time to effectively intervene.

[1] Flight Technologies and Procedures Division, *DOT/FAA/AFS400/2016/R/01, Safety Study on Simultaneous Independent Approaches Using Established on Required Navigation Performance Approach Procedures with Track-to-Fix Design* (Federal Aviation Administration, 2016).

1 Introduction

The EoR concept leverages performance based navigation to eliminate the requirement for 1000 ft vertical or 3 NM lateral aircraft-to-aircraft separation when turning onto simultaneous approaches.[2] This concept is one of the focus areas within the NextGen performance based navigation portfolio.

In July 2016, the FAA published a technical report on the safety of simultaneous independent EoR operations using TF turns. The TF turn study analysis indicated that EoR operations to runways spaced 3600 ft or more with an FMA and a no transgression zone (NTZ) result in a collision risk on the order of 10^{-9}, while operations to runways spaced more than 9000 ft resulted in a collision risk on the order of 10^{-10} or less without an FMA. The TF turn study assumed that aircrews selected the correct instrument approach procedure while flying EoR operations. Using the HITL experiment data collected during the TF turn study, this study utilized parametric analysis to address the increased risk associated with incorrect instrument approach procedure selection while flying EoR operations.

1.1 Background

Instrument approach procedure selection is a multi-phased activity using the flight management system (FMS) or other area navigation (RNAV) system. During pre-flight operations, flight crews input their expected arrival and approach procedure to the destination airport into the FMS. Flight crews usually update this information prior to descending from the en route structure using information from the Automatic Terminal Information Service. They may also be required to input this information again if a controller clears the flight crew for a different approach procedure than expected. When selecting the approach procedure, the names presented in the FMS are similar to those on the approach chart – for example, RNVZ 34L or RNVZ 34R in a General Electric Aviation (formerly Smiths Aerospace) flight management computer with Operating Program Version 10.8A. In certain FMSs, the instrument approach procedures may be presented on the same page and, due to the naming convention, may be identical with the exception of a single character. The map display of the flight path would not significantly mitigate the similarity because it depicts the landing runway and not the complete airport environment. To reduce the risk, flight crews follow a procedure where one pilot inputs the approach procedure into the FMS and the other pilot reviews the input and provides a verbal confirmation before execution. Also, standard air traffic procedures require flight crews to read back their clearances so controllers can verify their intended approach. These causes and mitigations do not significantly vary between instrument approach procedures designed with RF legs or TF turns.

Subject matter experts believe that a flight crew input error is the most likely cause for an incorrect approach selection. This risk would be increased by flight crew fatigue or when flight crews experience high workload levels, such as if air traffic issues a late change in approach clearance. However, controllers could also contribute to this risk. If a controller clears the aircraft for the incorrect approach procedure, this could result in a flight path deviation which increases collision risk. There is also a remote possibility that a controller may clear an aircraft for an incorrect instrument flight procedure and tag that aircraft with the incorrect landing runway in the FMA. In this case, it is possible that the FMA

[2] DIGITALiBiz, *FAA Performance Based Navigation Simultaneous Independent Established on RNP Concept of Operation* (Final Version 1.0 draft, 2014).

would not issue alerts associated with a path deviation.[3] We do not have data to support how quickly a controller would respond to a deviation resulting from an incorrect procedure selection without the use of an FMA. Therefore, we cannot quantify this risk without further experimentation. Subject matter experts suggest that this event would be sufficiently rare that such experimentation is not necessary.

As identified by Qantas and recorded in the Boeing EoR study, there is a plausible solution that eliminates the collision risk associated with incorrect flight procedure selection.[4] If the airspace is designed such that there is only one approach procedure that can be reasonably selected from the Standard Terminal Arrival, this would prevent flight crew selection of incorrect flight procedure options from the FMS. Implementations of approach procedures at Seattle-Tacoma International Airport used this design principal in part by deleting two runway transitions from original procedure designs; therefore, the Flight Technologies and Procedures Division (AFS-400) believed that it was reasonable to assume a similar airspace for the TF turn study.

However, the existing airspaces that could use the EoR operations have not been designed with these principles in mind. The EoR program intends to generate near term NextGen benefits, so a requirement for redesigning terminal airspace is undesirable. Furthermore, some airport environments may need to include transitions that do not conform to unique path design for compelling operational reasons.

We are not aware of a comprehensive study on the selection rate of incorrect approach procedures, especially in a simultaneous approach environment like EoR. A previous EoR study on dependent operations, conducted by Boeing, used a rate of 5 out of 32,500 approaches (1.5×10^{-4}) based on data from Qantas.[5] In addition, only one potential incorrect approach procedure was identified during simultaneous independent widely spaced RNP authorization required (AR) approach operations currently running at Denver International Airport (KDEN). As of August 31, 2016, KDEN had run 40,000 RNP AR approach procedures (2.5×10^{-5}). Related information from the oceanic environment can be found in the rate of lateral deviations, most of which can be attributed to differences between the filed flight plan and the cleared route. Considering that there were 477,191 trans-Atlantic flights of approximately 3.25 hours each in this period and the North Atlantic experienced 198 lateral deviations in 2015, the lateral deviation rate per flight hour was approximately 1.28×10^{-4} in 2015.[6] This information leads us to assume that the rate for incorrect approach procedure selection falls within the range of 10^{-4} and 10^{-6}. This aligns with previous assumptions for multiple runway operations course deviation rates: the rate of crossing to an incorrect ILS is 4.5×10^{-5} based on US-wide analysis of tracks and was originally assumed to be a higher rate of 5.0×10^{-4}.[7] While these rates most likely represent the probability that a flight crew selects any incorrect approach procedure, the following analysis would be best informed by a more precise value.

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[3] Raytheon Company, *Standard Terminal Automation Replacement System (STARS), Full STARS, STARS Adaptation Data Maintenance Manual* (Final Revision 22, S6.00R2, 2014).
[4] Boeing, *Seattle Greener Skies i2 Established on RNP (EoR) Simultaneous Dependent Closely-Spaced Parallel Approaches National Airspace System (NAS) Modeling and Simulation Report* (SE2020 Task Order 8, Deliverable 19, Version 2, 2014), 136.
[5] Ibid.
[6] North Atlantic Safety Oversight Group. Fourteenth Meeting. Summary of Discussions, Agenda Item 3 (2016).
[7] Flight Systems Laboratory. *DOT-FAA-AFS-450-56, Safety Study Report on Simultaneous Parallel Instrument Landing System (ILS) and Area Navigation (RNAV) or Required Navigation Performance (RNP) Approaches – Phases 3 and 4* (Flight Technologies and Procedures Division, Federal Aviation Administration, July 2010).

The instrument approach procedures at KDEN are a good example of a design that could induce an incorrect selection, see appendix B for the approach charts. As seen in figure 1-1, if the aircraft is transitioning from either the east or west downwind, there are four possible approach transitions that could be selected. During triple runway operations, there are three approach procedures with active traffic. If an aircraft selects an incorrect approach procedure, the flight instruments continue to display normal error characteristics while flying the selected approach procedure, but the aircraft may intersect one or more other traffic streams and may merge with no more than one traffic stream.

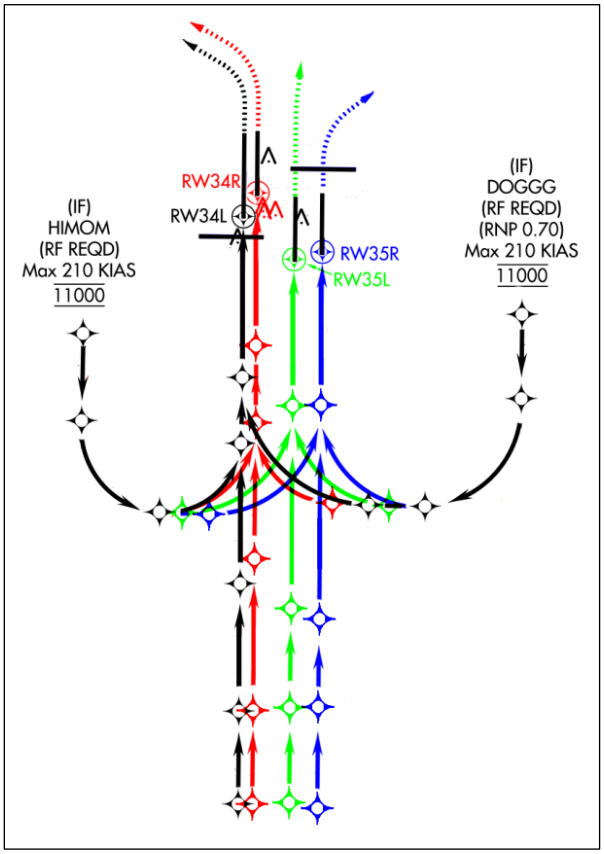


Figure 1-1: Possible Approach Transitions

A Denver Terminal Radar Approach Control (TRACON) safety risk management panel (SRMP) for EoR operations identified lateral track deviation as a risk and wrong runway approach as the most likely cause of possible lateral track deviation.[8] In response to the SRMP's finding, Denver TRACON Airspace and Procedures Office conducted two HITL demonstrations in 2015 and 2016.[9,10] Operating under a waiver to FAA JO 7110.65 based on the SRMP results, simultaneous instrument approaches to

[8] SRMD-D01/DEN ATCT RNP-AR Dual/Triple Waiver-2014-003, Version 1.2 (2015).
[9] D01 TRACON, Final Report, Denver Site Specific Established on RNP (EoR) Test, FAA JO 7110.65 para 5-7-9; Duals & Triples (2016).
[10] Ibid.

widely spaced parallel runways (greater than 9,000 ft between centerlines) have been authorized at KDEN, increasing the utilization of their RNP approaches.[11]

Both HITL demonstrations conducted by Denver TRACON included incorrect approach selection scenarios, referred to as wrong runway selections.[12, 13] Both demonstrations built confidence that EoR operations, including the possibility of incorrect approach selections, could be done with an equivalent level of safety to the existing "vector to instrument approach" system in use at KDEN. These HITL demonstrations were specific to the Denver TRACON. They assumed RNAV (RNP) approaches and wider minimum runway spacings than those used in this study.

Based on the concern identified in these safety discussions, Denver TRACON proposed additional air traffic procedures. The procedures were not intended to reduce the probability that the aircraft-to-aircraft collision occurs after an incorrect approach has been selected. Instead, the procedures intend to reduce the probability that the flight crew would enter the incorrect approach procedure into the FMS and, if they did input an incorrect approach procedure, that they would read the incorrect selection to air traffic, who would be able to correct the flight crew's mistake. The proposed air traffic procedures include five controls:

1. The feeder controller issues: "Expect RNAV Z RWY34R approach". The flight crew reads back the expected approach clearance.
2. The final controller issues the approach clearance: "Cleared RNAV Z RWY34R approach". The flight crew reads back the approach clearance.
3. The flight crew checks into the tower frequency, with both the final monitor and tower controllers listening, and states the assigned landing runway. This occurs before the start of the turn from downwind to the final approach course.
4. The tower controller issues the landing clearance: "Cleared to land RWY34R". The flight crew reads back the landing clearance.
5. In cases where one of the above controls is not performed, the final monitor controller will query the flight crew to verify the final approach fix for the selected approach procedure.

While the above mitigation procedures may reduce the rate of incorrect approach selection, it is difficult to quantitatively assess the effect the procedures have on the collision risk of the EoR operation. We could assume that the incorrect approach entry rate is 1 in 100, the probability that the pilots do not catch the incorrect entry is 1 in 100, and the probability that each subsequent check by air traffic control fails to catch the incorrect entry is 1 in 100. If the controllers verify the intended approach three times, the rate of selection could be expressed as $(10^{-2})^5 = 10^{-10}$. However, this statement assumes that the events are independent. It is plausible that if a pilot makes a cognitive error, many similar inquiries may become rote, and the probability of detection with the second similar check may be dependent on whether the flight crew responded incorrectly the first time they were queried. Fully exploring the effectiveness of these mitigations would require more extensive analysis, additional subject matter expert review, or HITL experimentation that is not included in this study.

[11] SRMD-D01/DEN ATCT RNP-AR Dual/Triple Waiver-2014-003, Version 1.2 (2015).
[12] D01 TRACON, Denver Site Specific Established on RNP (EoR) Test.
[13] Ibid.

The TF turn study covered a wide range of topics, from nuisance Traffic Alert and Collision Avoidance System alerts to instrument approach procedure design.[14] However, we primarily examined aircraft-to-aircraft mid-air collision (MAC). We partitioned the MAC risk into multiple cases to simplify the analysis:[15]

$$P(MAC) = P(\text{Collision}|\text{Normal Ops}) \times P(\text{Normal Ops}) + \sum_{\substack{x \in \text{Set of all} \\ \text{Non-Normal States}}} P(\text{Collision}|\text{Non-Normal State x}) \times P(\text{Non-Normal State x}) \quad (1)$$

Although the collision risk is a sum, in most cases, one non-normal state contributes much more collision risk than normal operations or any other non-normal state, so the collision risk can be accurately estimated using just one term. In previous safety studies, the analysis of simultaneous independent operations assumed that collision risk was best characterized by a sudden departure of up to 30° from the approach path where the aircraft would continue to deviate on a constant heading toward the other approach for an extended period of time without the flight crew responding to controller communications.[16] For the TF turn study, stakeholder feedback indicated that the most significant risk would not be posed by the more conservative and rare scenario used in previous studies, but instances where some aircraft failure caused the flight crew to deviate from the approach path. To assess this scenario, AFS-400 conducted a HITL experiment where pilot responses to a variety of flight deck failures were collected.[17] Additionally, AFS-400 used the data collected to characterize normal aircraft performance and calculated the normal collision risk as well.

Although common practice, partitioning the collision risk as described above adds risk to the analysis methodology because it is very difficult to identify every possible non-normal state of the operations that could result in a collision. Ultimately, the analysis team must make certain assumptions regarding which risks are most important for assessment to create a manageable study. Many possible non-normal states do not need to be assessed due to either rarity of the non-normal condition or its insignificant effect on collision risk. Other potential cases may also not be assessed due to subject matter expertise regarding relative priorities. For example, the TF turn study did not include a detailed analysis of Global Positioning System (GPS) satellite failures, even though this was examined in prior related work because subject matter experts determined that the safety risk for this failure was unlikely to be significant.[18]

[14] Flight Technologies and Procedures Division, *DOT/FAA/AFS400/2016/R/01*.
[15] Note: This equation says that the total risk of collision is equal to the risk of collision when everything is operating as expected (i.e. normal operations) plus the sum of the probability of collision when something goes wrong with at least one aircraft (i.e. the operation is in a non-normal state) times the probability that something goes wrong for every possible thing that could go wrong.
[16] Flight Systems Laboratory, *DOT-FAA-AFS-450-69, Simultaneous Independent Close Parallel Approaches – High Update Radar Not Required* (Flight Technologies and Procedures Division, Federal Aviation Administration, 2011).
[17] Flight Technologies and Procedures Division, *DOT/FAA/AFS400/2016/R/01*.
[18] Boeing, *Seattle Greener Skies.*

2 Purpose and Scope

This report quantifies the risks associated with airspace designs that include EoR operations to runways other than those associated with the intended operation. Risks that were considered include collision risk and wake separation loss. Nuisance alerts from safety systems were not considered because we only examined a non-normal event; normal operations are assessed in other EoR reports.[19, 20]

[19] Flight Technologies and Procedures Division, *DOT/FAA/AFS400/2016/R/01*.
[20] Boeing, *Seattle Greener Skies.*

3 Analysis

All potential aircraft collisions caused by the selection of an incorrect instrument flight procedure with EoR separation standards can be categorized as one of three cases based on the aircraft being placed at risk. The three cases are:

Case 1: Intended Runway Traffic Intersection

In this case, an aircraft flying an approach to the runway that the deviating aircraft should have selected is at risk, see section 3.1.

Case 2: Merge with Landing Runway Traffic

In this case, an aircraft flying an approach to the runway that the deviating aircraft incorrectly selected is at risk, see section 3.2.

Case 3: Intermediate Runway Traffic Intersection

In this case, an aircraft flying an approach to any runway between the intended runway and the incorrectly selected runway is at risk, see section 3.3.

One of the most widely accepted mathematical models of aircraft collision risk was developed by the Royal Aircraft Establishment and published by P.G. Reich in 1966.[21] Recent work in AFS-400 has generalized this model to work with time-dependent variables by combining the model with the Hsu collision risk model.[22, 23] By using these models with input variables collected in the EoR HITL experiments, we modeled the collision risk of normally performing aircraft. Although flying the incorrect approach procedure is a non-normal event, the errors of the aircraft relative to a well-defined path are best characterized by normal performance, making a model of normal aircraft performance appropriate. Although there may be some vertical separation at the time of the intersection, due to the complexities of how the procedures may be designed, it is not feasible to calculate what this vertical separation will be in implementation. Therefore, we calculated results without nominal separation at the point of intersection.

3.1 Case 1: Intended Runway Traffic Intersection

Any airspace configuration that merges EoR traffic with other aircraft flying along the extended runway centerline to the same (intended) landing runway, such as on an Instrument Landing System (ILS) approach, includes an intersection, see figure 3-1. While a nominal aircraft intersection would be depicted by the aircraft rolling out on the extended runway centerline for the intended landing runway, an off-nominal/deviating aircraft whose pilot selected the incorrect approach procedure would deviate across the extended runway centerline as shown in figure 3-1 (red circle).

[21] Reich, P.G., Analysis of Long Range Air Traffic Systems: Separation Standards – I, II, and III (Journal of Navigation 19), 88-96, 169-176, 18-338.
[22] Greenhaw, Richard, A Relationship between the Reich and Anderson Models for Lateral Separation with Applications (Federal Aviation Administration, Flight Technologies and Procedures Division, September 18, 2015).
[23] Hsu, D., The Evaluation of Aircraft Collision Probabilities at Intersecting Air Routes (Journal of Navigation 34 (1), 1981), 78-102.

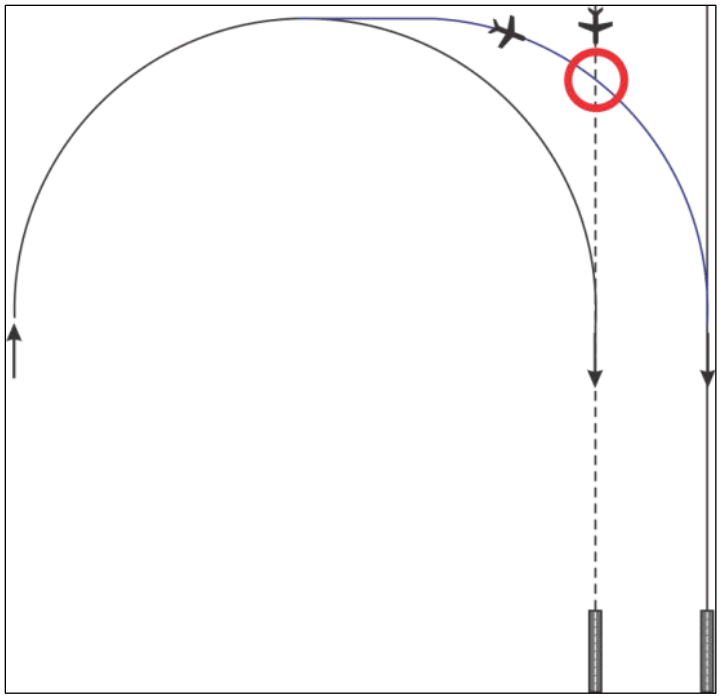


Figure 3-1: EoR Straight-In Intersection

Unlike the other two cases, the deviating aircraft does not pass through the NTZ between the parallel runways prior to producing a collision risk to intersecting traffic. The deviating aircraft's position at the intersection would not generate an FMA alert with enough time for adequate mitigation by the controller. On the other hand, the controller would be attempting to establish correct in-trail spacing between the EoR aircraft and any straight-in traffic along the extended runway centerline. Although the deviating aircraft would intersect the path earlier than expected, the required in-trail spacing is the primary mitigation preventing the trailing aircraft from being in a position that would result in a collision.

We did not believe that a wake analysis was needed for this case. First, the controller would not have time to intervene prior to a loss of wake separation due to the position of the NTZ. Furthermore, induced roll associated with this case would likely be lower in many scenarios where a wake vortex was encountered because the wake core would not be aligned with the straight-in traffic. Note, however, that the likelihood of encountering both wake vortices and larger vertical impact would be possible if a wake were encountered in this case.

3.1.1 Collision Risk Methodology

First, we assessed the collision risk without any mitigation. If we assume that the in-trail spacing is insufficient to prevent a collision, then the paths intersect. If the spacing between the intended landing runway and the incorrectly selected runway is sufficiently large, then the intersection will be perpendicular. Otherwise, the intersection is between a circular segment and a line. However, if we assume that the collision is perpendicular, which is least conservative, and locally straight, we are able to get an approximate result for the probability of collision given the intersection case. For most of these assessments, we consider that there is one aircraft every 3 NM. This can be thought of as a density of aircraft on the approach path. In this case, however, we are assuming that the paths are intersecting just

beyond the minimum in-trail spacing. Furthermore, it seems inappropriate to assume the typical 3 NM density. Instead, we varied the aircraft density between 0.5 NM and 1.5 NM around the point of intersection. This allowed us to estimate the effect of some spike in the probability density of the aircraft's lateral position near the expected point. Using the perpendicular intersection assumption, we can derive the following equation from the foundational collision risk model:

$$CR(T) = 4.58673 \times {\lambda_{xy}}^2 \times \left(\frac{\overline{|\dot{z}|}}{2\lambda_z} + \frac{2V_{rel}}{\pi\lambda_{xy}}\right)$$

$$\times \int_0^T \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_A(a) \times f_A(-c) \times f_C(c) \times f_C\left(a + S_y(t)\right) dc\, da\, dt \qquad (2)$$

The probability of vertical overlap was estimated to be 55%, which is an optimistic value because it assumes a vertical performance similar to those used for aircraft using lower vertical navigation specifications in similar models even though the fleet that flies simultaneous operations typically has better vertical navigation performance.[24] The radius of the cylinder used to describe the aircraft's volume, λ_{xy}, was 265 ft and the height of that cylinder, λ_z, was 160 ft.[25] The relative lateral speed, V_{rel}, was $\sqrt{2}$ times the groundspeed. The relative vertical speed, $\overline{|\dot{z}|}$, was set to 1.5 knots, which is typical for this model.[26] The probability density function of the along track error, f_A, was the probability density function of a uniform distribution between plus or minus one half of the in-trail density assumed. The probability density function of the cross track error, f_C, was the probability density function of a normal distribution with a mean equal to zero and the standard deviation equal to 0.05447 NM, per the analysis in the TF turn study.[27] The nominal lateral separation, $S_y(t)$, started at a particular distance and decreased linearly as a function of time. It was determined that the initial and terminating distances did not change the results if the values were reasonably large.

With these assumptions, the two variables that are most likely to differ in implementation are the local density of the aircraft and the groundspeed. Table 3-1, in section 3.1.2, shows how the collision risk, given that an incorrect approach selection occurs and the in-trail spacing is insufficient to mitigate it, varies with changes in those assumptions. In summary, the collision risk is fairly high due to the likelihood of the other aircraft being in that location of the intersection. Assuming that flight crews select an incorrect approach procedure at a rate of 10^{-4} to 10^{-6}, the probability of collision if the in-trail spacing does not mitigate the collision risk is above 10^{-5} or 10^{-7}, respectively. Therefore, if the minimum in-trail separation is an effective mitigation (meaning that the in-trail spacing is not violated at a rate greater than 10^{-2} to 10^{-4}), then this case does not contribute substantial risk to the operations.

After determining that the collision risk was above commonly accepted values if the aircraft intersect outside of the intended in-trail spacing required when the EoR aircraft is on final, we needed to determine under what conditions that would occur. To model these conditions, we needed to make some

[24] International Civil Aviation Organization, *Doc 9689-AN/953 Manual on Airspace Planning Methodology for the Determination of Separation Minima*, (First Edition, 1998; Amendment 1, 2002).
[25] 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, 2011).
[26] International Civil Aviation Organization, *Doc 9689-AN/953*.
[27] Flight Technologies and Procedures Division, *DOT/FAA/AFS400/2016/R/01*.

assumptions regarding the design of the approach procedures. EoR operations are intended to be conducted using approach procedures designed with TF fly-by turns or RF turns. TF designs are similar to RF designs with respect to the ground-track flown to the intended landing runways but, due to restrictions on the bank angles of expected TF designs, they would be less likely to include a leg that traverses the airport environment perpendicular to potential landing runways. This type of leg represents a bounding case because it minimizes the amount of time to intersect the intended landing runway's extended centerline. Therefore, a constant RF turn construction with flight paths diverging at the apex of the turn to final is an appropriate case to model. Alternatively, it has been proposed that the paths should diverge while the aircraft are still on the downwind leg. Approaches designed with a given distance between where the intended and selected paths diverge from the downwind leg (with perpendicular leg lengths near the apex of the turn equivalent to the runway separation distance, as in the apex divergent case) represent another fundamental construction for EoR approaches. Appendix F demonstrates that these two constructions also bound all expected TF fly-by designs.

Based on these two procedure paths, we first considered the intended aircraft configuration if the EoR aircraft merged with the straight in traffic as expected. A diagram of this case can be seen in figure 3-2. All of the points of interest fall on the extended runway centerline; therefore, we can mathematically express this as a one dimensional problem. If we call the point where the EoR aircraft merges onto the extended runway centerline zero, then the area where other aircraft are not permitted would be the interval $\{-\mu, \mu\}$ at the moment the EoR aircraft merges into straight-in traffic. The NAS requires most terminal approaches to maintain 3 NM of in-trail spacing between aircraft. However, some airports qualify for 2.5 NM in-trail spacing.[28] Heavy aircraft may require as many as 8 NM in-trail spacing to mitigate wake vortex encounters. This analysis assumed a range of values between 2 NM and 3 NM to accommodate for potential future reductions in required in-trail spacing.

Sufficient in-trail spacing between EoR and straight-in aircraft must be planned to allow successful merging of traffic. Doing so properly creates gaps in the straight-in traffic flow. Controllers intentionally design those gaps using speed controls and vectoring. With some assumptions and geometry, we can estimate where that gap would be at the time of the intersection, see figure 3-2.

[28] Air Traffic Organization, *Air Traffic Control Order 7110.65W* (U.S. Department of Transportation, 2015).

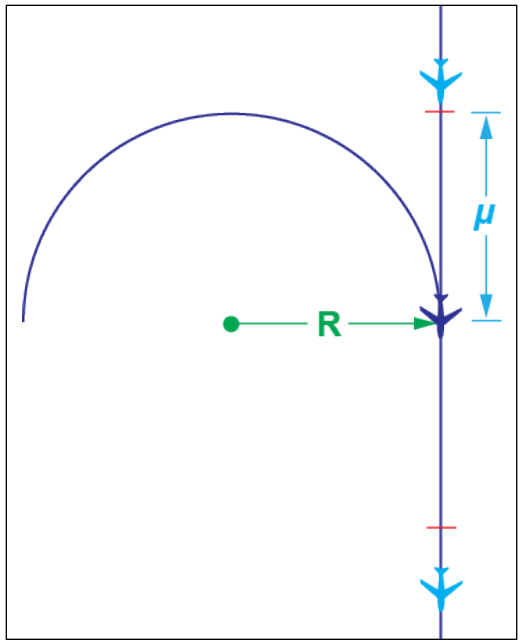
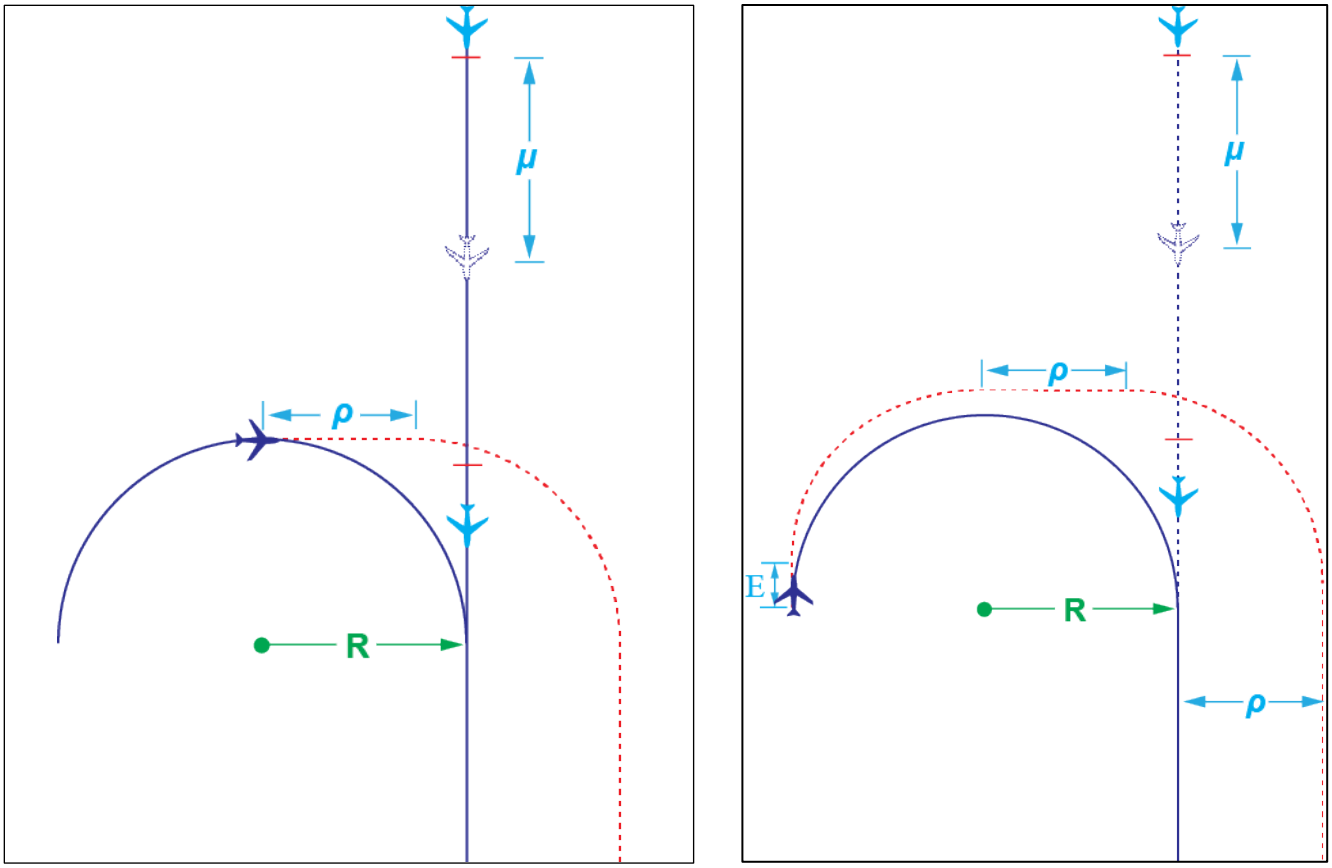


Figure 3-2: EoR Approach Merging with Straight-In Approach

We assumed that the aircraft were traveling at a constant groundspeed over the interval of time in question. If we calculate the distance along the EoR path from the time that the aircraft is at the final roll-out point to the time where the aircraft deviates from the approach, $\pi \times R$, we can divide this value by the average groundspeed of the EoR aircraft, V_{EoR}, to estimate the time distance. If we then multiply this value by the groundspeed of each aircraft on the extended runway centerline, V_S, and add it to the interval when the EoR aircraft should have merged, we know the position of the gap at the moment that the paths diverge:

$$\left\{-\mu + \left(\frac{(\pi \times R)}{V_{EoR}}\right) \times V_S, \quad \mu + \left(\frac{(\pi \times R)}{V_{EoR}}\right) \times V_S\right\} \tag{3}$$

This geometry is easy to visualize using figure 3-3. The red dashed line represents the incorrectly selected approach and the white aircraft is the position where the EoR aircraft is intended to merge into existing traffic.



(a) Common Apex **(b) Varied Downwind Lengths**

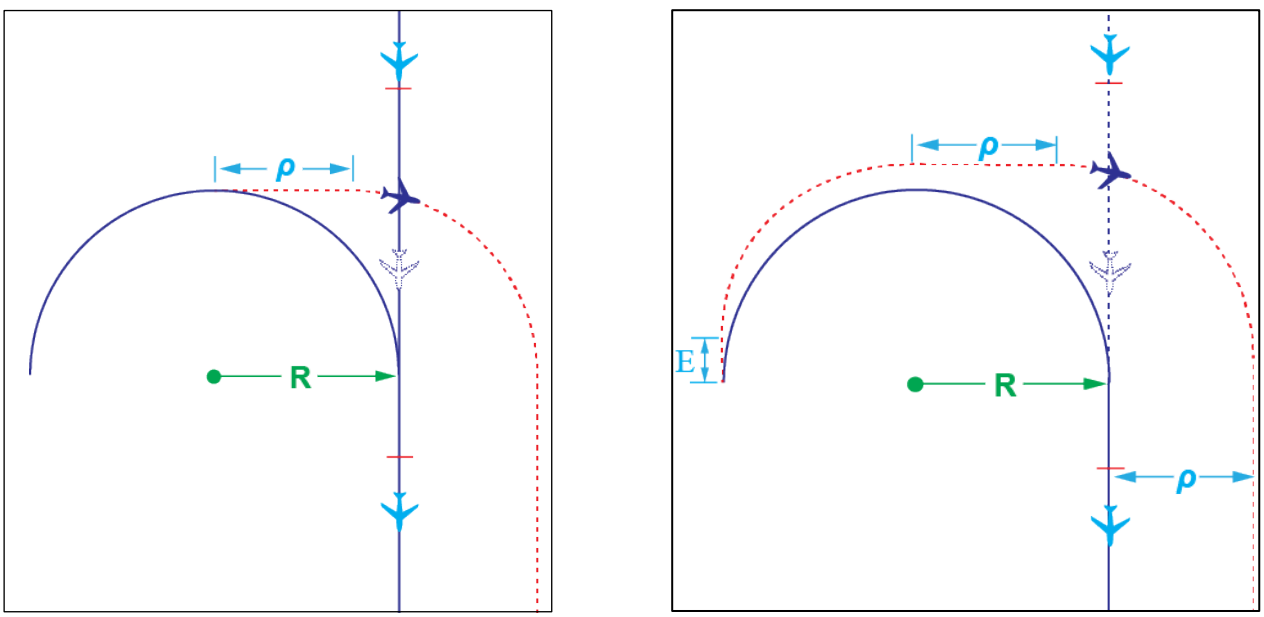
Figure 3-3: Incorrect Approach Selected

The interval's location at the time of intersection requires moving the interval in the opposite direction, towards the runways, based on the amount of time that it takes the EoR aircraft to fly from its position in figure 3-2 to the location of the intersection, as seen in figure 3-3. When the runway spacing is greater than or equal to the turn radius, the distance traveled by the EoR aircraft is equal to the sum of the differences in length between the downwind paths, E, the length of the quarter circle used to fly to the base leg, $(\pi/2) \times R$, and the turn radius, R. Otherwise, the distance from the apex of the turn to the path intersection (R in the previous discussion) must be slightly increased to account for the path curvature. To account for this, we considered the triangle formed by the point of intersection, the final roll out point of the intended approach, and the center of the incorrect approach turn. The portion of the circle turn that occurs after the intersection is the arccosine of the turn to the bottom edge of the triangle, which is the length of the turn radius minus the runway spacing divided by the hypotenuse of the triangle, which is also the turn radius. Subtracting this angle from the quarter turn starting at the apex and ending at the final approach course and multiplying by the turn radius yields the amount of time spent in the turn before the intersection. Adding this to the straight portion of the path, which is equal to the runway spacing, yields the corrected path length. This can be divided by the EoR aircraft's groundspeed then multiplied by the straight-in aircraft's groundspeed to determine the distance traveled by the straight-in aircraft. Note that in equation 4, we can substitute V_S/V_{EoR} with a single variable for

the relative groundspeed. This modifies the model context by allowing us to assume that the relative groundspeeds are constant rather than assuming that each absolute groundspeed is constant. The interval at the point of intersection is:

$$\text{Protected Interval} = \begin{cases} \left\{-\mu + \left(\frac{(\pi\times R)-\left(\mathrm{E}+\left(\frac{\pi}{2}\times R\right)+R\right)}{V_{EoR}}\right)\times V_S,\quad \mu + \left(\frac{(\pi\times R)-\left(\mathrm{E}+\left(\frac{\pi}{2}\times R\right)+R\right)}{V_{EoR}}\right)\times V_S\right\} & \rho > R \\ \left\{\begin{array}{l} -\mu + \left(\frac{(\pi\times R)-\left(\mathrm{E}+\left(\frac{\pi}{2}\times R\right)+\left(R\times\left(\frac{\pi}{2}-\cos^{-1}\left(\frac{R-\rho}{R}\right)\right)\right)+\rho\right)}{V_{EoR}}\right)\times V_S, \\ \mu + \left(\frac{(\pi\times R)-\left(\mathrm{E}+\left(\frac{\pi}{2}\times R\right)+\left(R\times\left(\frac{\pi}{2}-\cos^{-1}\left(\frac{R-\rho}{R}\right)\right)\right)+\rho\right)}{V_{EoR}}\right)\times V_S \end{array}\right\} & \rho \le R \end{cases} \tag{4}$$

If the point of intersection falls within the interval as shown in figure 3-4, a collision is not possible unless the controller erroneously sets up a traffic sequence that violates the in-trail spacing requirements or some other major failure occurs.



(a) Common Apex **(b) Varied Downwind Lengths**

Figure 3-4: Interval at the Point of Intersection

The location of the intersection relative to the final roll out point is the turn radius if the runway spacing is greater than the turn radius, and equal to a corrected distance if the runway spacing is less than the turn radius. This corrected distance can be calculated by applying the Pythagorean Theorem to the same triangle described for the distance traveled to intersection equation.

$$\text{Intersection} = \begin{cases} R + \text{E} & \rho > R \\ \text{E} + \sqrt{R^2 - (R - \rho)^2} & \rho \leq R \end{cases} \tag{5}$$

3.1.2 Results

Using the collision risk model described in section 3.1.1, we calculated a variety of collision risk values for an orthogonal intersection with varying aircraft densities and groundspeeds. Regardless of the variables selected, all possible collision risk values indicated that the probability of collision given an incorrect approach procedure when the intersection occurs outside of the anticipated along-track spacing interval is greater than 10%, see table 3-1. Considering the frequency of incorrect approach, this would result in a collision risk between 10^{-7} and 10^{-5} for those operations. Thus, geometries that could result in a same-path intersection without the intersection occurring within the anticipated along-track scaling interval present a collision risk between 10^{-7} to 10^{-5}.

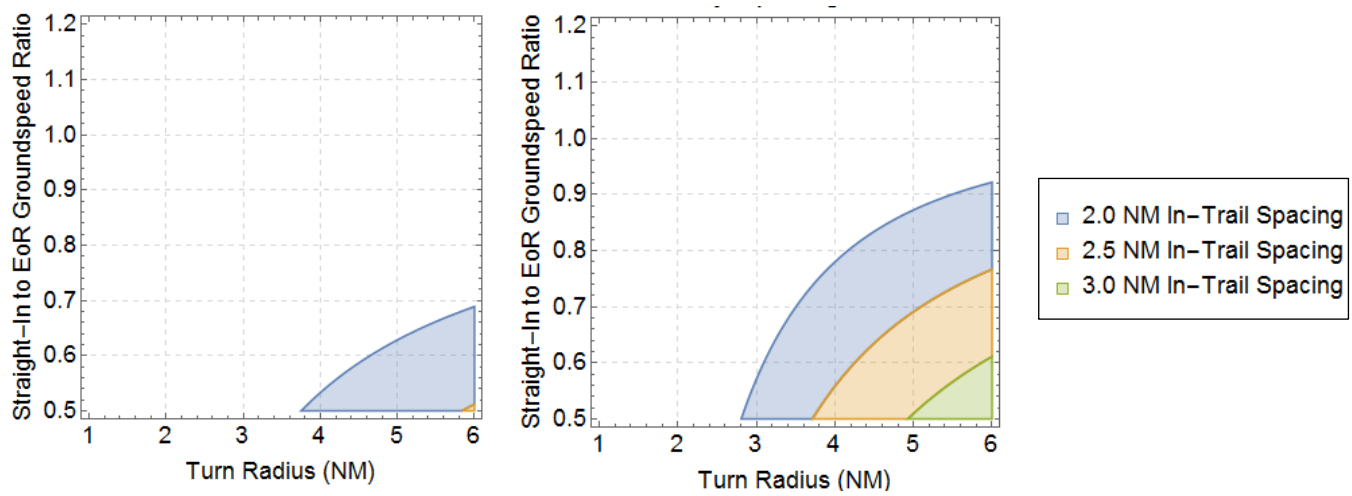
Table 3-1: Case 1 Collision Risk without Controller Spacing

Groundspeed	Along-Track Aircraft Density		
	2 aircraft per NM	**1.0 aircraft per NM**	**1 aircraft per 1.5 NM**
170 kts	0.273587	0.136794	0.091196
210 kts	0.273168	0.136584	0.091057
250 kts	0.272883	0.136442	0.090961
290 kts	0.272676	0.136339	0.090892

Once we identified that airspace geometries that could result in an intersection have significant collision risk, we needed to inform which geometries could result in an intersection. This determination was based on a comparison of the point of intersection to an in-trail spacing interval. This is described in equations 4 and 5 in section 3.1.1. This inequality is a function of runway spacing, turn radius, downwind length distance, minimum in-trail spacing requirements, and the groundspeeds of aircraft on either path. The wider runway spacings are more likely to result in an unprotected intersection; therefore, we used 9000 ft because it is the widest runway spacing that requires a final monitor for EoR and 16,000 ft because it is a runway spacing greater than those we would anticipate at representative airports in the NAS. For visualization, we replaced the individual aircraft groundspeeds with the ratio of the groundspeeds. This means that 0.7 on the y-axis indicates that the straight-in aircraft is going 70% of the speed of the EoR aircraft. As mentioned above, the in-trail separations evaluated were between 2 NM and 3 NM. Turn radii evaluated included values from 1 NM, which represents a lower bound, and 6 NM, which is the largest that we believed would be considered operationally acceptable.

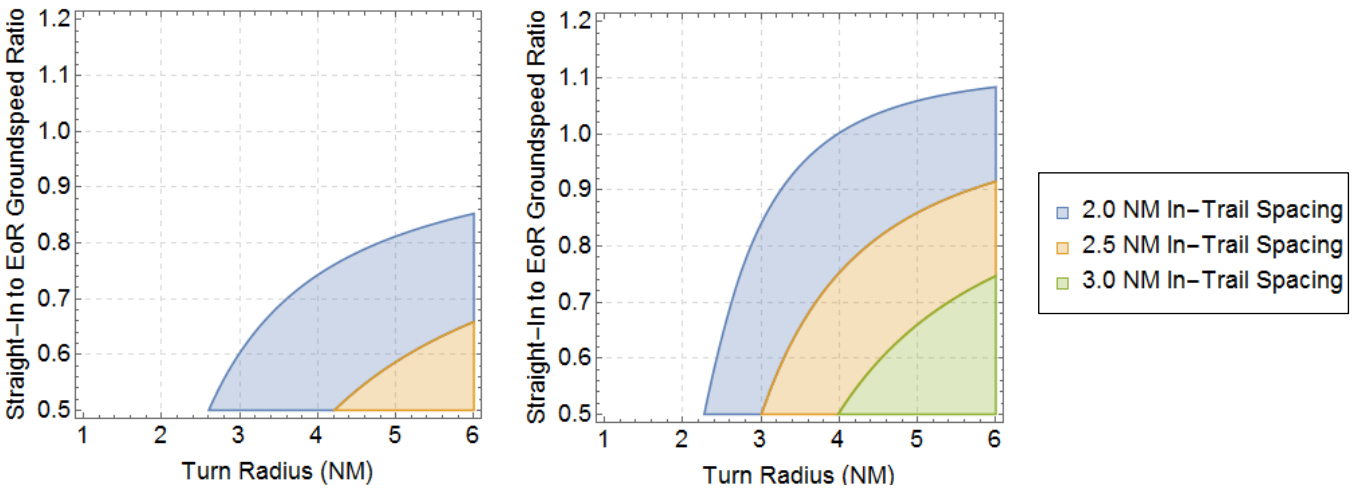
In conclusion, if approach procedures are designed with typical turn radii and the straight-in traffic is flying approximately the same speed as the EoR aircraft when the turns diverge at the apex, case 1 does not pose significant collision risk as shown in figure 3-5 (a) and (b). If in-trail spacing on the straight-in approach is reduced below 2.5 NM at any facility, this conclusion may need to be re-evaluated. Figure 3-5 (c) through (h) demonstrates that increasing the downwind length difference rapidly erodes the safety margin provided by the in-trail spacing for the EoR aircraft. When the in-trail spacing mitigation erodes, intervention by air traffic will need to mitigate the collision risk prior to any FMA

alert. Although the controller-initiated response distributions were collected during operations with an FMA, the response times collected from human-in-the-loop experimentation suggest that approximately 50 seconds would be sufficient to prevent crossing this traffic prior to the apex of the turn, see section 3.4.



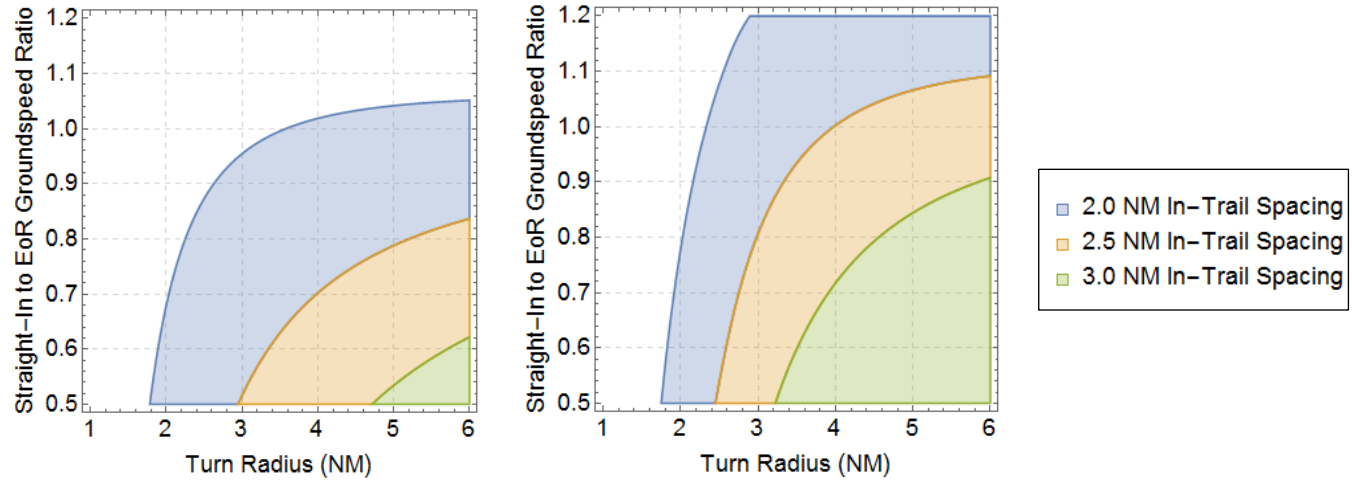
(a) Common Apex; Runway Spacing: 9000 ft

(b) Common Apex; Runway Spacing: 16,000 ft



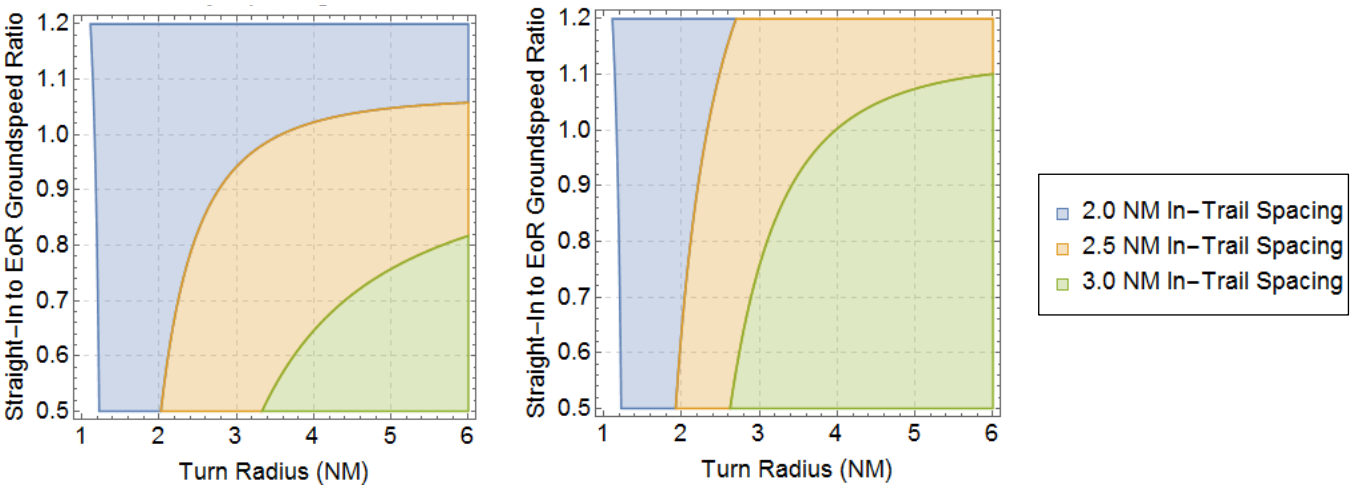
(c) Downwind Length Δ: 0.25 NM; Runway Spacing: 9000 ft

(d) Downwind Length Δ: 0.25 NM; Runway Spacing: 16,000 ft



(e) Downwind Length Δ: 0.5 NM; Runway Spacing: 9000 ft

(f) Downwind Length Δ: 0.5 NM Runway Spacing: 16,000 ft



(g) Downwind Length Δ: 0.75 NM; Runway Spacing: 9000 ft

(h) Downwind Length Δ: 0.75 NM Runway Spacing: 16,000 ft

Figure 3-5: Conditions Where the In-Trail Spacing Does Not Prevent a Case 1 Collision

3.2 Case 2: Merge with Landing Runway Traffic

For case 2, we evaluated the collision risk between an aircraft flying an incorrect approach and the aircraft flying to the same runway. This case would occur in any geometry where the flight crew could select an approach procedure that flies to an active arrival runway. This case is different from the previous case for several reasons:

- Rather than a point of intersection with all of the collision risk occurring during a very short period of time, this case is characterized by two flight paths merging together, as seen in figure 3-6. Thus collision risk increases at a less than linear rate during the early stages of aircraft path merging, then increases linearly after the two aircraft paths fully merge.

- For case 1, the primary mitigation was the in-trail spacing required to accommodate the EoR aircraft's merge into the traffic to the intended landing runway. For case 2, the primary collision risk mitigation was the controller in the final monitor position.
- This case can assume that the positions of the aircraft are independent, meaning that the local along-track aircraft density used in the collision risk model is lower than in the previous case.

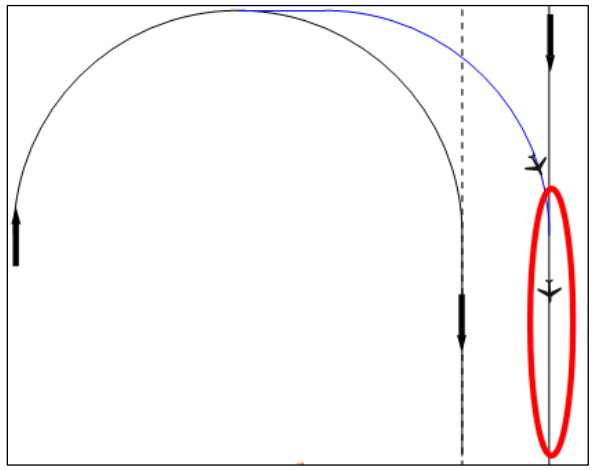


Figure 3-6: Merge with Landing Traffic

The risk of losing wake separation may be considerable under some circumstances in this case. It is evaluated in the following sections.

3.2.1 Collision Risk Methodology

Before addressing other components of the equation, we first modeled the aircraft-to-aircraft midair collision risk as a function of time. Fortunately, much of this work was similar to the normal performance assessment completed for the TF turn study nominal case. As with that case, we described what the separation between the two aircraft would be as a function of time. These equations were based on a constant radius turn from the apex to the final approach course as a reasonable approximation of sequential TF fly-by turns for normal collision risk. EoR operations are simultaneous independent approaches and, therefore, the dependent spacing is uniformly distributed across the 2.5 NM or 3 NM along-track spacing interval. The lateral separation can be described by equation 6:

$$S_y(t) = \begin{cases} R - \sqrt{R^2 - \left(R - S_x(t)\right)^2} & 0 \le t \le \dfrac{\pi \times R}{2 \times V} \\ 0 & t > \dfrac{\pi \times R}{2 \times V} \end{cases}$$

$$S_x(t) = \begin{cases} R - R\cos\left(\dfrac{V \times t}{R}\right) & 0 \le t \le \dfrac{\pi \times R}{2 \times V} \\ V\left(t - \dfrac{\pi \times R}{2 \times V}\right) + R & t > \dfrac{\pi \times R}{2 \times V} \end{cases} \tag{6}$$

where R is the turn radius in NM, V is the groundspeed in knots, t is the time from the apex of the turn in hours, $S_y(t)$ is the lateral separation at time t in NM, and $S_x(t)$ is the distance travelled along the extended runway centerline at time t in NM.

When we assume that the position error can be represented as a symmetric binormal distribution, that the probability of vertical overlap is fixed at 73% which represents a conservative assumption based on the EoR TF HITL data, and that there is only one pairing of aircraft that should significantly contribute to collision risk, the modified collision risk model can be expressed as seen in equation 7.

$$CR(T) = 4.58673\lambda_{xy}{}^2 \left(\frac{\overline{|\dot{z}|}}{2\lambda_z} + \frac{2V_{rel}}{\pi\lambda_{xy}}\right) \int_0^T \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_A(a)^2 \, f_C(c) \, f_C\left(c + S_y(t)\right) dc \, da \, dt \tag{7}$$

In the above equation, λ_{xy} is the radius used to model the aircraft laterally in NM, while λ_z is the height used to model the aircraft vertically. $\overline{|\dot{z}|}$ is the relative vertical velocity at the time of lateral overlap in knots, while V_{rel} is the relative lateral velocity at the time of vertical overlap in knots. f_A is the probability density function of the along-track error, which is a uniform distribution from either -1.25 NM to 1.25 NM or -1.5 NM to 1.5 NM. f_C is the probability density function of the cross-track error, which is a normal distribution with a mean of 0 and a standard deviation of 0.05447.

Using this mathematical collision risk model, we calculated the midair collision risk values for the flight crew continuing to fly the incorrect approach procedure to touchdown by setting T equal to the time spent in the turn $(\pi \times R)/(2 \times V)$ plus the amount of time spent on the final approach path, which is the length of the final approach path divided by the groundspeed, see figure 3-15 in section 3.2.3 and tables E-6 through E-9 in appendix E. Without other mitigations, collision risk values given an incorrect approach selection vary between 9% and 59%. With incorrect approach selection rates between 10^{-4} and 10^{-6}, it is necessary to consider collision risk mitigations.

In the TF turn study, collision risk modeling included the probability that the flight crew would mitigate a collision regardless of controller intervention. In the incorrect approach selection case, there is the analogous event associated with a pilot either recognizing on their own accord that they have input the incorrect approach procedure after they made the initial input error, or some situational awareness cue that triggered a response based on some alert or display, such as Traffic Alert and Collision Avoidance System. Unfortunately, minimal data has been collected that helps describe the reaction time for this type of correction, so it was not feasible to model it without an additional HITL experiment.

For this operation, there is a requirement for controllers at the terminal approach control facility to monitor aircraft flying these approaches using a high resolution, color monitor that is equipped with alerting algorithms, such as the FMA in the standard terminal automation replacement system, at runways spacings less than 4300 ft for dual runway operations and 5000 ft for triple runway operations. In this case, a controller would receive an aural and visual alert when the aircraft that selected the incorrect approach procedure was predicted to enter the NTZ within the next 10 seconds. Around the time of the aural alert, the monitor controller should override the tower frequency and contact the deviating aircraft, instructing the aircrew to return to the correct approach course. At the same time, a separate monitor controller should contact any other aircraft put at risk by the deviating aircraft, instructing them to take evasive maneuvers.

Based on this monitoring, it is reasonable to expect that a controller will intervene in the event of an incorrect approach selection after some amount of time. The controller will do so by either instructing the deviating aircraft to return to the correct final approach course or by providing breakout instructions to the deviating or victim aircraft. In either case, we can consider the collision risk to stop accumulating past a certain point in the function described above. To account for this, we adjusted the bounds of integration within the collision risk equation. To further simplify the problem, we broke the integration into a sum of two integrals: before and after the paths merge completely. While the integral before the merge must be calculated numerically, the integration after the merge simplifies after applying all of the values defined in equation 7, except the aircraft density along the path which we retained as a variable to accommodate the variance between facilities. The result of this simplification can be seen in equation 8. Figure 3-7 shows how the collision risk changes as the aircraft flies along the approach procedure.

$$CR_{simplified}(T) = \begin{cases} CR(T) & T < \dfrac{\pi \times R}{2 \times V} \\ CR\left(\dfrac{\pi \times R}{2 \times V}\right) + \dfrac{21.0731 \times \left(T - \dfrac{\pi \times R}{2 \times V}\right)}{\mu} & T \geq \dfrac{\pi \times R}{2 \times V} \end{cases} \tag{8}$$

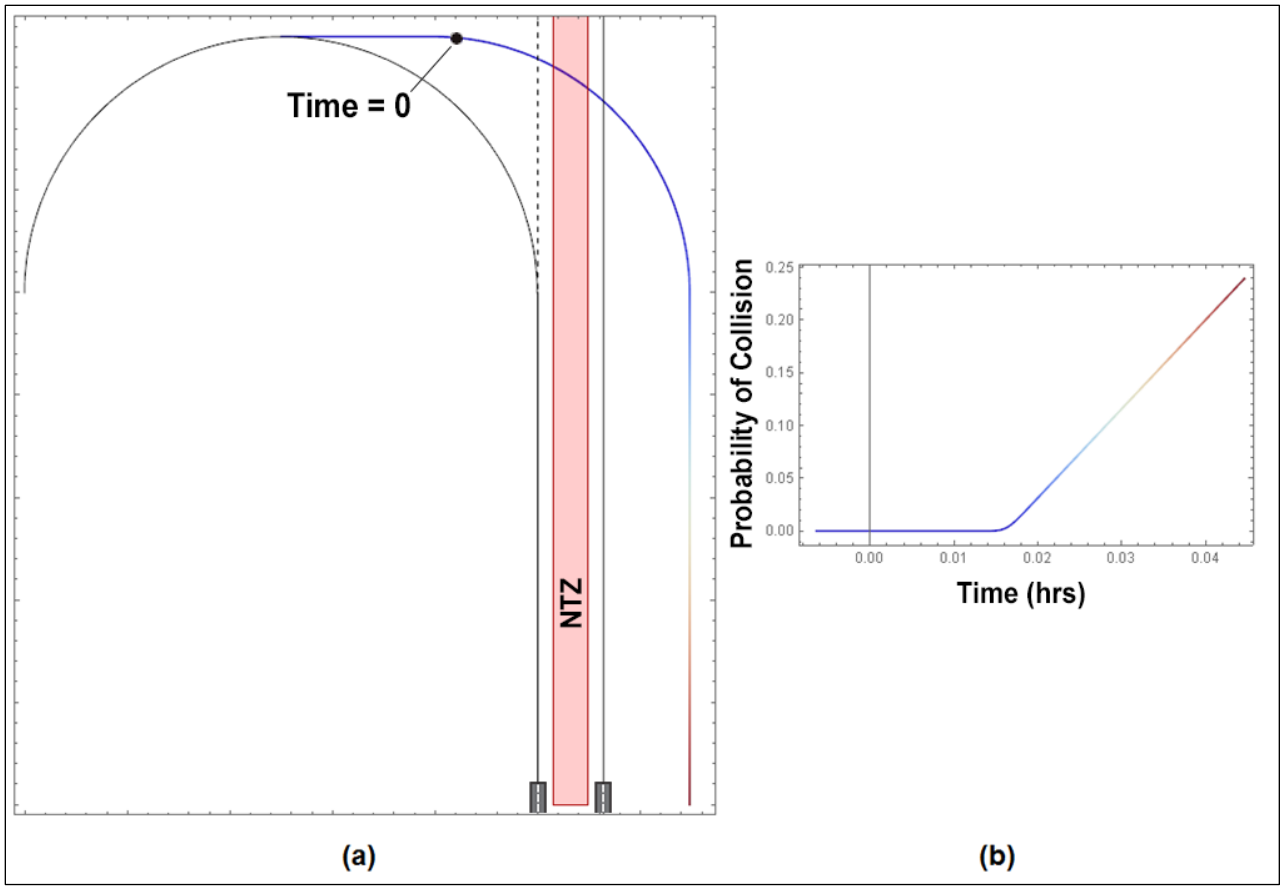


Figure 3-7: Probability of Collision

Next, we determined how long controllers delayed before intervening in an incorrect approach selection situation and, once they intervened, how long it took for pilots to enact that guidance. During the TF turn study HITL experiment that collected response time information from controllers, we collected data on a scenario where an aircraft flew the incorrect approach procedure during a TF turn EoR operation. We also collected pilot response time data from 28 flight crews across 3 different full-flight aircraft simulators for an event where non-subject controllers issued an evasion command to the flight crews. If we assume that controller-initiated pilot correction and controller-initiated evasion responses are similar, we can use these two datasets to develop a statistical model to determine how long it takes for controllers and pilots to mitigate the incorrect approach procedure selection scenario. The development of this model and associated sensitivity analysis can be found in section 3.4.

Although the data was collected using flight procedures constructed with TF fly-by turns, the approach procedure for this case was modeled as a constant RF turn from the apex of the turn to the final approach course. Any turn construction that traverses the airport environment perpendicular to extended final approach provides the least amount of time to intervene, see figure 3-8. We anticipate TF fly-by procedures will avoid this configuration, and we believe approach procedures designed with RF legs are the most likely candidates for including a perpendicular leg. Therefore, the constant RF turn from the apex of the turn to the final approach course with a perpendicular leg to traverse to the incorrectly selected approach runway extended centerlines represents the worst-case risk scenario and it is most suitable for analysis.

The response times are all relative to the time of the FMA caution alert. This alert occurred when the FMA predicted that the aircraft would enter the NTZ within the next 10 seconds. Although there is some variation in the time of the FMA caution alert relative to the approach geometry due to radar errors, the time of the alert can be estimated deterministically. Due to the complexity of modeling the radar errors based on different radar configurations, we assumed that the FMA alerts the controller at a theoretical time based on the same airspace geometry assumptions. The estimate is described in equation 9 and its derivation explained in figure 3-8.

$$Time\ from\ Apex\ of\ Turn\ to\ FMA\ Caution \coloneqq \tau$$

$$= \begin{cases} \dfrac{\left(\left(\frac{\pi}{2} - \theta - \varphi\right) \times R\right)}{V} & L + \left(V * \dfrac{\nu}{3600}\right) < R \\ \dfrac{R - L}{V} - \dfrac{\nu}{3600} & L + \left(V * \dfrac{\nu}{3600}\right) \geq R \end{cases}$$

$$L = \left(\frac{2000}{6076.115}\right) + \frac{\rho_{Nearest} - \left(\frac{2000}{6076.115}\right)}{2} + \left(\rho_{Landing} - \rho_{Nearest}\right) \tag{9}$$

$$\varphi = \cos^{-1}\left(\frac{R - L}{\sqrt{\left(V * \frac{\nu}{3600}\right)^2 + R^2}}\right)$$

$$\theta = \tan^{-1}\left(\frac{V \times \nu}{R \times 3600}\right)$$

In equation 9:

- R is the turn radius;
- V is the groundspeed;
- $\rho_{Nearest}$ is the runway spacing between the intended runway and the nearest intermediate runway in nautical miles;
- $\rho_{Landing}$ is the runway spacing between the intended runway and the landing runway for the incorrectly selected approach in nautical miles;
- θ is the amount of turn between where the path intersects the NTZ and the aircraft rolls onto final in radians;
- φ is the amount of turn from the estimated time of the FMA caution alert to the time that the aircraft enters the NTZ in radians;
- (2000/6076.115) is the width of the NTZ in nautical miles;
- π/2 is the amount of turn from the apex of the turn to rolling out on final in radians;
- ν is the number of seconds that the aircraft position is predicted forward for the FMA caution alert; and
- 3600 is the number of seconds in an hour.

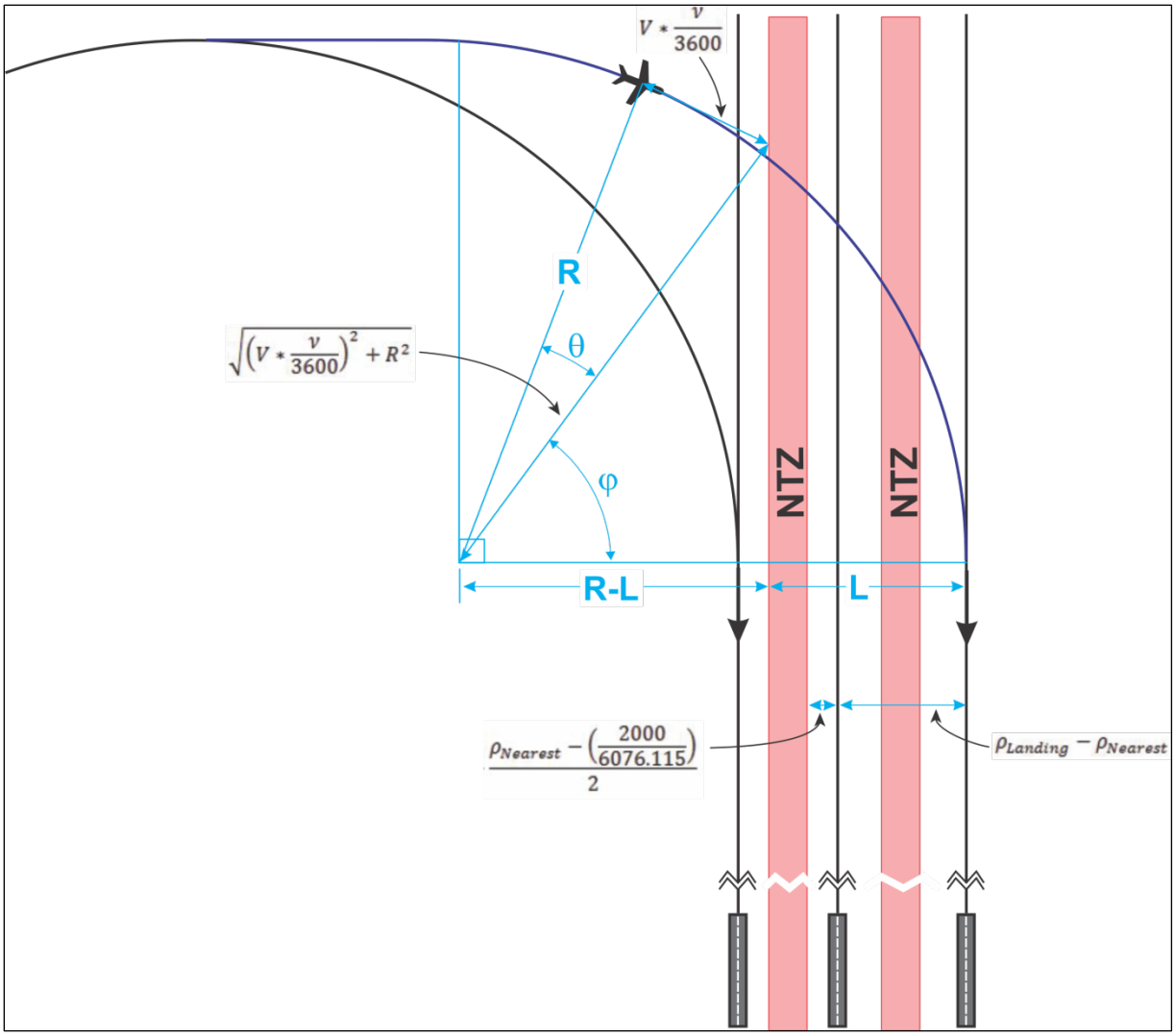


Figure 3-8: Aircraft Penetration of the NTZ

If we use an input value of 10 seconds for the predictor length, there are two delays to the reaction time that we could account for by directly extending the reaction time. The first delay is the amount of time from when the aircraft violates the NTZ airspace to when the automation system provides the FMA caution alert (which is associated with the surveillance system update rate and automation platform processing time). The second delay is the amount of time from when the flight crew initiated the breakout (i.e. achieved a bank of 7.5° or 12.5°, respective to the flight management computer TF logic, see appendix D) to when the collision risk became negligible.

The first delay should range between approximately 2.2 and 7.5 seconds.[29] A deviation correction should take roughly 5 to 10 seconds before adequate separation is established. Therefore, we summed

[29] Federal Aviation Administration, *NAS-RD-2013 National Airspace System Requirements Document*, (U.S. Department of Transportation, 2014).

these two delays and modeled them from the minimum value of 7.2 seconds to the maximum value of 17.5 seconds with a uniform distribution. Rather than model the decreasing risk as separation increases, it is conservative to include all of the collision risk until the aircraft fully corrects its deviation and returns to the approach path.

Using the more conservative distribution, we are able to determine the likelihood that the aircraft is on the approach path at any given time. For an example with 3600 ft runway spacing, 2.5 NM turn radius, 200 knot groundspeed, and the minimum delay of 7.2 seconds, see figure 3-9.

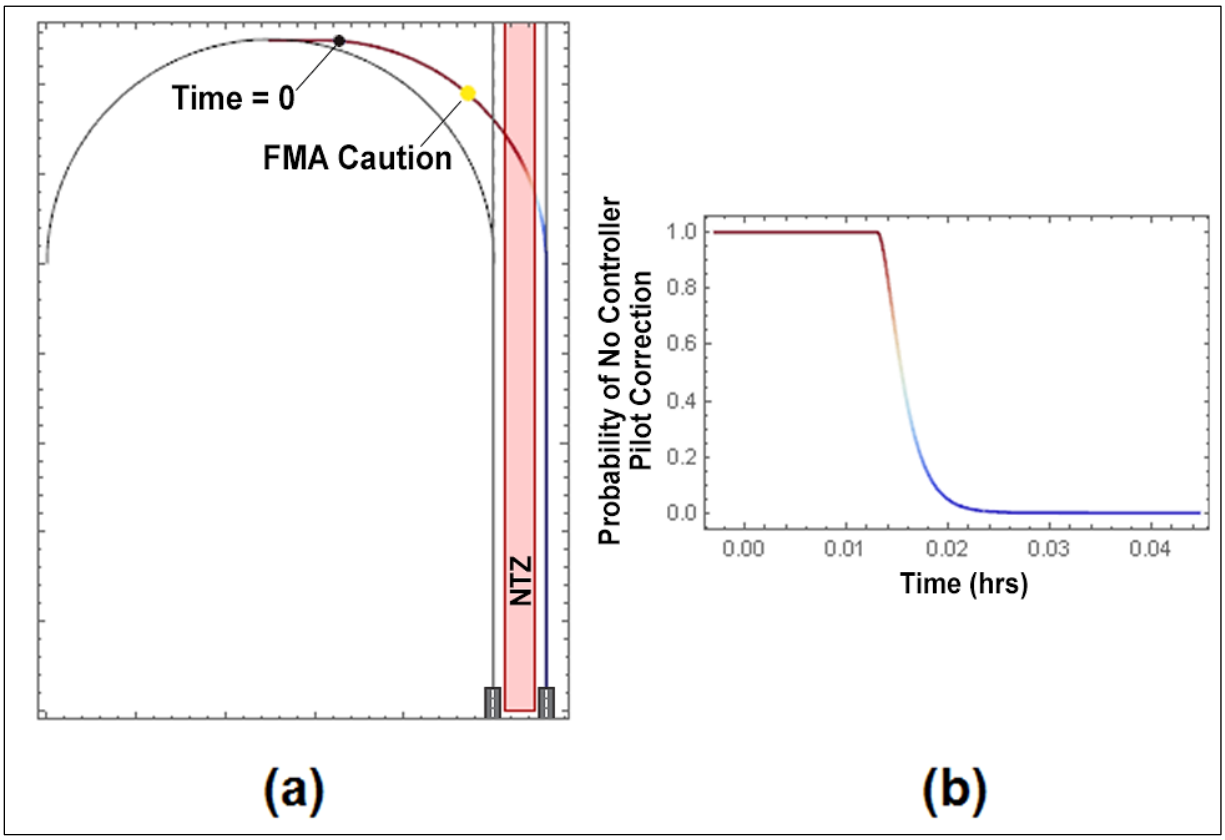


Figure 3-9: Probability of No Controller Pilot Correction

Having developed the probability that an aircraft experiences a collision given the amount of time that they stay on the approach and the probability that controller intervention removes one or both aircraft from the flight path by a given time, we calculated the probability of collision by multiplying those two functions, applying the definition of conditional probability for each time, then integrating over time. This is equivalent to multiplying the function in figure 3-7 (b) with the function in figure 3-9 (b), to yield the function in figure 3-10 (b). This function is then integrated over all possible times to get the full collision risk. Figure 3-10 (a) shows how the function applies to the approach path.

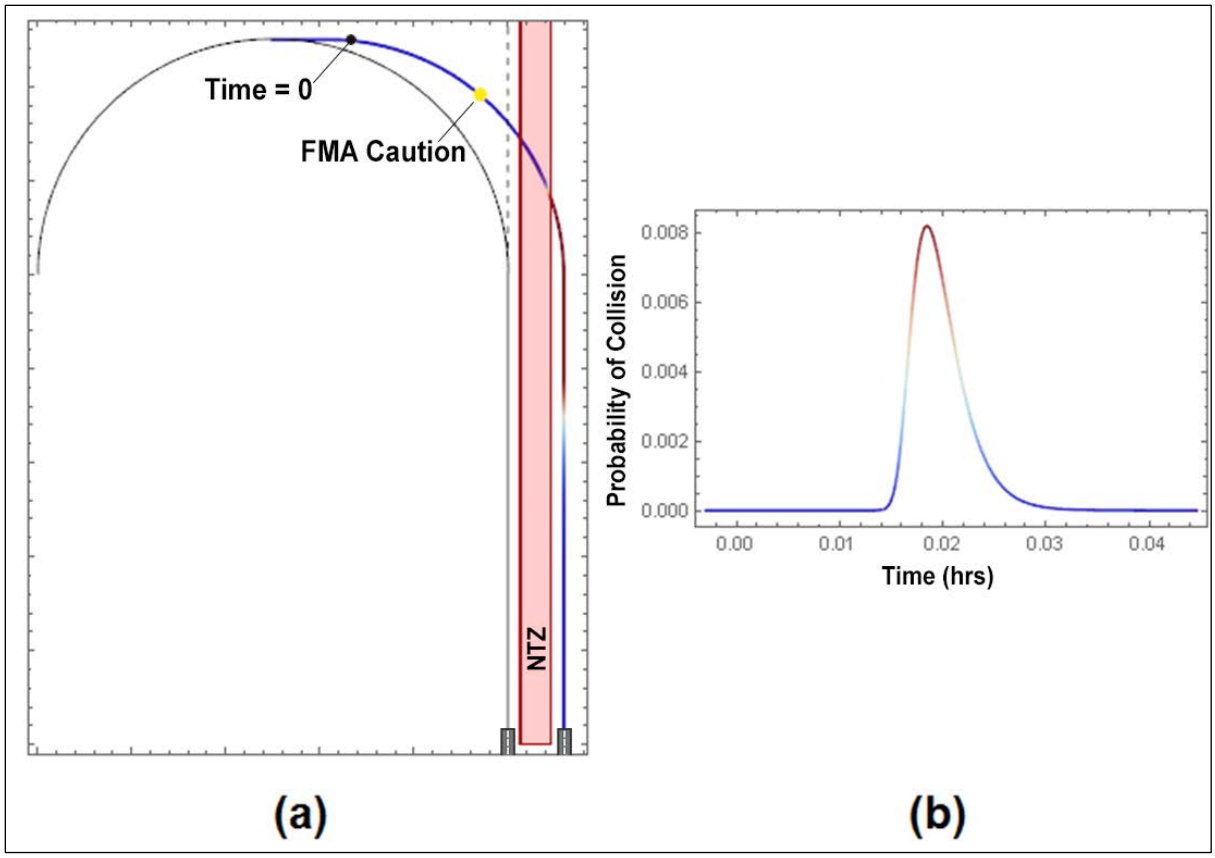


Figure 3-10: Probability of Collision

Since the calculation of the collision risk is numerical, we integrated it for each second of the approach and then interpolated those results into a function which was multiplied by the reaction time survival function for numerical integration. These integrated results indicated the probability of collision given the selection of an incorrect approach. We then converted the results to indicate a probability of collision by multiplication with the probability of selecting an incorrect approach, which is considered to be within the range 10^{-4} and 10^{-6}. To facilitate understanding the impact of each input parameter, a one-factor-at-a-time sensitivity analysis was performed on this model, see appendix A.

3.2.2 Wake Separation Loss Risk Methodology

Coordination with the wake vortex research team in Research and Development Integration Division (ANG-C2) and the chief scientific and technical advisor to the FAA for wake turbulence indicated that a thorough wake analysis would require a collection of empirical data. This represents a substantial effort and, therefore, the wake analysis here informs whether data collection would be required to support airspace designs that include the possibility of merging traffic due to an incorrect approach selection.

Based on historical data, the FAA typically does not require wake vortex encounter risk analysis for simultaneous independent parallel approaches to runways spaced greater than 2500 ft. Therefore, if the aircraft flying along an incorrect approach made a correction before getting within 2500 ft of the adjacent track, the simultaneous lateral wake separation would not be violated. In practice, aircraft do

not arrive at an airport at the minimum in-trail wake separation sequentially. In reality, then, it would be possible to lose 2500 ft lateral wake separation and the aircraft may still have in-trail wake separation. However, typical assumptions for terminal separation standard analysis assume maximum aircraft density on the parallel tracks. With this assumption, any loss of the 2500 ft lateral wake separation requirement would result in a loss of wake separation. This can be visualized as a region around the adjacent track that, if entered, guarantees a wake separation loss with the maximum aircraft density assumption, see figure 3-11.

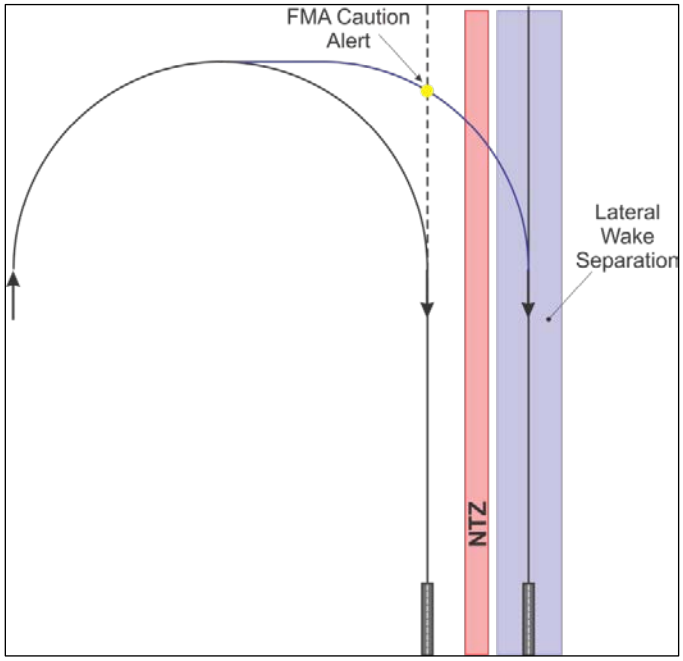


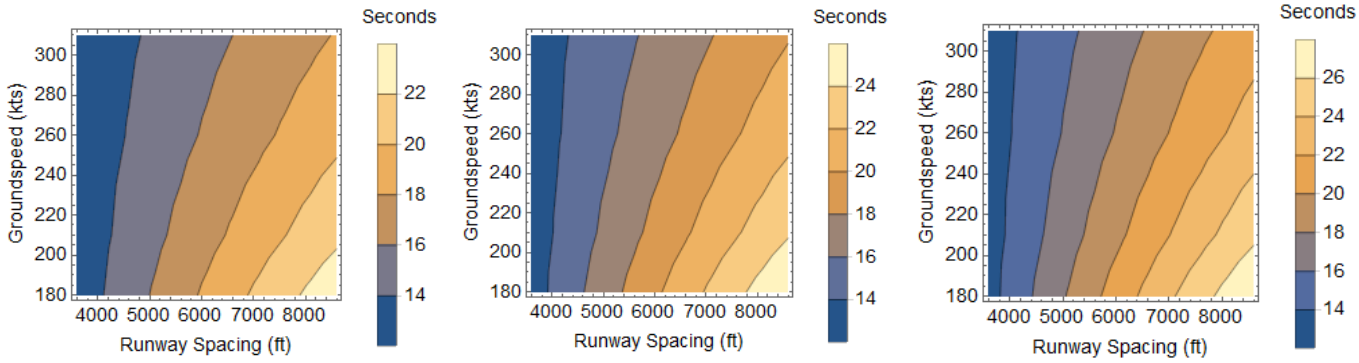
Figure 3-11: Wake Separation Loss Region

The time that the region would be entered by an aircraft flying an incorrect approach to the nearest adjacent runway can be given by the following equation:

$$Wake\ Separation\ Loss\ Time = \begin{cases} R\left(\frac{\pi}{2} - \cos^{-1}\left(\frac{D}{R}\right)\right)\Big/_{V} & R > 2{,}500\ ft \\ D\big/_{V} & R \leq 2{,}500\ ft \end{cases} \tag{10}$$

$$D = R - (2{,}500\ ft\ Lateral\ Wake\ Separation)$$

Based on the difference between equation 9 and equation 10, the amount of time available for aircraft to resolve an incorrect approach selection varies between approximately 12.5 seconds and 28 seconds, see figure 3-12 and table E-1 in appendix E. This amount of time is then integrated against the response distributions, see section 3.4.



(a) Turn Radius: 2 NM **(b) Turn Radius: 3 NM** **(c) Turn Radius: 4 NM**

Figure 3-12: Time Available for Air Traffic Intervention before Wake Separation Violation

3.2.3 Results

From preliminary analysis, it was clear that the length of the final approach did not change the collision risk; therefore, it was not varied to calculate these results. Furthermore, the analysis in section 3.3 shows that scenarios involving transitions that cross multiple runways to land at the opposite side of the airport from the downwind introduce significantly increased risk due to potential collisions with aircraft arriving to the center runway(s). For this reason, we will only include the subset of cases that include transitions from the downwind to the nearest inboard runway in figures 3-13 and 3-14. This is equivalent to setting the nearest runway spacing equal to the incorrectly selected runway spacing. Any triple runway configuration with an equivalent spacing between the intended runway and the selected runway would have lower collision risk because the NTZ would be centered between the intended runway and an intermediate runway, which would cause the FMA caution alert to occur earlier. Based on the variable reduction above, there are five remaining input parameters: delay, runway spacing, turn radius, groundspeed, and in-trail spacing. Furthermore, the results of the model must be multiplied by the rate of incorrect approach selection for the result to be meaningful. For the following data presentation, we plotted the two most common in-trail spacings as two sets of images: 2.5 NM and 3.0 NM. We assumed that the delay was uniformly distributed over the plausible range. Furthermore, we leveraged the relationship between groundspeed and turn radius. For smaller turn radii, we know that the maximum groundspeed cannot exceed a certain value based on procedure design criteria. Therefore, we assumed the maximum groundspeed for small turn radii. However, the assumed groundspeed was not permitted to exceed the maximum plausible value, which was set to 310 knots. We generated three subplots based on the range of assumed incorrect approach selection: 1×10^{-4}, 1×10^{-5}, and 1×10^{-6}. This leaves only turn radius and runway spacing for input parameters, which were plotted using a contour plot, see figures 3-13 and 3-14.

Other conclusions from the above analysis show that some variables increase collision risk as they increase, such as delay and groundspeed, and others reduce collision risk as they increase, such as runway spacing and turn radius. Turn radius, however, influences the collision risk in a complex way. At smaller turn radii, high groundspeeds are not possible, which mitigates some of the risk associated with the small turn radius. Beyond a certain turn radius, however, the conflict between these variables is no longer visible in the chart due to the maximum assumed groundspeed.

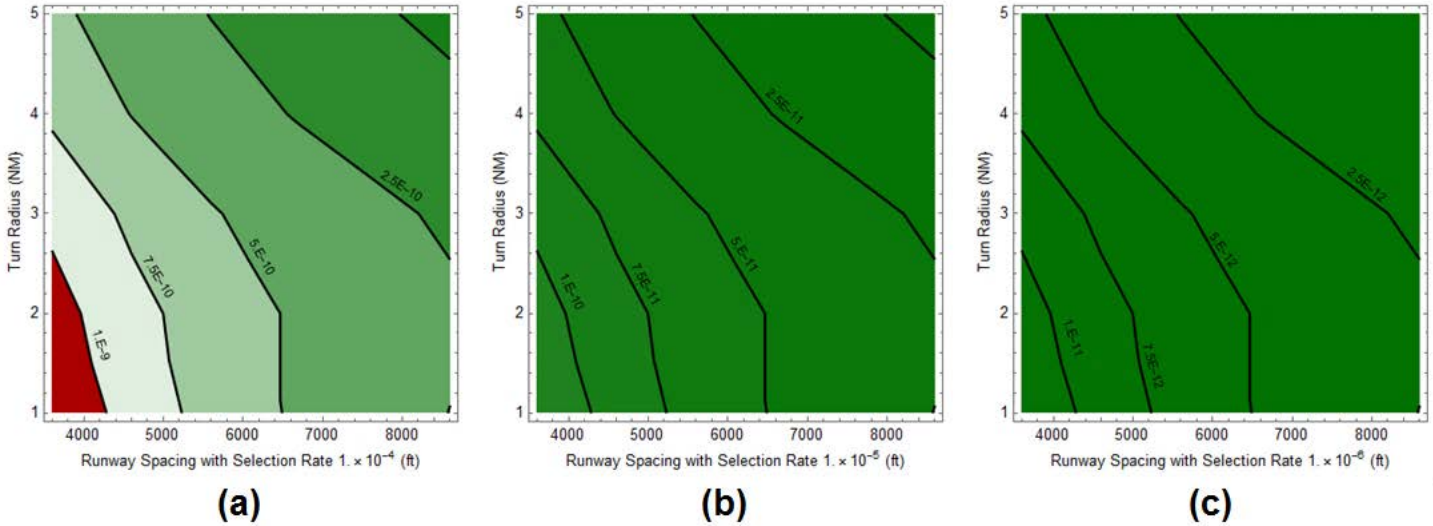


Figure 3-13: Collision Risk Associated with One Merging Case for 3.0 In-Trail Spacing

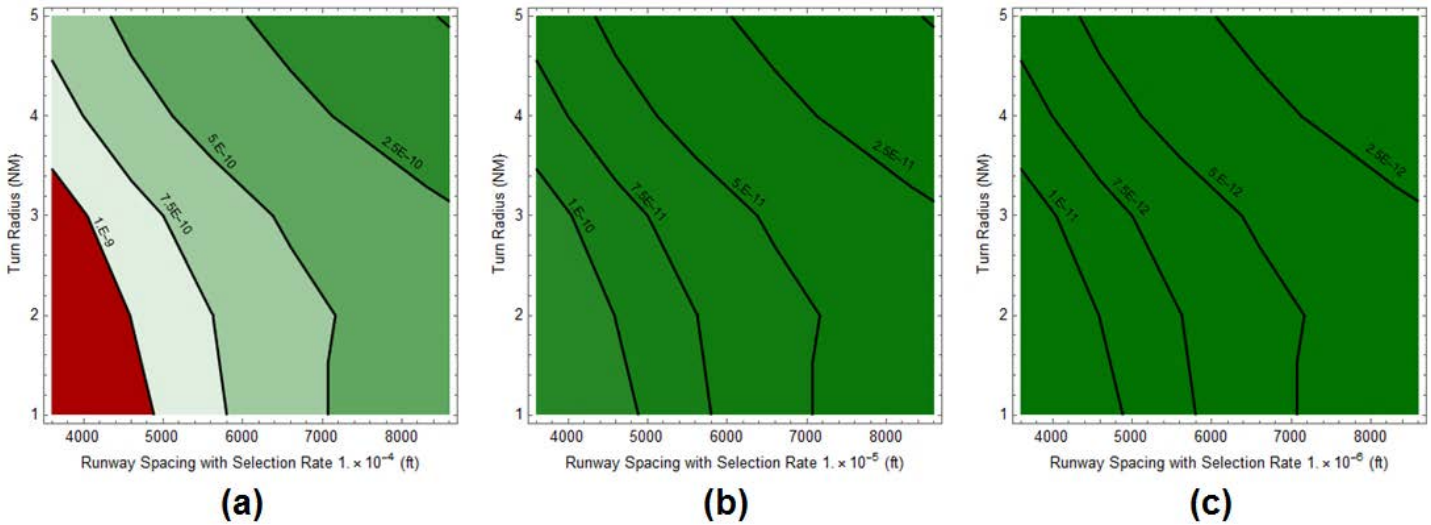
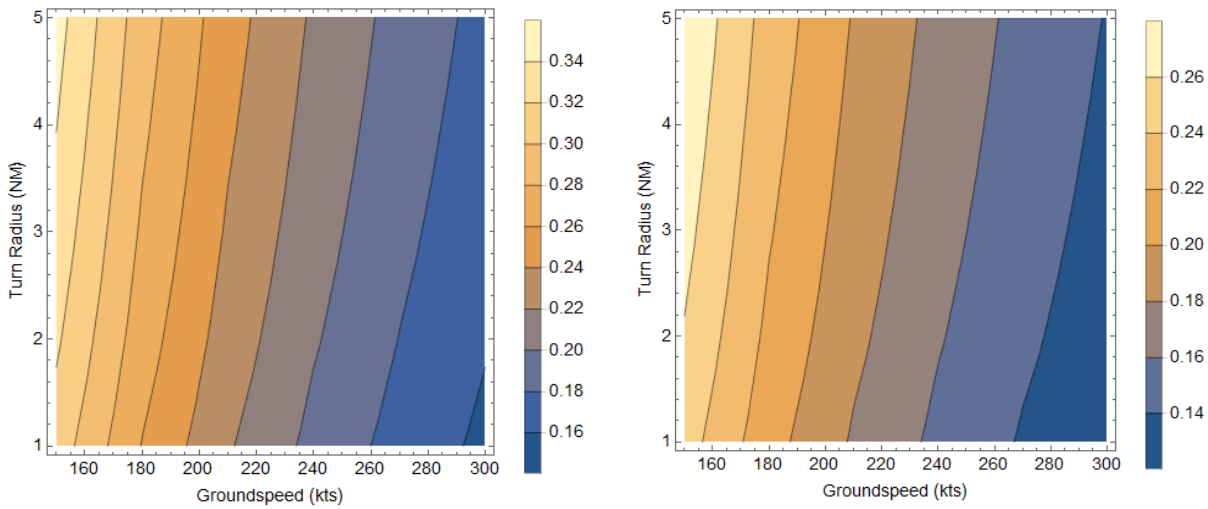


Figure 3-14: Collision Risk Associated with One Merging Case for 2.5 In-Trail Spacing

The collision risk, in this case, varies by approximately one order of magnitude over the input parameters selected if the incorrect approach selection rate is fixed. The incorrect approach selection rate affects the collision risk linearly over the three order of magnitude range considered in the study.

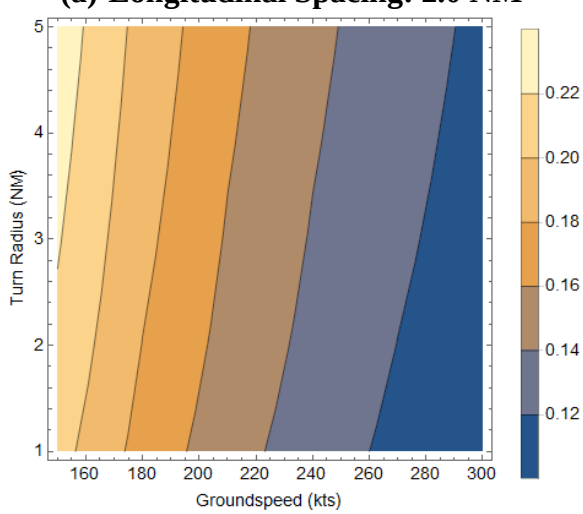
Additionally, we calculated some intermediate values from the collision risk model to accommodate development of innovative airspace designs. The results relating to the amount of time required to execute a controller initiated breakout are contained in section 3.4.

If an aircraft flies the incorrectly selected approach to touchdown without controller intervention, the collision risk model provides the results in figure 3-15. The specific values can be found in tables E-6 through E-9 in appendix E.

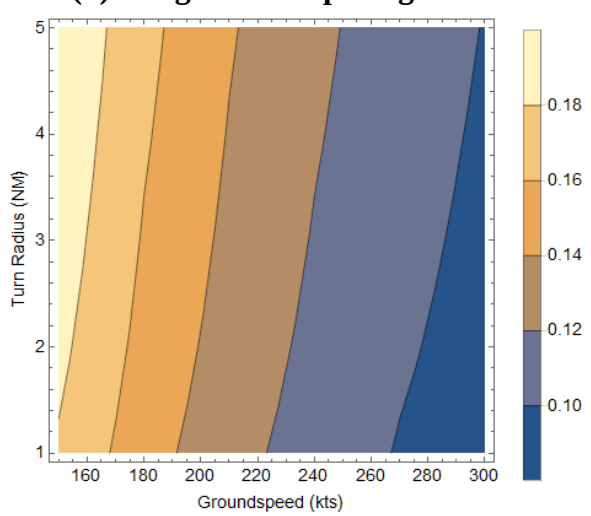


(a) Longitudinal Spacing: 2.0 NM

(b) Longitudinal Spacing: 2.5 NM



(c) Longitudinal Spacing: 3.0 NM



(d) Longitudinal Spacing: 3.5 NM

Figure 3-15: Collision Risk without Controller Intervention Assuming a 4 NM Length along the Final Approach Course

Using a delay uniformly distributed between 7.2 seconds and 17.5 seconds and setting groundspeed and turn radius to optimistic values of 180 knots and 5 NM respectively, we calculated the probability of wake separation violation given incorrect approach selection, see figure 3-16 and table E-5 in appendix E. As the runway spacing increases to 9000 ft, approximately one order of magnitude of wake separation violation is mitigated. This is the probability that the two tracks get within 2500 ft when the EoR aircraft flies an incorrect approach. The result, therefore, applies to both wake turbulence generated by a leading straight-in aircraft threatening the EoR aircraft and to wake turbulence generated by the EoR aircraft threating a trailing straight-in aircraft.

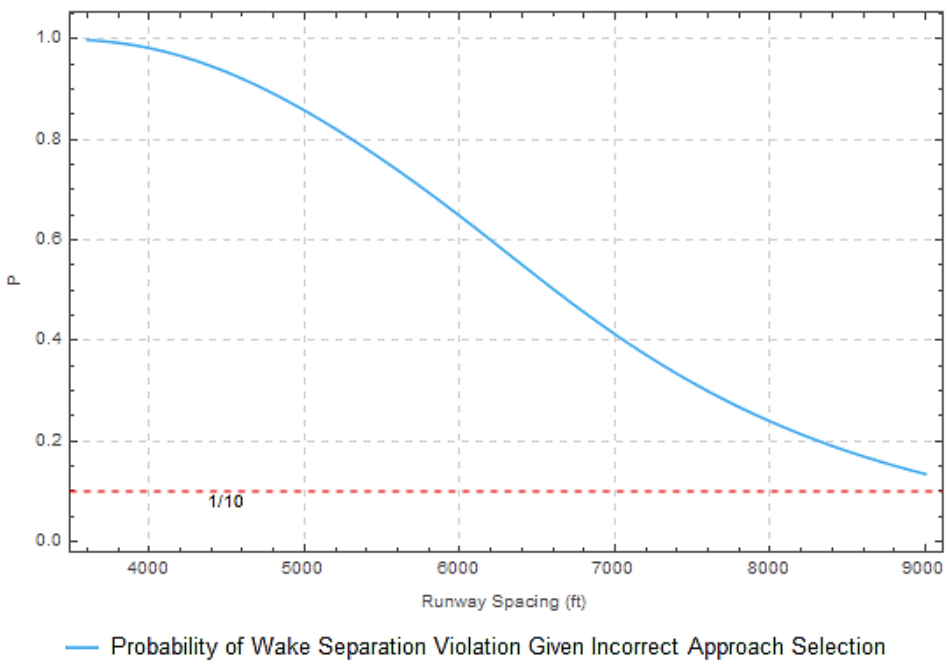


Figure 3-16: Wake Separation Violation Probability Given Runway Spacing Assuming 180 knot Groundspeed and 5 NM Turn Radius

Based on these results, we suggest further study of the wake vortex encounter risk associated with any airspace design that includes the possibility of merging traffic due to an incorrect approach selection to support a safety case that authorizes these airspace designs. Any airspace design that provides at least 50 seconds from the point where unique approach paths are first discernable to the controller to the time that the 2500 ft wake region is penetrated would not require a wake analysis.

3.3 Case 3: Intermediate Runway Traffic Intersection

The last case that we evaluated was the collision risk between the off-nominal/deviating aircraft and an aircraft flying an approach to one of the runways between the intended landing runway and the incorrectly selected runway, shown in figure 3-17. This case would only occur in airspace geometries with three or more runways and there is an approach procedure that can be selected that could intercept an approach path to neither the intended approach nor the selected approach. From an analytical perspective, this case has elements of both of the previous analyses. Similar to the collision risk calculation in case 1, described in section 3.1, the collision risk, in this case, is an intersection. Therefore, the closure rates are much higher, the intersection angle is orthogonal or nearly orthogonal,

and the collision risk can be considered to occur at approximately a discrete time. Similarly to the collision risk for case 2, described in section 3.2, the intersection occurs after the deviating aircraft has passed through the NTZ and we can expect that the final monitor would intervene. Also, the at-risk traffic is not anticipating merging with the deviating aircraft, so the aircraft density would be uniform along the track.

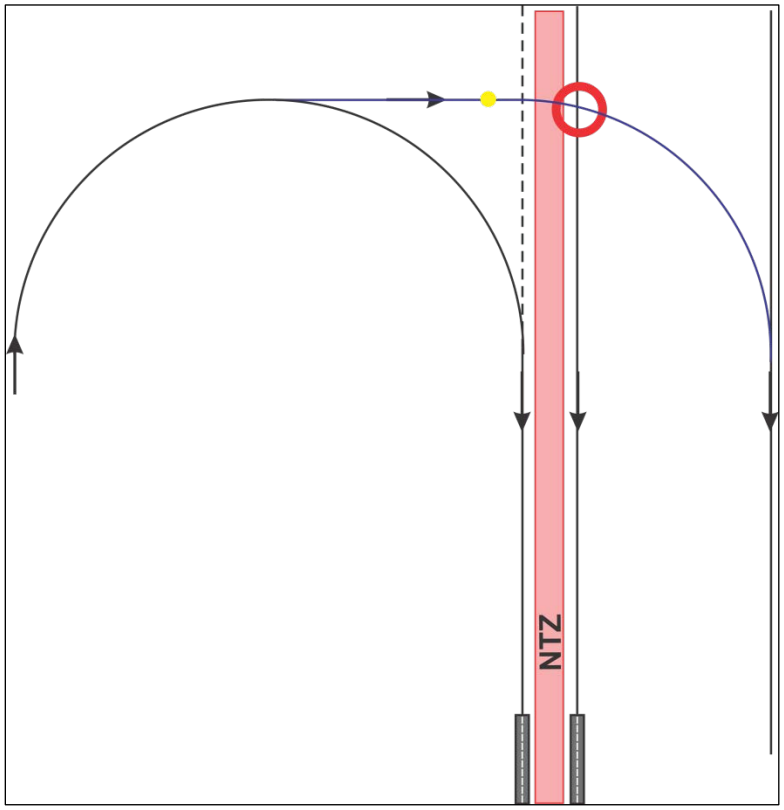


Figure 3-17: Intermediate Runway Traffic Intersection

As in case 1, we did not believe that an analysis of wake turbulence was needed for this case. Results from this section indicate that the amount of time available for controller intervention is generally insufficient to prevent collision, which implies that it would certainly be insufficient to prevent loss of wake separation. Furthermore, if the wake vortex is encountered, there is a chance that the wake vortex core will not be aligned with the other approach path which reduces the likelihood that the aircraft will experience significant induced roll.

3.3.1 Collision Risk Methodology

We used the same collision risk methodology described in section 3.1, but adjusted the along-track aircraft density to plausible minimum in-trail spacing values and applied the 73% vertical assumption from case 2. In all cases, the collision risk given an incorrect approach selection with an intersection does not exceed 1/10 nor fall below 5/100. See table 3-2 in section 3.3.2 for a table of results.

The approach procedure construction and reaction times are the same as those used in section 3.2. Furthermore, the trigger for the start of the reaction time was calculated in the same way. However, the collision risk, in this case, occurs at a particular intersection time, which can be calculated using

equation 11. Therefore, the correction must start and the correction must effectively prevent the collision before the path intersection, see figure 3-18.

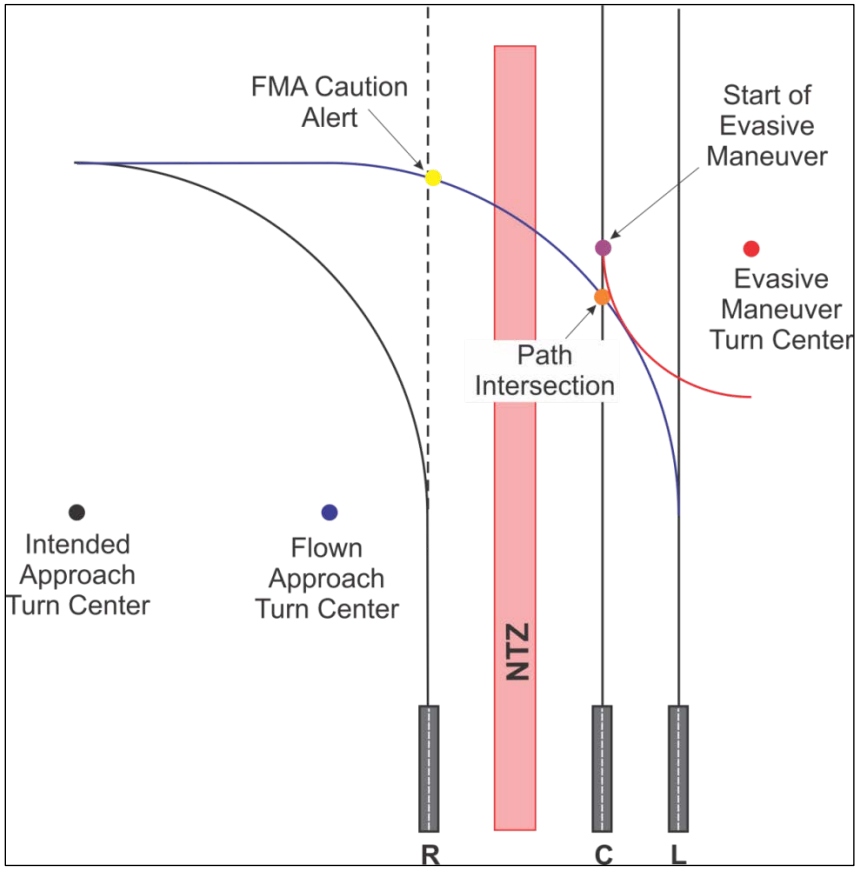


Figure 3-18: Correcting Prior to Path Intersection

$$Path\ Intersection\ Time = \begin{cases} R\left(\frac{\pi}{2} - \cos^{-1}\left(\frac{D}{R}\right)\right)\Big/_{V} & \left(\rho_{Landing} - \rho_{Nearest}\right) < R \\ D\big/_{V} & \left(\rho_{Landing} - \rho_{Nearest}\right) \geq R \end{cases} \tag{11}$$

$$D = R - \left(\rho_{Landing} - \rho_{Nearest}\right)$$

The largest reasonable difference between the time of the caution alert and the time of the path intersection time was calculated for a turn radius of 4 NM, a groundspeed of 165 knots, the nearest runway 9000 ft away from the intended runway and the selected runway separated from the nearest runway by 3900 ft. This yielded a time of 39.7 seconds; for additional results, see section 3.3.2. From this time, we subtracted two additional values: the delay between the idealized time that the caution alert may occur and the actual time of alert given delays in the radar and automation platform, and the delay from the time of the start of the reaction to the time that the reaction successfully eliminated collision risk. As discussed above, the first value fell between 7.2 and 17.2 seconds. Taking 39.7 and subtracting 7.2 yielded the largest amount of time to react possible, 32.5 seconds.

Using the same delay assumptions as the merging case, which is fairly optimistic, controllers would not react with enough time for the flight crew to initiate a correction 0.5% of the time with one response distribution and 0.068% of the time with the most optimistic response distribution. Considering that the lowest probability of incorrect approach selection is 10^{-6}, the probability of collision given an intersection case without correction is no better than 5 in 100, and the probability of failed mitigation is 6.8 in 10,000, at the best, the most optimistic collision risk is 3.4×10^{-11} without considering the necessary merging case. The conservative reaction distribution yields 2.5×10^{-10} for this same set. These optimistic values, however, quickly deteriorate as less optimistic assumptions are made. When the delay increases to 13.3 seconds, the conservative distribution yields a collision risk of 10^{-9}. When the runways are spaced as few as 8300 ft with the maximum 17.5 second delay, the optimistic distribution yields a collision risk of 10^{-9}. Based on these results, it appears that the low collision risks are only observed in unusual approach configurations.

3.3.2 Results

Table 3-2 describes the collision risk associated with the intermediate runway traffic intersection without controller intervention. Note that the collision risk is much more sensitive to the assumed aircraft density than the groundspeed.

Table 3-2: Collision Risk in Intermediate Runway Traffic without Controller Intervention

		Along-Track Aircraft Density		
		1 aircraft per 2.0 NM	**1 aircraft per 2.5 NM**	**1 aircraft per 3.0 NM**
Groundspeed	**170 kts**	9.15E-2	7.32E-2	6.10E-2
	210 kts	9.12E-2	7.30E-2	6.08E-2
	250 kts	9.10E-2	7.28E-2	6.07E-2
	290 kts	9.09E-2	7.27E-2	6.06E-2

Figures 3-19 through 3-22 show the sensitivity of the difference between the caution alert time and the time of intersection to its input parameters, with baseline parameters of 3900 ft between triple runways, a turn radius of 2.5 NM and a groundspeed of 250 kts. The probability of collision, in this case, is very dependent on the amount of time available; therefore, we know that as the amount of time for a reaction decreases, the collision risk increases. To explore how the available time compares to the amount of time with which we can be assured of an effective pilot and controller response, see tables E-2 and E-3 in appendix E in conjunction with figures 3-19 through 3-22. The following figures inform our understanding of how the collision risk changes based on the input parameters. In figure 3-19, note that the collision risk increases as the runway spacing increases because the amount of time to react decreases as the runway spacing increases. The amount of time to react decreases because, as the distance between the overflown extended runway centerline and the incorrectly selected runway centerline increase, less of the turn is included in the region between the FMA caution and the intersection. The turn has a longer path length than a straight segment perpendicular to the extended runway centerline. In this figure, the nearest runway is spaced 3900 ft from the intended runway and the distance between the intended runway and the selected runway is the variable on the x-axis. Therefore, as the variable increases, the amount of curved path decreases.

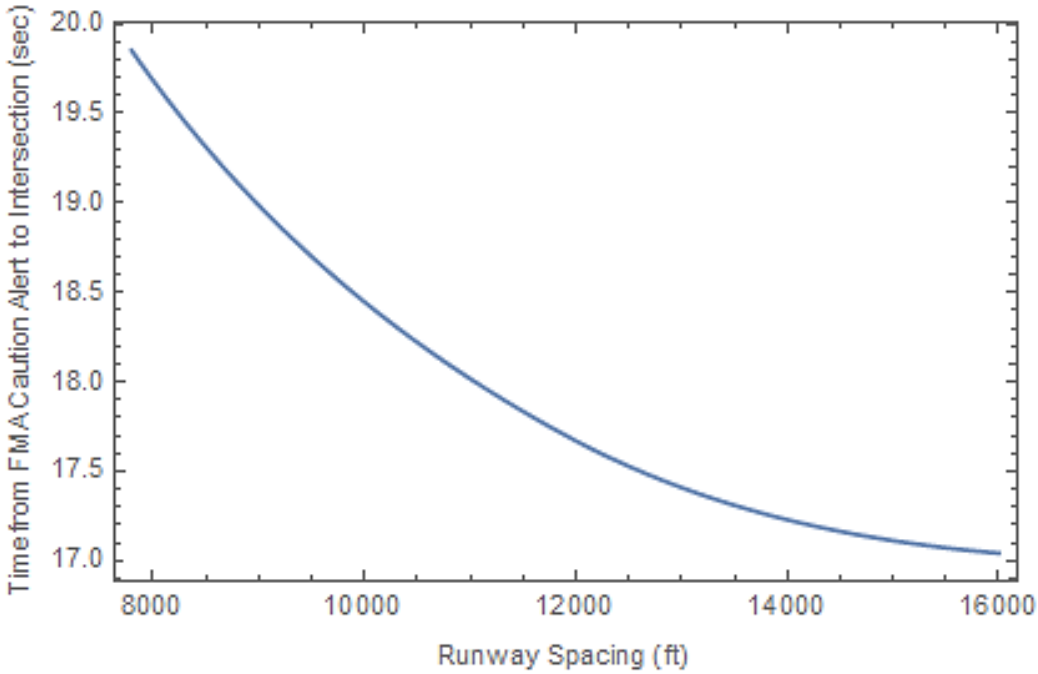


Figure 3-19: Time Sensitivity to Runway Spacing between Intended and Selected Runways with the Distance between the Intended and Nearest Runways Fixed to 3900 ft

In figure 3-20, note that the collision risk decreases as the runway spacing increases because the amount of time to react increases as the runway spacing increases. In this figure, the distance between the nearest runway and the selected runway is fixed at 3900 ft, and the distance between the intended runway and the selected runway is the variable at the bottom of the figure. The amount of reaction time available increases because the normal operating zone width increases, creating more distance between the FMA caution alert time and the intersection.

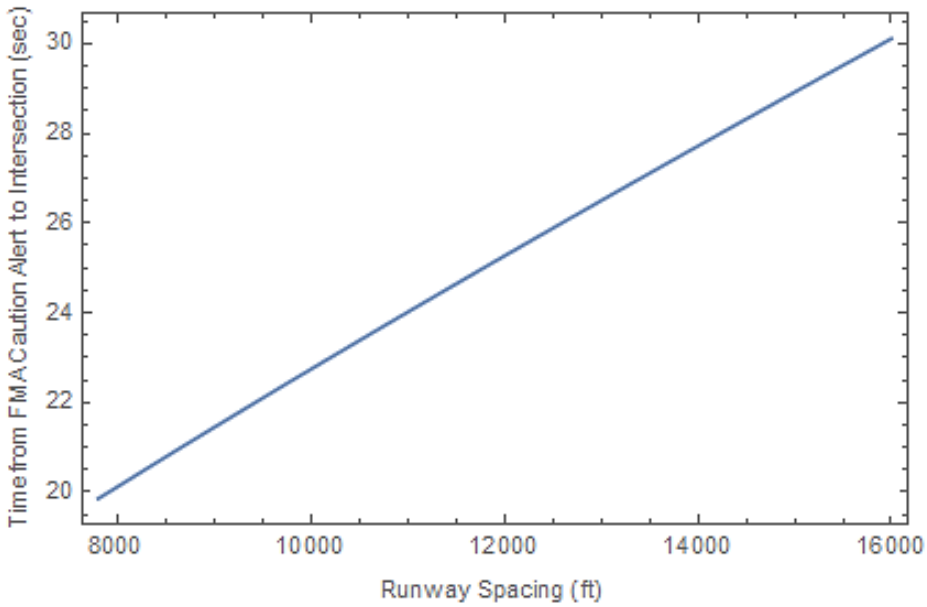


Figure 3-20: Time Sensitivity to Runway Spacing between Intended and Selected Runways with the Distance between the Nearest and Selected Runways Fixed to 3900 ft

In figure 3-21, note that the collision risk increases as the groundspeed increases because the amount of time to react decreases as the groundspeed increases. This is because the path length is constant, but the amount of time required to travel the same path length is reduced as groundspeed increases.

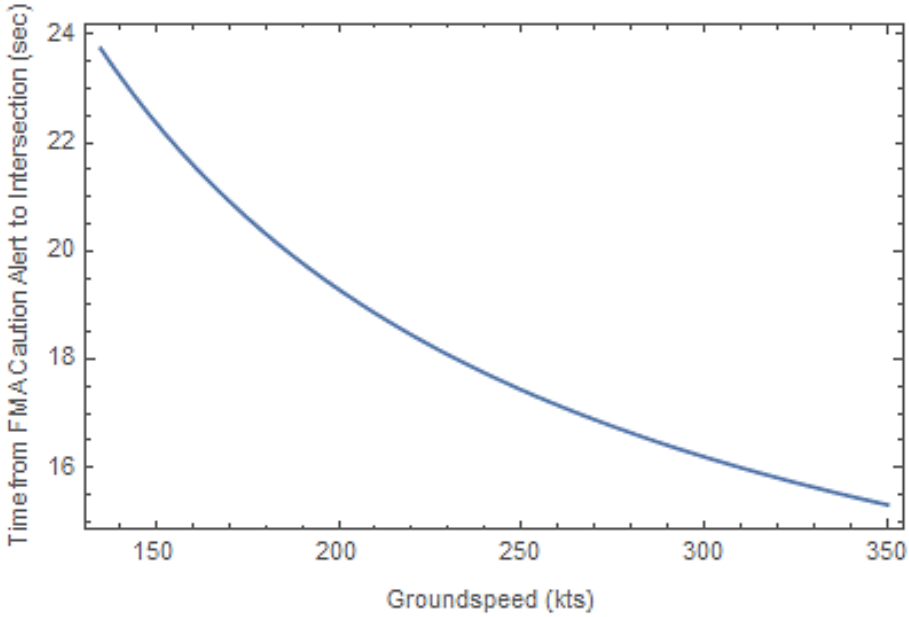


Figure 3-21: Time Sensitivity to Groundspeed

In figure 3-22, note that the collision risk decreases as the turn radius increases because the amount of time to react increases as the turn radius increases. With an increased turn radius, many airspace

geometries will include more path length due to the increased path curvature, increasing the amount of time before an intersection.

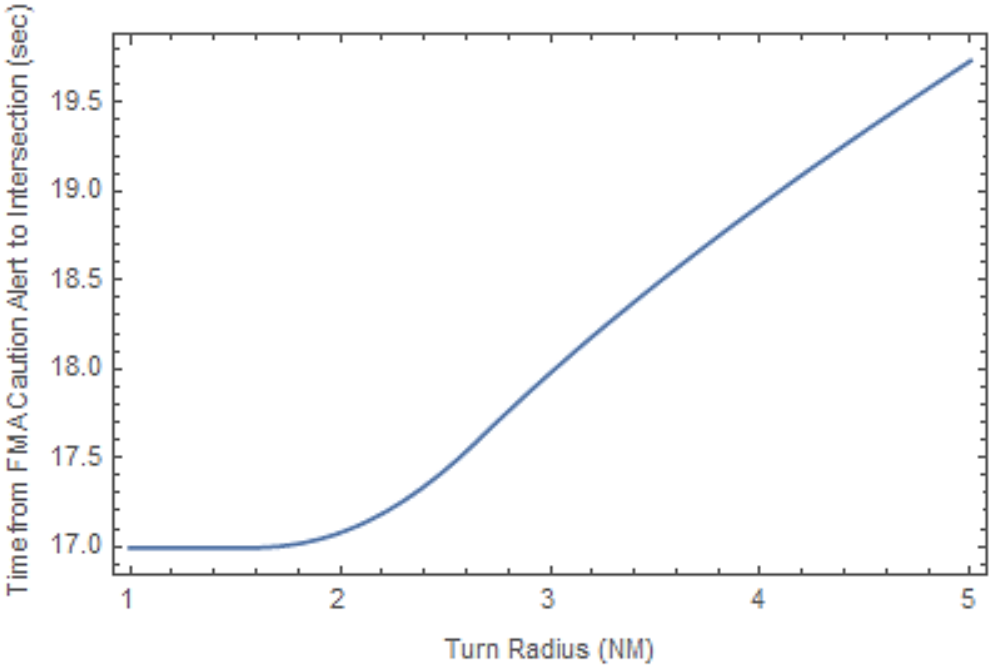


Figure 3-22: Time Sensitivity to Turn Radius

Leveraging the understanding between the different variables, we examined an intermediate case to understand a midpoint for the collision risk and a conservative case to understand an upper bound for collision risk. For the most typical case, we used something similar to the merging baseline in section 3.2.1: 2.5 NM turn radius, 210 knot groundspeed, 2.5 NM in-trail spacing, and a 7.2 second delay, but all runways separated by 3900 ft. Before the delay, the calculation yields a value of 21.6 seconds, which is 14.4 seconds after subtracting the delay. Applying the conservative reaction time distribution, controllers and pilots would fail to successfully execute the evasion in time 26.7% of the time. The other distribution yields 10.8% failed correction. Using the middle incorrect approach selection rate, 10^{-5} and the 3 NM collision risk given intersection of approximately 6%, we estimated the collision risk to be 1.6×10^{-7} or 6.5×10^{-8} using moderate assumptions and the conservative and optimistic controller response distributions, respectively.

Based on the sensitivity analysis performed, the worst case is characterized by a small turn radius, a high groundspeed, a large distance between the nearest and selected runways, but a small distance between the intended and nearest runways. Furthermore, the collision rate given intersection should be higher and the delay should be larger to achieve the worst case analysis. To meet these requirements, we assumed a 1.25 NM turn radius with the maximum groundspeed using a 30° bank angle, which is 222 knots. Furthermore, we set the distance between the nearest and selected runways to 11,000 ft but set the distance between the nearest and intended runways to only 3900 ft. Finally, the delay was 17.5 seconds and the probability of collision given intersection was 7.5%. With these input parameters, the amount of time before the delay was 17.9 seconds. The amount of time after the delay was 0.4 seconds. This means that controller intervention was never effective in the conservative reaction time distribution and it was

ineffective 79% of the time with the optimistic distribution. Using the highest occurrence rate, we conclude that the upper bound of collision risk for the intersection case is around 5.9×10^{-6} to 7.5×10^{-6}.

With a 10^{-6} incorrect selection rate and the 3 NM in-trail spacing, the controller breakout must effectively prevent a collision 98% of the time. That is, it must not fail with a rate greater than 1.7%. Compiling the data in the same way as the figures in section 3.2.3, the rate that the controller intervention is not effective can be seen in figure 3-23. As shown, even under the most ideal circumstances, effective controller intervention rates fail at rates well above 1.7%.

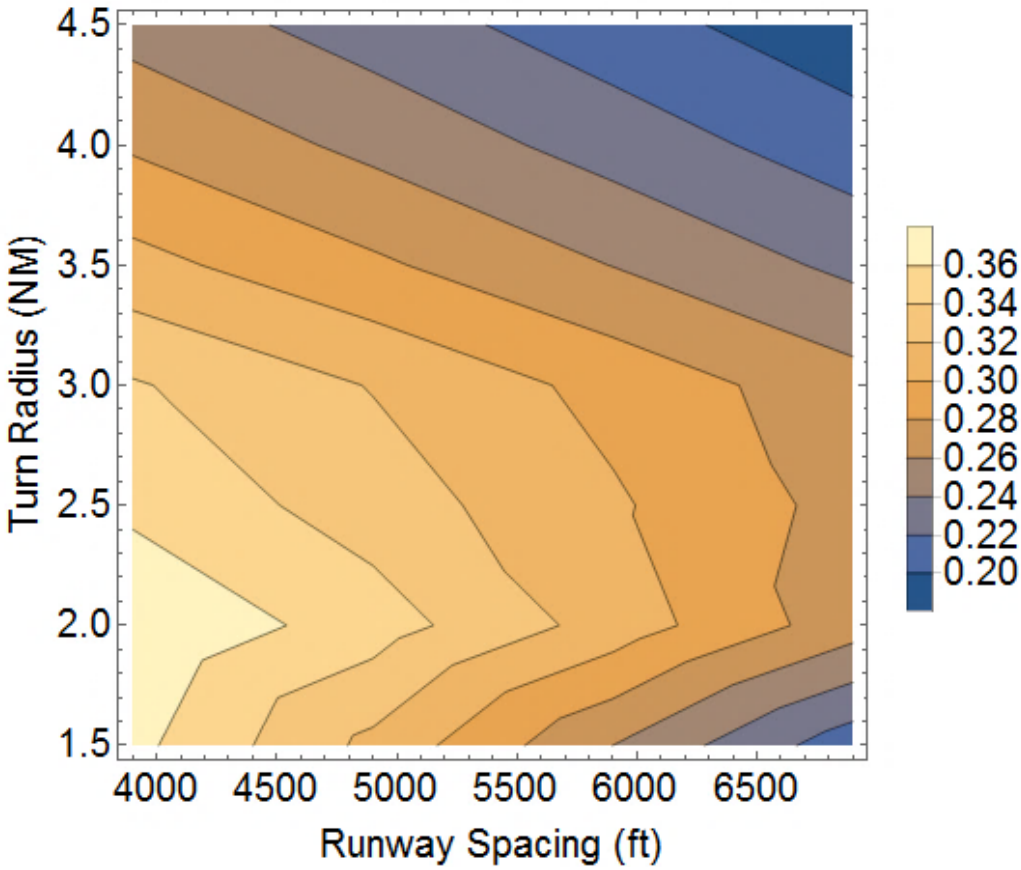


Figure 3-23: Probability that Controller Fails to Prevent a Path Intersection Given Incorrect Approach Selection

Although some individual model outputs may be below 10^{-9}, those results must be combined with other equally likely combinations. When this is done, the collision risk associated with an intermediate runway intersection for any runway spacing less than 9000 ft typically falls within the range of 10^{-7} to 10^{-6}. This risk can be mitigated by procedure designs that provide sufficient time for controllers to intervene based on an observable difference in the flight paths. Intermediate results on the amount of time necessary for controller interventions following an aural and visual alert can be found in section 3.2.3. In the above optimistic example, collision risk would be on the order of 10^{-9} if controllers had 28 seconds following an automated alert to respond to a conflict. In the conservative example, the collision risk would also be on the order of 10^{-9} if controllers had 48 seconds following an automated alert. Additional time to identify an incorrect approach procedure selection before the alert would also

mitigate this risk, but the magnitude of this effect has not been evaluated. For implementation, the reaction times collected with the final monitor aid were considered to approximate controller reactions (which may occur by the final controller instead of final monitor controller and will occur much further from the parallel traffic in the proposed application) and approximately 50 seconds would be required between the point of recognizable divergence to the intercept with any intermediate approach paths.

3.4 Controller-Initiated Breakout Maneuver

The primary mitigation for collision risk during an incorrect flight procedure selection is the intervention of a monitoring controller. This intervention includes four components:

1. The time from when the aircraft enters the NTZ to the FMA caution alert (which includes surveillance update rate and automation system delay),
2. The time from the caution alert to when the controller gives an instruction to the flight crew,
3. The time from the controller instruction to when the flight crew responds, and
4. The time from when the flight crew initiates their response to the time the response effectively prevents a collision.

For the TF turn study, controller response times were measured from the time of the start of the lateral path deviation to the time the controller pressed the push-to-talk button to give the evasion command. Manually reviewing a sample of data for the incorrect approach scenario, however, suggested that many of these responses occurred in response to or in anticipation of the FMA caution alert. See appendix C for details of several example controller responses. Reprocessing the controller experimental data to measure from the time of the FMA caution alert to the time the controller pressed the push-to-talk button yields the dataset shown in figure 3-24. Note that many of the responses anticipate the FMA caution alert, but still seem to be relative to that event. However, that portion of the distribution may be somewhat dependent on the amount of time between the start of the deviation and the FMA caution alert. The airport environment used for that test was KDEN with dual EoR TF turn operations to 35L and 35R, which are separated by 5300 ft. Though the results are presented with optimistic and conservative distributions below for all runway spacings, the conservative distribution is most appropriate for runways less than 5300 ft.

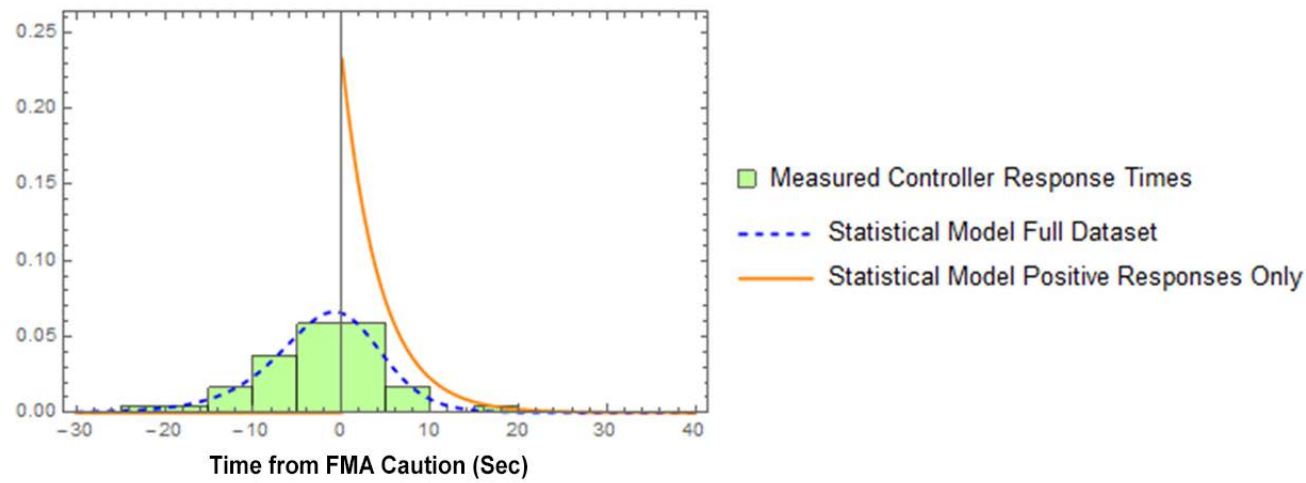


Figure 3-24: Controller Response Times

Figure 3-25 shows the statistical model used to describe the full dataset. It is a Johnson unbounded distribution with shape parameters $\gamma = 0.7090$ and $\delta = 2.017$ with a location parameter of 2.471 and a scale parameter of 11.57. A Pearson χ^2 test indicates that this distribution can be used to model the dataset with a p-value of 0.19. The statistical model used to describe only the positive responses was an exponential distribution with a minimum value of 0 and a scale parameter equal to 0.2340. A Kolmogorov-Smirnov test indicates that this distribution can be used to model the filtered dataset with a p-value of 0.24.

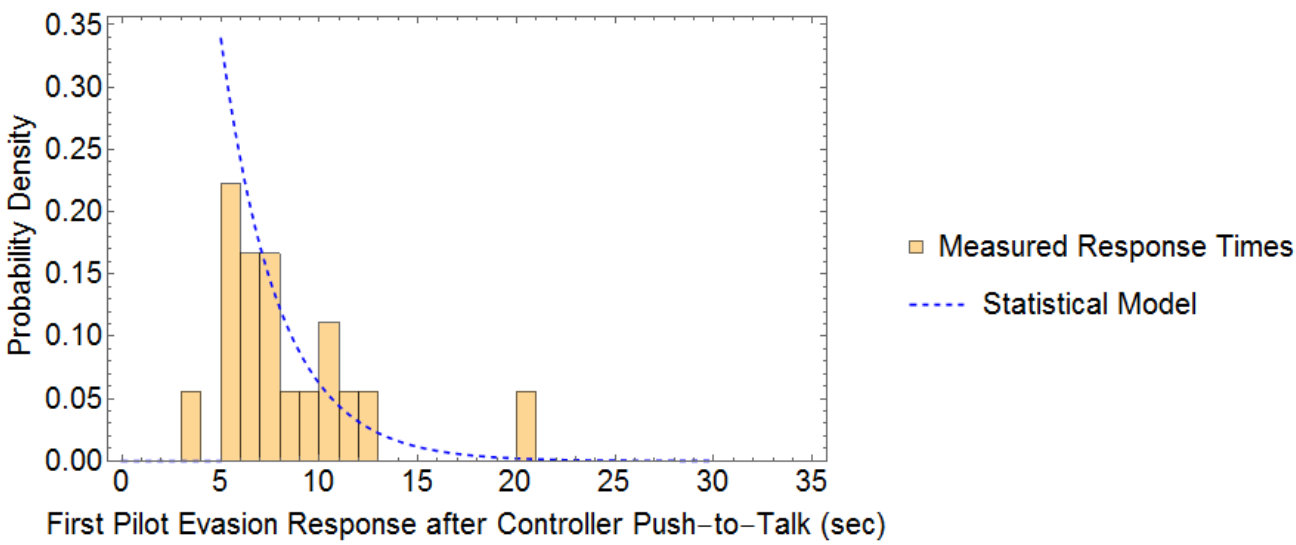


Figure 3-25: Histogram and Fitted Statistical Model for Pilot Response Time

Figure 3-26 depicts the pilot responses filtered down to only those responses where neither pilot made visual contact with the other aircraft during the approach. This data was measured from the time that the non-subject controller pressed the push-to-talk button to the time that the aircraft corrected by achieving 2.5° bank above that expected for the concurrent 10° final approach course interception followed by the local bank maxima used to complete the full evasion. See appendix D for additional pilot response data.

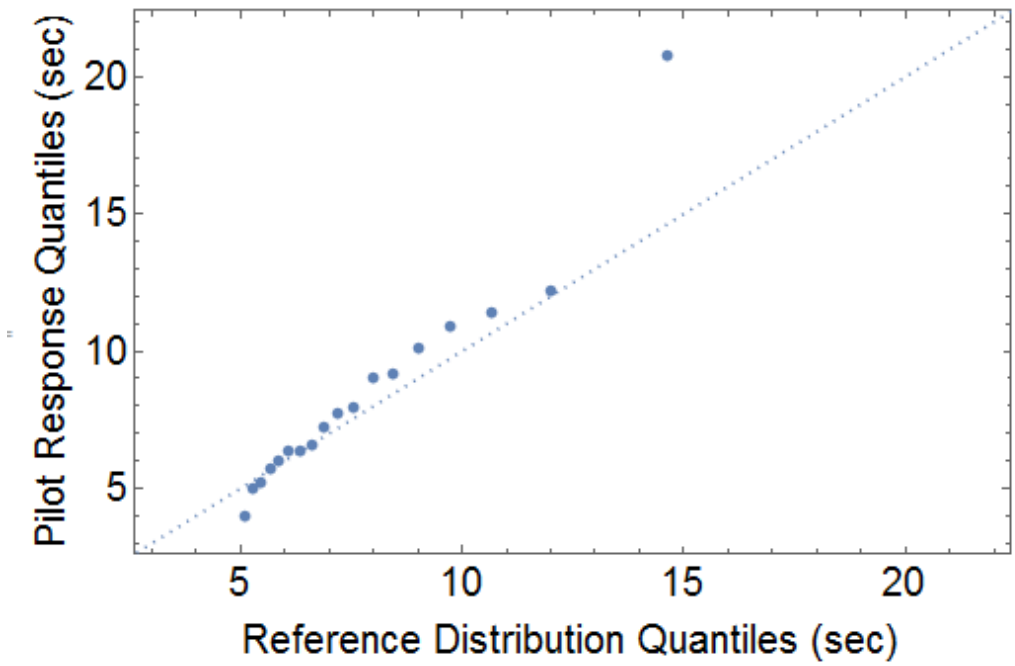


Figure 3-26: Quantile-Quantile Plot Comparing Pilot Response Times and Fitted Statistical Model

The statistical model used to describe this dataset was an exponential distribution with a minimum value of 5 and a shape parameter of 0.34. A Kolmogorov-Smirnov test showed that this distribution could be used to model this dataset with a p-value of 0.71.

By convolving these distributions and adding in an additional delay for the time for evasive maneuvers to be effective and to account for surveillance update rates and delay, we are able to estimate the likelihood that a controller-initiated evasion prevents a collision. Figures 3-27 and 3-28 display the probability of the controller initiated evasion being effective in a certain number of seconds past the FMA caution alert. The figures only characterize the uncertainty associated with the pilot and controller response distributions, with the first figure using the conservative controller response and the second figure using the optimistic controller response.

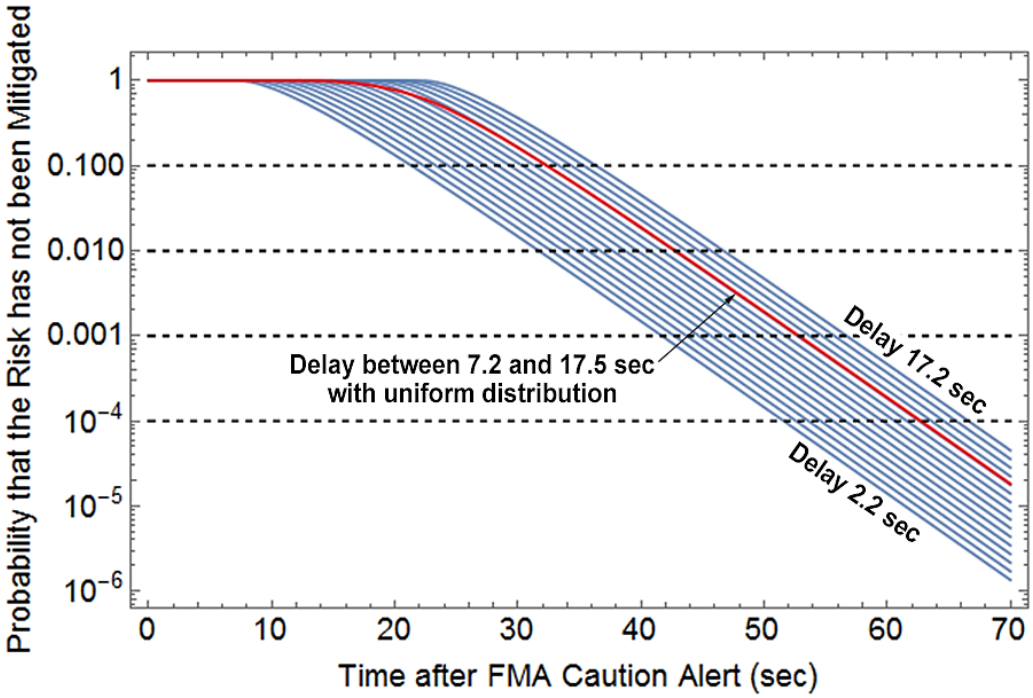


Figure 3-27: Probability of Controller-Induced Pilot Evasion Not Being Effective Prior to Some Time after FMA Caution Alert Using the Conservative Reaction Distribution

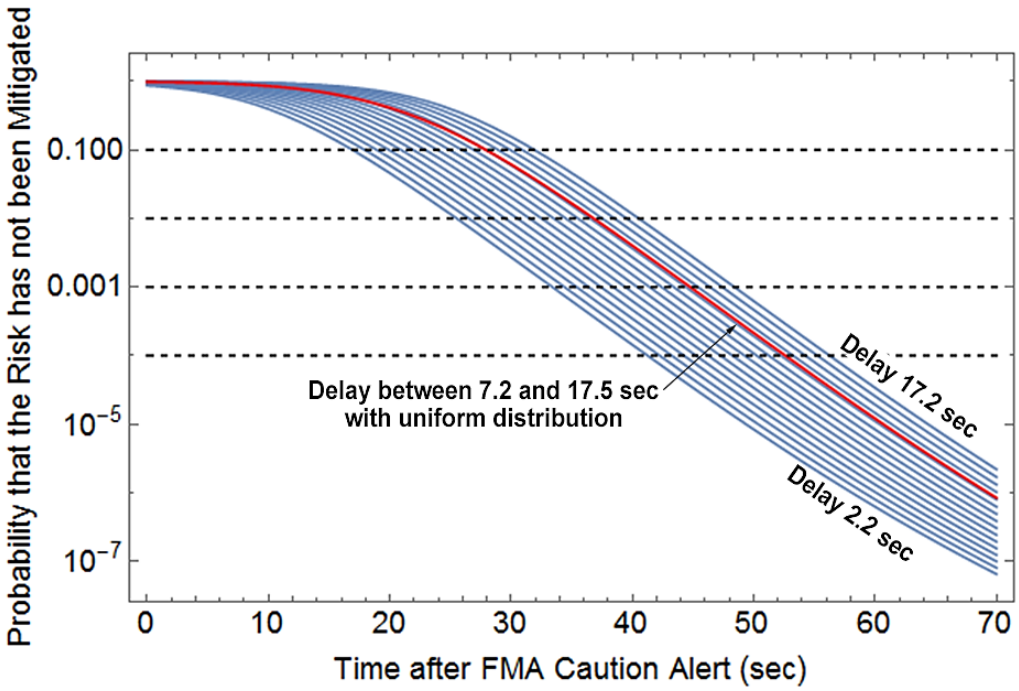


Figure 3-28: Probability of Controller-Induced Pilot Evasion Not Being Effective Prior to Some Time after FMA Caution Alert Using the Optimistic Reaction Distribution

Tables E-2 and E-3 in appendix E describe where the curves in the above figures fall below particular thresholds. This information, in conjunction with the information in table E-4, can be used to estimate whether an innovative procedure design will provide adequate safety from aircraft-to-aircraft collision. For example, if the designer assumes that aircraft select an incorrect approach at a rate of 10^{-4}, then we need to be confident that a collision does not occur more often than once every 100,000 incorrect approaches. However, not every flight path merging scenario results in a collision. Therefore, we can roughly estimate the density of the aircraft on the other path using (265*2)/(In-trail spacing *6076.115). In a typical application, this is approximately 3 out of 1000, which is between 1 out of 100 and 1 out of 1000. Applying this to the incorrect approach rate, the designer would only need to ensure that the reaction is sufficient in somewhere between 999 out of 1000 and 99 out of 100 cases. That is, between 52.8 seconds and 42.8 seconds using the conservative distribution and 44.8 and 36.8 seconds using the optimistic distribution. The aircraft do not need to get entirely on the same path to be at risk; the lateral error of the straight-in aircraft may shorten the distance. Knowing that we model straight-in area navigation RNAV error with a normal distribution with a standard deviation of 0.04 NM, the designer could consider the aircraft at risk at when a certain threshold is met, such as when the deviating aircraft is within 0.08 NM (486 ft) of the other approach path. If it can be shown that there is this much time between an audio-visual alert to the controller and the first time that the incorrect path comes within the distance threshold, a designer could be confident that the innovative design meets any given risk threshold.

These results do not directly apply to operations without an FMA, because the response data was collected in an experimental environment that included FMA alerting, see appendix C. However, many of the observed reactions occurred before the FMA caution alert. In other scenarios, controllers established communications before the FMA caution alert, but issued breakout instructions after the alert

occurred. Therefore, it is likely that some truncation of the response time distribution occurred due to the FMA alerts, but many of the responses would have likely occurred in the same timeframe regardless of the FMA caution alert. Thus, these response time distributions were applied to cases where FMA alerting may not be necessary to inform how much time may be needed to prevent a collision if the downwind is extended, see section 3.1.2. While the time allowed for controller intervention of 50 seconds is plausible and gives an approximation appropriate for implementation, it is questionable whether these reaction times are statistically representative of reaction time distributions that would be observed in practice. Depending on the airspace design and air traffic procedures, the controllers may respond to an incorrect approach selection in a substantially less critical portion of the approach than in the airspace design used for the human-in-the-loop experiment and, in fact, the aircraft may still be on the final controller frequency or be transferring to the tower frequency at the time that the paths diverge. Furthermore, the existing separation standards state that a high-resolution color monitor with alert algorithms, such as the final monitor aid, must be used for runways spaced less than 4300 ft for dual simultaneous independent operations and 5000 ft for triple simultaneous independent operations.[30] With the runways spaced 4301 ft, a 30° blunder flying 200 kts groundspeed would only allow 25 seconds for controller intervention before lateral path intersection. The same scenario with runways spaced 5001 ft, would only allow 30 seconds for controller intervention. If a 20° blunder is used, runways spaced 4300 ft yield 37 seconds for reaction and 5000 ft runways yield 43 seconds for reaction. Therefore, in case 1 and case 3, where vertical separation could be expected, similar times for controller intervention may be acceptable without the additional assurance of the FMA alerting (i.e. from when the paths are discernably unique to where they intersect) in certain airspace designs. For instance, 5000 ft between the intended and nearest runway, 3900 ft between the nearest and landing runway, a turn radius of 2.5 NM, and 200 kt groundspeed yields 37.7 seconds from the point where the paths diverge to where a case 3 collision could occur. Additional human-in-the-loop experimentation would provide a much stronger basis for decisions relating to controller intervention without automation system alerting.

[30] Air Traffic Organization, *Air Traffic Control Order 7110.65W*, para 5-7-9.

4 Conclusions

Although this parametric analysis was designed to determine the collision risk for a wide variety of airspace designs, from triple EoR approach procedures at an airfield with four parallel runways to dual EoR approach procedures at an airport with two runways, the large differences in collision risk between the three cases simplify the conclusions. The first case examined the collision risk of the deviating aircraft and an aircraft flying an approach to the runway that the deviating aircraft should have selected. This case will not result in a significant collision risk in expected airspace designs that diverge at the apex. When the downwind length differences are relatively small, collision risk continues to be mitigated by the in-trail spacing. However, when downwind length differences are larger, collision risk is not mitigated by in-trail spacing designed for the EoR aircraft on the intended path and it will require early controller identification of an incorrect approach selection to maintain the same level of safety. To assure controller intervention and successful evasive maneuvers, flight procedures should be designed with at least 50 seconds from the point where the distinct paths are discernable to the controller to the point where the potential incorrect paths intersect the intended landing runway extended centerline.

In the second case, we examined the collision risk to an aircraft flying to the runway that the deviating aircraft incorrectly selected. This case has a collision risk that could be on the same order of magnitude as the EoR collision risk with RNAV (GPS) approach procedures designed with TF legs. This means that, depending on the actual incorrect flight procedure selection rate and the design being considered, case 2 collision risk could be on the order of 10^{-10} or below (when the rate is 10^{-5} or less), could be enough to double the collision risk per operation, leaving it on the order of 10^{-9} (when the rate is 10^{-4} with large turn radii or runway spacings), or could increase the collision risk above 10^{-9} (when the rate is 10^{-4} with small turn radii or runway spacings, see section 3.2.3). Based on analysis that indicates that wake separation would be regularly violated especially at reduced runway spacings, further study is suggested to determine the wake vortex encounter risk associated with any airspace design that includes the possibility of merging traffic due to an incorrect approach selection.

The third case examined the collision risk as the deviating aircraft crosses the traffic to any runway between the intended runway and the incorrectly selected runway. This case introduces a collision risk on the order of 10^{-7} to 10^{-6} per operation for all plausible input parameters. To assure controller intervention and successful evasive maneuvers, flight procedures should be designed with at least 50 seconds from the point where unique approach paths are first discernable to the controller to the point where incorrect approach procedures intersect any intermediate extended final approach course. This intersection will always occur following the intended runway extended final approach course intersection, meaning that this can be achieved with the mitigation used for case 1.

The following mitigations could significantly improve the collision risk:

- Any air traffic procedure or technology that could be used to reduce the rate of incorrect approach selection would substantially reduce the collision risk. Although verbal checks of the approach procedure, landing runway, or final approach fix could reduce the collision risk, any air traffic procedure must reduce the incorrect approach selection rate to at least 10^{-7} to reduce the collision risk of case 3. Alternatively, automated incorrect approach selection detection could be designed using data communication technologies or an adaptation of FMA.
- If the approaches were designed to ensure vertical separation at the points where the approaches intersect, the collision risk of the third case may be significantly reduced. We assumed for the

analysis that the aircraft were crossing at the same nominal altitude in all cases. Due to the varying path lengths, it would be necessary to design approach transitions with a descent rate less than a 3° glideslope. This uncertainty regarding the vertical design prevented us from including vertical separation between the paths at the intersection.

- Designing the approach transitions such that controllers could identify whether the aircraft had selected the correct approach just after the start of the turn would reduce the collision risk drastically. The most effective method for doing this would be to design unique lateral paths for approach transitions to each runway; however, it may be possible that controllers would be able to detect differences in the vertical path or groundspeed as well.

Based on the results of the study of these operations, airspace designs that include the potential for case 2, but do not include the potential for case 3 would be approximately 1000 times safer than those that include case 3. However, for procedure design considerations, designing RF or TF EoR procedures that include unique paths for each landing runway should be a primary focus when applying these procedures to the NAS. For existing procedures, several of the collision risk mitigations discussed in this study could be highly effective and easy to implement, but unnecessary if unique paths are designed into EoR procedures. If an implementation airport or facility has a compelling interest to operate with an airspace design that potentially includes case 2 intersections, it may be possible to justify implementation using these results depending on the specific airspace design and operational concerns after further investigation of wake vortex encounter risk has occurred.

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Appendix A: Case 2 Collision Risk Sensitivity Tables

The following section provides numerical results of a one-factor-at-a-time sensitivity analysis used in section 3.2.3.

Table A-1: Reaction Time Delay and Collision Risk

Reaction time delay (seconds)	Collision risk given incorrect approach selection
7.2	1.2E-5
9.2	1.6E-5
11.2	2.2E-5
13.2	2.9E-5
15.2	3.8E-5
17.2	4.9E-5

Table A-2: Incorrectly Selected Runway Spacing and Collision Risk with Variable Runway Spacing

Incorrectly selected runway spacing (ft)	Nearest runway spacing (ft)	Collision risk given incorrect approach selection
3600	3600	1.2E-5
4100	4100	1.0E-5
4600	4600	8.8E-6
5100	5100	7.5E-6
5600	5600	6.4E-6
6100	6100	5.5E-6
6600	6600	4.7E-6
7100	7100	4.1E-6
7600	7600	3.5E-6
8100	8100	3.1E-6
8600	8600	2.7E-6

Table A-3: Incorrectly Selected Runway Spacing and Collision Risk with 3,600 ft Runway Spacing

Incorrectly selected runway spacing (ft)	Nearest runway spacing (ft)	Collision risk given incorrect approach selection
3600	3600	1.2E-5
4100	3600	8.8E-6
4600	3600	6.4E-6
5100	3600	4.7E-6
5600	3600	3.5E-6
6100	3600	2.7E-6
6600	3600	2.0E-6
7100	3600	1.5E-6
7600	3600	1.2E-6
8100	3600	9.1E-7
8600	3600	7.1E-7

Table A-4: Length of Final Approach Segment and Collision Risk

Length of final approach segment (NM)	Collision risk given incorrect approach selection
2.5	1.2E-5
5.5	1.2E-5
10.5	1.2E-5

Table A-5: Turn Radius and Collision Risk

Turn radius (NM)	Collision risk given incorrect approach selection
1.0	2.7E-5
1.5	1.9E-5
2.0	1.5E-5
2.5	1.2E-5
3.0	1.0E-5
3.5	8.7E-6
4.0	7.5E-6
4.5	6.5E-6
5.0	5.7E-6

Table A-6: Groundspeed and Collision Risk

Groundspeed (kts)	Collision risk given incorrect approach selection
150	5.8E-6
165	7.3E-6
180	8.9E-6
195	1.1E-5
210	1.2E-5
225	1.4E-5
240	1.5E-5
255	1.7E-5
270	1.8E-5
285	2.0E-5
300	2.1E-5

Table A-7: In-Trail Spacing and Collision Risk

In-trail spacing (NM)	Collision risk given incorrect approach selection
2.00	1.5E-5
2.25	1.4E-5
2.50	1.2E-5
2.75	1.1E-5
3.00	1.0E-5
3.25	9.4E-6
3.50	8.7E-6

These tables are summarized in figure A-1 where the minimum value in the leftmost column of each table is 0 percent of the parameter range and the maximum value in the leftmost column of each table is 100 percent of the parameter range.

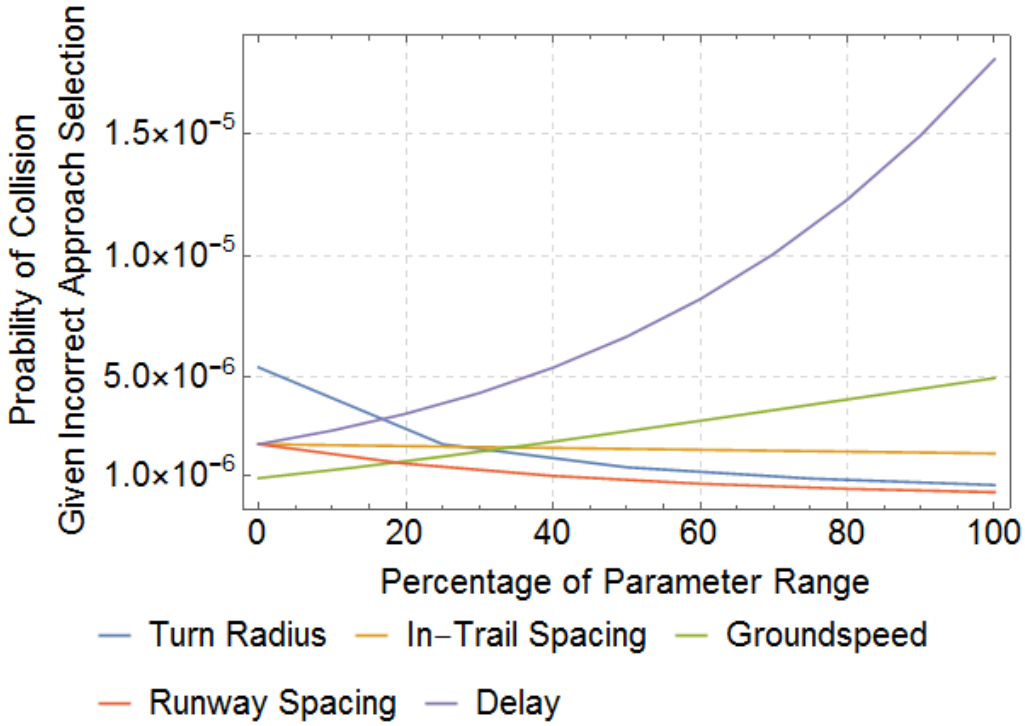

Figure A-1: One-Factor-at-a-Time Sensitivity Analysis for Case 2

Appendix B: Denver International Airport Approach Charts

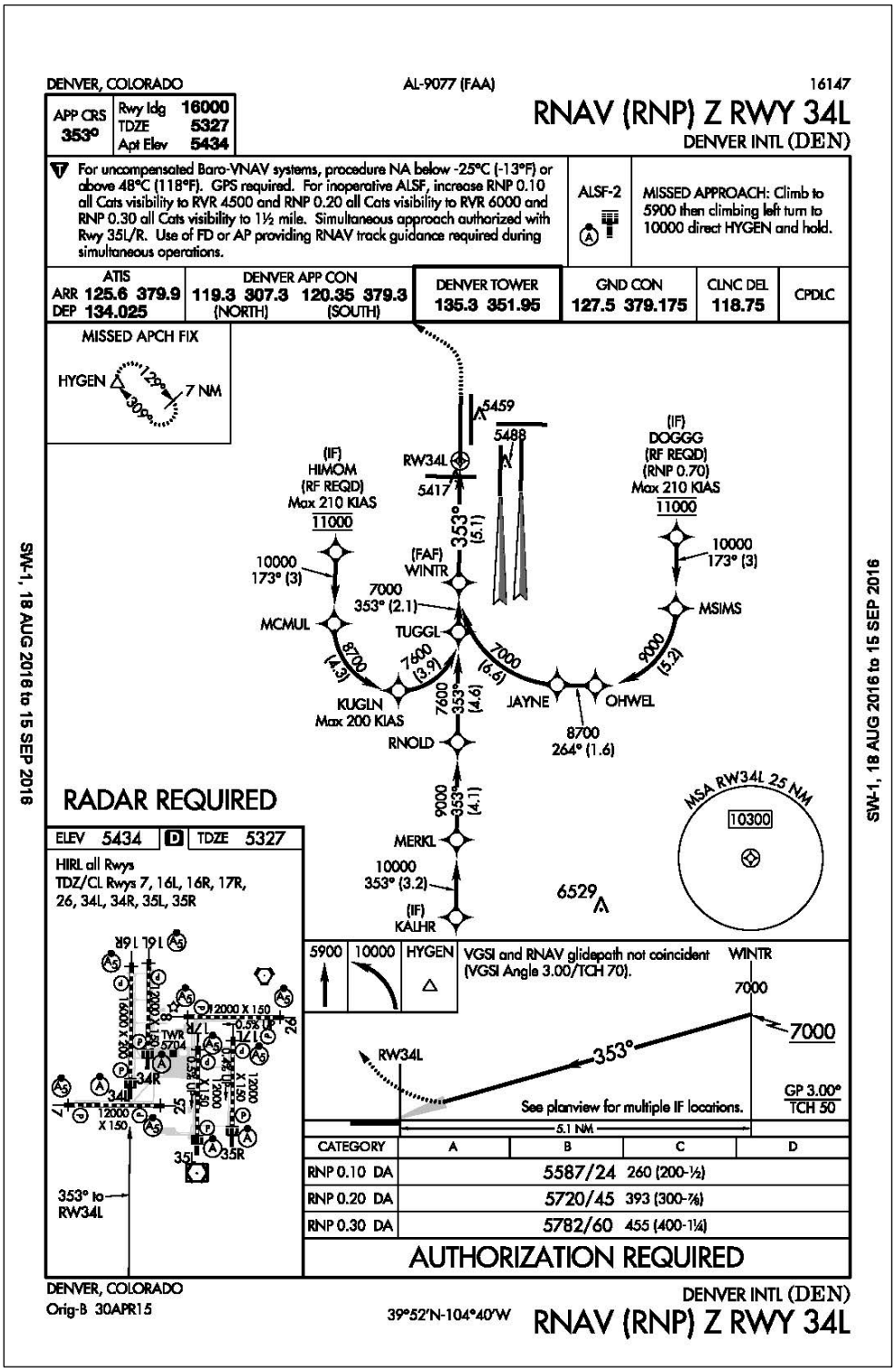

Figure B-1: Runway 34L

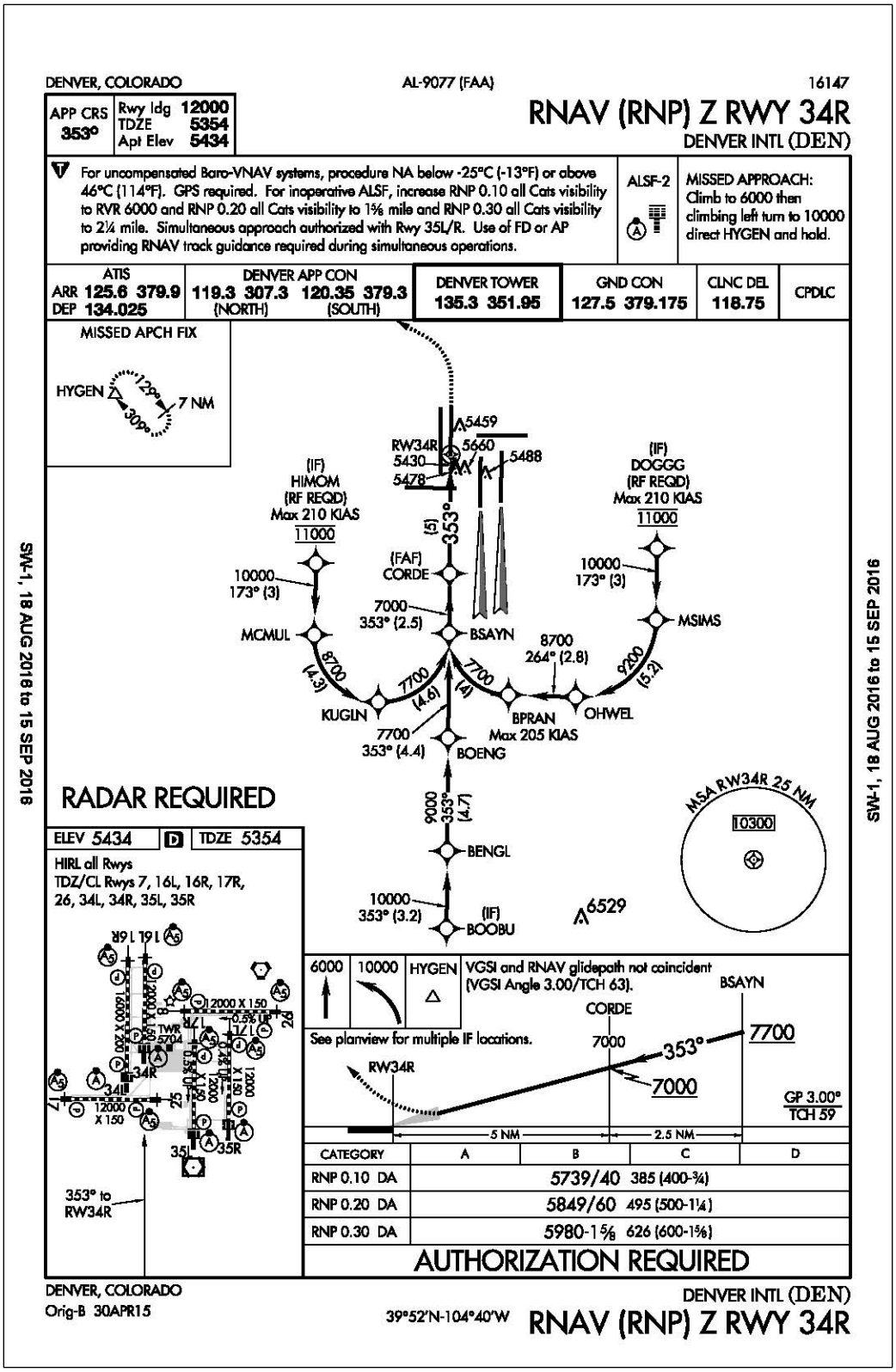

Figure B-2: Runway 34R

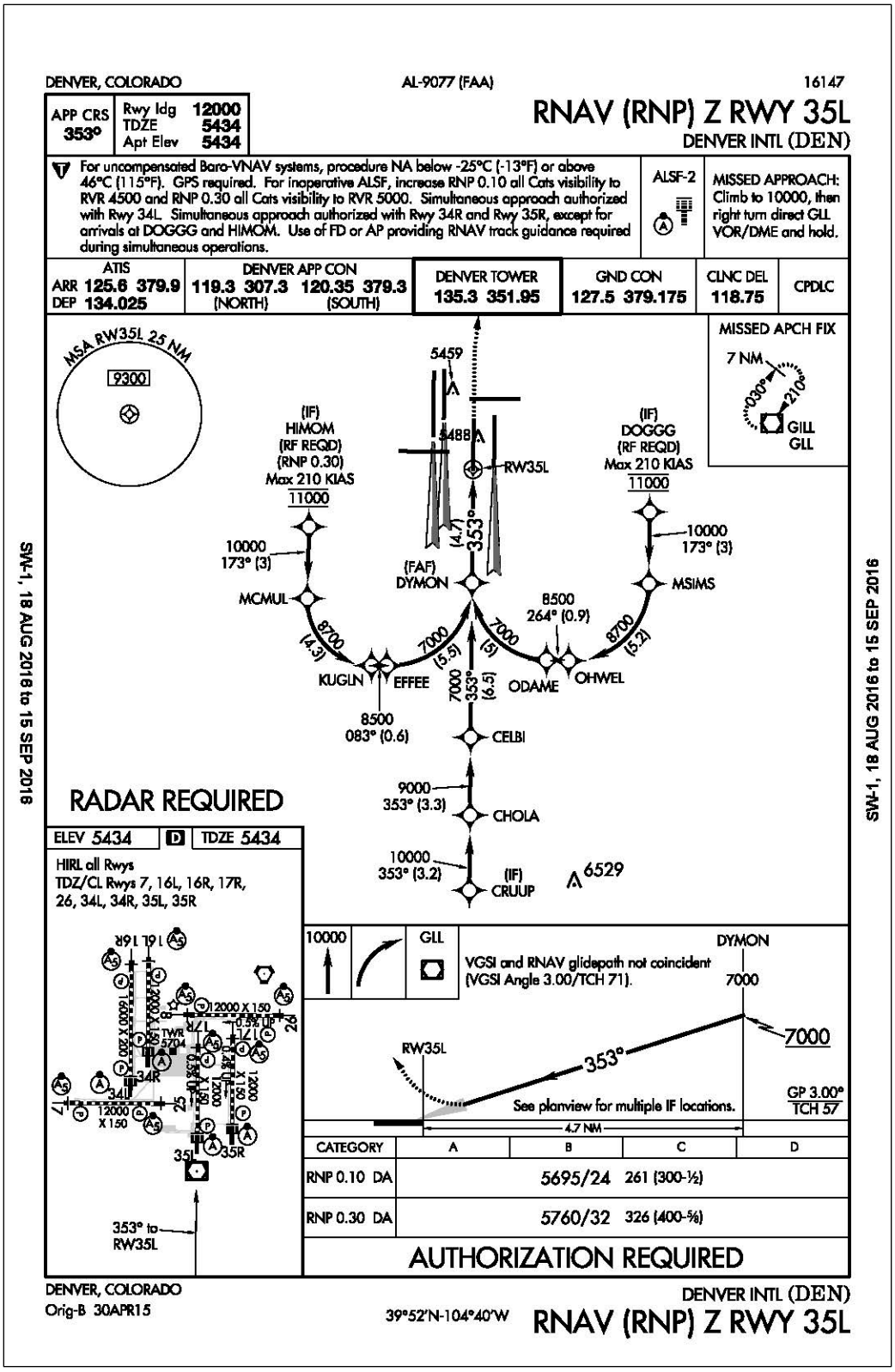

Figure B-3: Runway 35L

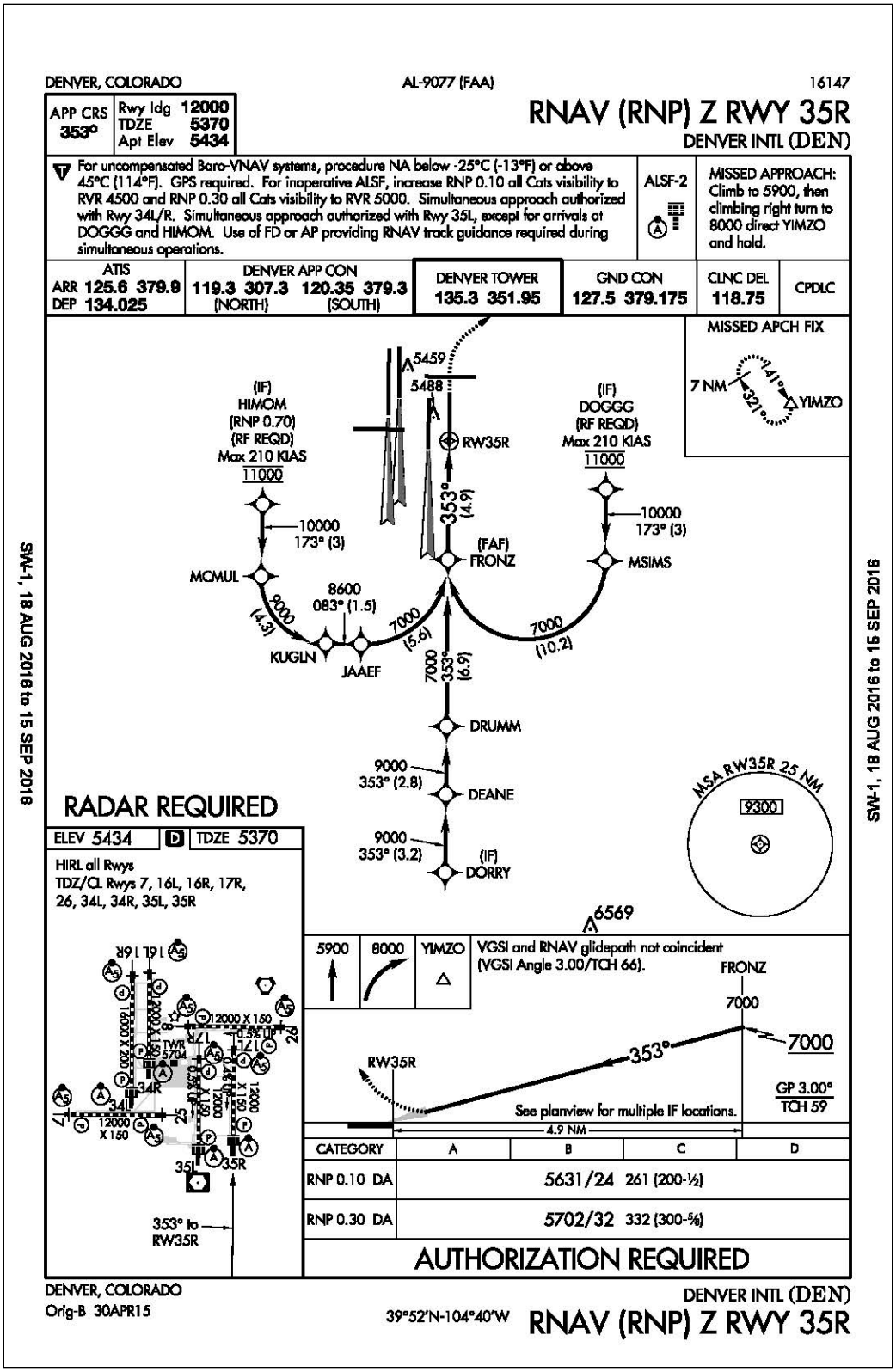

Figure B-4: Runway 35R

Appendix C: Controller Reaction Data from the TF turn study HITL Experiment

The following information was collected in a controller HITL experiment conducted from February 18 through March 3, 2015. Six different types of EoR approaches were observed for inclusion in this appendix. They were grouped into the following categories:

- Category A: Evading aircraft executes evasive maneuver;
- Category B: Evading aircraft descends during the evasive maneuver;
- Category C: Deviating aircraft only executes evasive maneuver;
- Category D: Both evading and deviating aircraft execute evasive maneuvers; and
- Category E: Significant maneuvering by both aircraft executing evasive maneuvers.
- Category F: Both aircraft experience NTZ warnings and alerts during evasive maneuvers.

In each example cited, a transcription of verbal communication between controllers and pseudo-pilots is listed, followed by a picture of the actual approaches executed. A timestamp precedes the exact communication occurring between pseudo-pilot and controller. The NTZ warning and alert time stamps are bold print and are not necessarily in chronological order, but are listed in a logical sequence for each example. Yellow dots represent NTZ warnings and red dots represent NTZ alerts.

Category A: Evading Aircraft Executes Evasive Maneuver

Example A-1: UAL 369 is left of course on the approach to runway 35 right and is crossing the NTZ into the path of UAL 300 on the approach course for runway 35 left. UAL 300 is directed to cancel the approach clearance and turn left immediately to avoid UAL 369.

Table C-1: Deviating aircraft: UAL 369 | Evading aircraft: UAL 300

Time	Direction
11:24:41	"UAL 369, turn right immediately, heading 020. Rejoin the localizer."
11:24:45	"UAL 369, roger."
11:24:45	**NTZ WARNING UAL 369**
11:24:47	"UAL 300, traffic 3 o'clock and 3 miles, turning back to the northeast. Airbus 319."
11:24:49	"UAL 369, traffic 12 o'clock and 3 miles, northeast bound at 6 thousand."
11:24:54	"UAL 300, roger, we're looking."
11:24:54	**NTZ ALERT UAL 369**
11:24:56	"UAL 369, roger traffic."
11:24:56	"UAL 300, approach clearance canceled. Turn left heading 310. Maintain 6 thousand."
11:25:03	"Heading 310, maintain 6 thousand, UAL 300."
11:25:06	"UAL 300, traffic alert. Traffic off your right side. Turn left immediately heading 310."
11:25:14	"Left turn immediately heading 310, UAL 300."

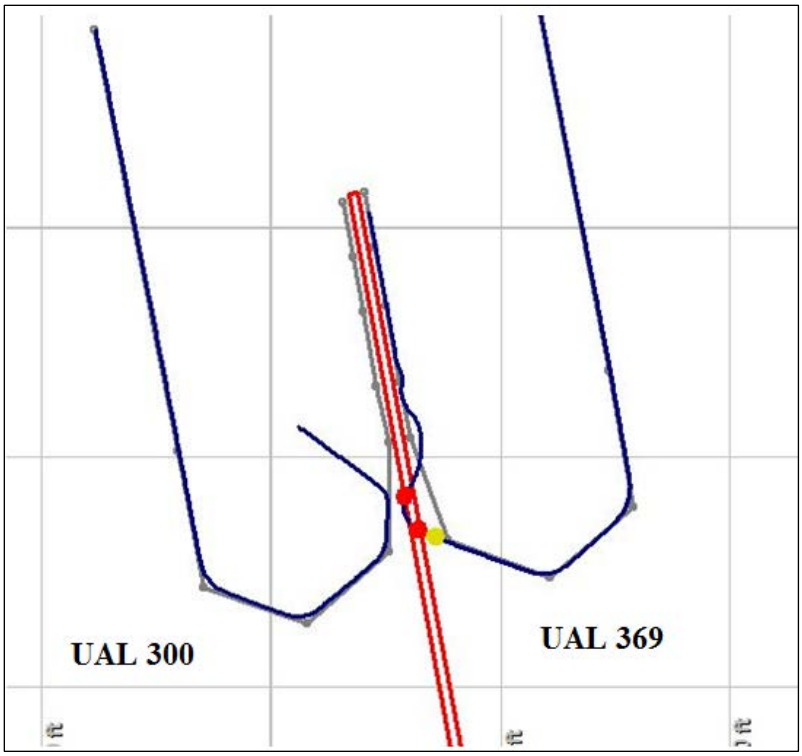

Figure C-1: Example A-1

Example A-2: SKW 6198 goes right of the approach course to runway 35 left and penetrates the NTZ. ASQ 5263 is directed off of the approach course to runway 35 right.

Table C-2: Deviating aircraft: SKW 6198 | Evading aircraft: ASQ 5263

Time	Direction
11:36:02	**NTZ WARNING SKW 6198**
11:36:04	"ASQ 5263, final monitor. Turn right immediately heading 040."
11:36:04	"SKW 6198, turn left immediately, join the localizer."
11:36:09	"Turn left to rejoin, SKW 6198."
11:36:10	"Immediately right to 040, ASQ 5263."
11:36:12	**NTZ ALERT SKW 6198**
11:36:14	"ASQ 5263 descend and maintain 6 thousand."
11:36:18	"6 thousand for ASQ 5263."
11:36:26	"ASQ 5263, continue descent and maintain 5 thousand."
11:36:31	"5 thousand for ASQ 5263."
11:36:33	"SKW 6198, maintain 6 thousand."
11:36:34	"ASQ 5263, fly heading 030 now."
11:36:36	"Maintain 6 thousand, SKW 6198."
11:36:38	"Heading 030, ASQ 5263."

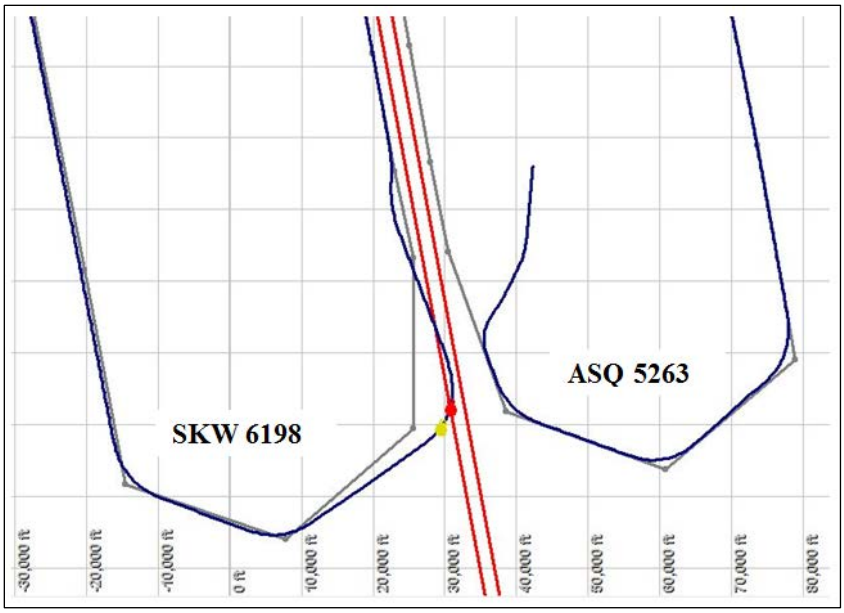

Figure C-2: Example A-2

Category B: Evading Aircraft Descends During Evasive Maneuver

Example B-1: SKW 6198 fails to follow the approach course to runway 35 left and penetrates the NTZ at 6000 ft altitude. UAL 323 is directed to turn out of the approach course and descend to 5000 ft.

Table C-3: Deviating aircraft: SKW 6198 | Evading aircraft: UAL 323

Time	Direction
11:33:00	"SKW 6198 final monitor. Cancel approach clearance. Turn left heading 360."
11:33:01	"UAL 323, final monitor. Turn right heading 040. Descend and maintain 5 thousand. Traffic 10 o'clock, 4 miles northeast bound, CRJ descending out of 6500, for the other runway."
11:33:06	"Turning left heading 360 SKW 6198."
11:33:08	"UAL 323, right to 040, descending to 5 thousand."
11:33:08	**NTZ WARNING SKW 6198**
11:33:14	"SKW 6198, turn left heading 320."
11:33:18	"Heading left 320, SKW 6198, roger."
11:33:18	**NTZ ALERT SKW 6198**
11:33:30	"SKW 6198, maintain 6 thousand, heading 320."
11:33:36	"UAL 323, fly heading 020, maintain 5 thousand. Contact departure."
11:33:37	"Maintain 6 thousand, 320 on the heading, SKW 6198."
11:33:41	"020, 5 thousand, switch to departure, UAL 323."
11:34:22	"SKW 6198, maintain 7 thousand. Contact departure.

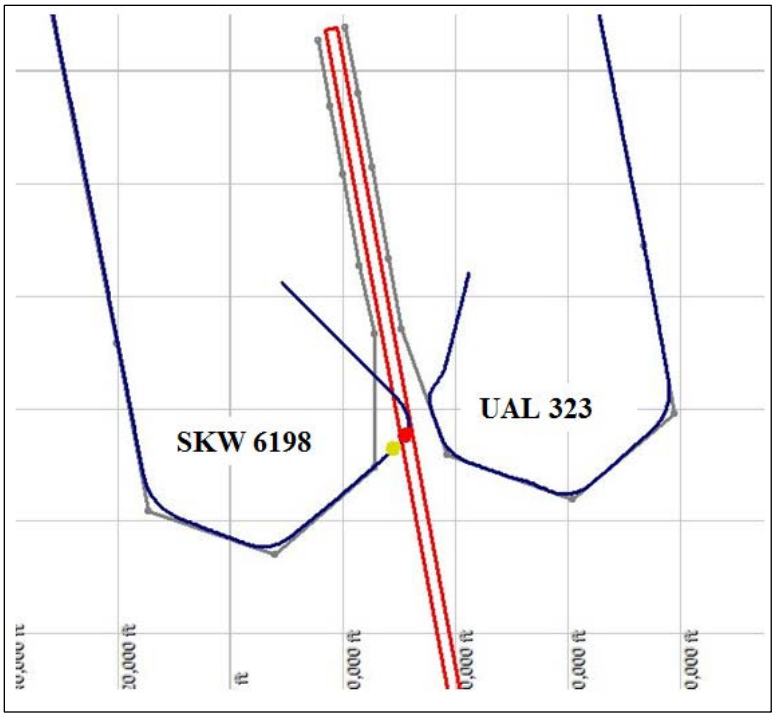

Figure C-3: Example B-1

Example B-2: ASA 742 is working a landing gear issue and requests to go-around. The problem apparently draws the flight crew off of the approach course for runway 35 left. ASA 742 penetrates the NTZ as it turns left to the directed heading at 7000 ft. ASA 180 is directed to cancel the approach clearance to runway 35 right, issued an immediate right turn, and descend to 6000 ft.

Table C-4: Deviating aircraft: ASA 742 | Evading aircraft: ASA 180

Time	Direction
11:58:08	"ASA 742, we'd like to go around. We are working a gear problem."
11:58:15	"ASA 742, roger. Fly heading 350. Maintain 7 thousand."
11:58:21	"Heading 350, 7 thousand, ASA 742."
11:58:35	"ASA 742, traffic 12 o'clock and 4 miles, Airbus 320. Turn left immediately heading 350. Climb and maintain 8 thousand."
11:58:40	"ASA 180, traffic alert. Traffic 11 o'clock and 6 miles opposite direction. A320 at 7 thousand. Descend and maintain 6 thousand."
11:58:44	**NTZ WARNING ASA 742**
11:58:45	"Roger traffic. Heading 350 and up to 8 thousand. Looking for traffic, ASA 742."
11:58:52	"ASA 180, roger, 6 thousand."
11:58:52	"ASA180, cancel approach clearance. Turn right immediately heading 030."
11:58:54	**NTZ ALERT ASA 742**
11:58:57	"Immediate right turn to 030, ASA 180."
11:58:57	"ASA 742, traffic alert. Traffic 12 o'clock and 2 miles. Climb and maintain 8 thousand immediately."
11:59:03	"Climbing to 8 thousand, ASA 742."
11:59:10	"ASA 180, turn right heading 030."
11:59:13	"ASA 180 in the turn."
11:59:15	"ASA 180, traffic no factor. Contact departure for re-sequencing."
11:59:32	"ASA 742, contact departure."
11:59:33	"Roger, switching, ASA 742."

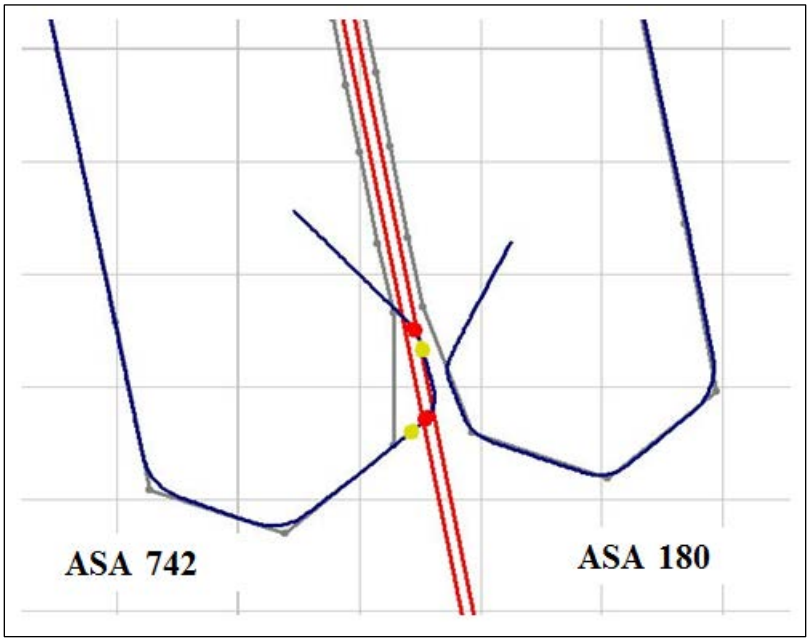

Figure C-4: Example B-2

Category C: Deviating Aircraft Executes Evasive Maneuver

Example C-1: FLG 3762 is right of the approach course for runway 35 left and is issued an immediate left turn and climb instructions. AAL 686 continues on the approach course for runway 35 right.

Table C-5: Deviating aircraft: FLG 3762 | Evading aircraft: AAL 686

Time	Direction
13:01:49	"Traffic alert FLG 3762. Traffic 12 o'clock and 5 miles. MD80 at 7 thousand. Turn left immediately heading 320. Climb and maintain 9 thousand."
13:01:56	"9 thousand, left turn to 320 immediately, FLG 3762."
13:01:59	**NTZ WARNING FLG 3762**

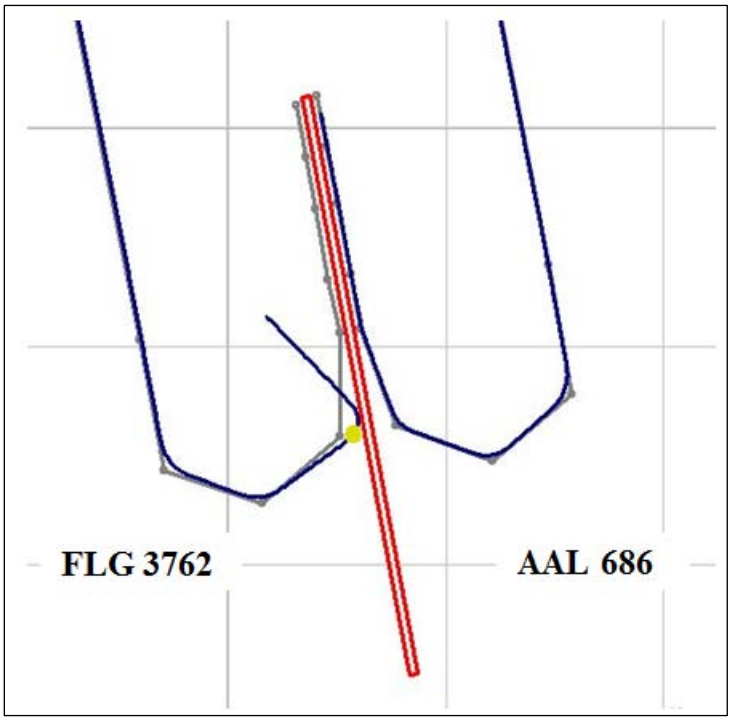

Figure C-5: Example C-1

Example C-2: SWA 681 is right of the approach course for runway 35 left and has the approach clearance canceled. SWA 681 is directed to climb and turn left. UAL 558 continues its approach to runway 35 right.

Table C-6: Deviating aircraft: SWA 681 | Evading aircraft: UAL 558

Time	Direction
11:36:04	"SWA 681, you're right of final approach course. Turn left to join the localizer."
11:36:10	"Left to rejoin the localizer, SWA 681."
11:36:12	**NTZ WARNING SWA 681**
11:36:13	"SWA 681, cancel approach clearance. Climb and maintain 8 thousand. Turn left heading 320."
11:36:20	"Cancel approach clearance. Left to 320 and 8 thousand, SWA 681."
11:36:44	"SWA 681 contact departure."
11:36:51	"SWA 681 switching."

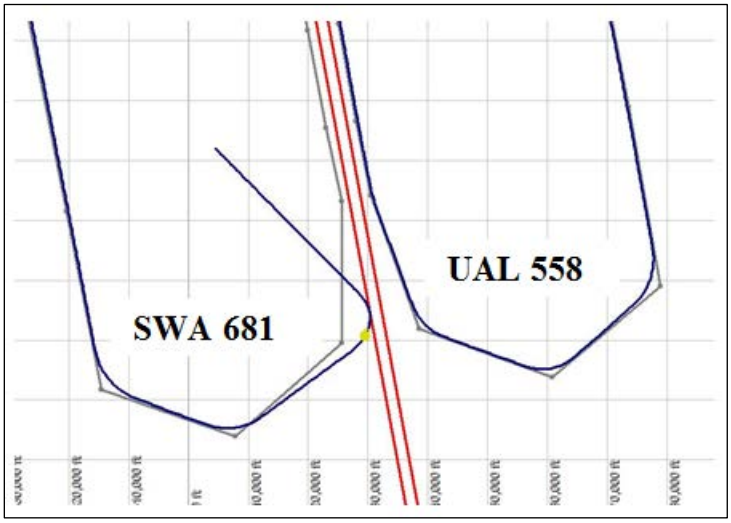

Figure C-6: Example C-2

Category D: Both Evading and Deviating Aircraft Execute Evasive Maneuvers

Example D-1: DAL 2291 overshoots the approach course for runway 35 right and is directed to turn right immediately and issued climb instructions. DAL 2012 is issued a traffic alert and directed to turn left immediately.

Table C-7: Deviating aircraft: DAL 2291 | Evading aircraft: DAL 2012

Time	Direction
13:52:39	"DAL 2291, turn right immediately. Climb and maintain 8 thousand. Fly heading 020."
13:52:43	"DAL 2012, traffic alert. Turn left heading 320 immediately. Maintain 6 thousand."
13:52:45	**NTZ WARNING DAL 2291**
13:52:50	"Heading 020 climbing to 8 thousand, DAL 2291."
13:52:50	"Maintain 6 thousand, heading left to 320, DAL 2012."
13:52:54	"DAL 2291, climb immediately. Traffic alert, 11 o'clock and 2 miles northeast bound, 6,600 Airbus 320."
13:52:55	**NTZ ALERT DAL 2291**
13:53:02	"DAL 2291, roger in the climb."
13:53:22	"DAL 2291 contact departure."
13:53:22	"DAL 2012 contact departure."

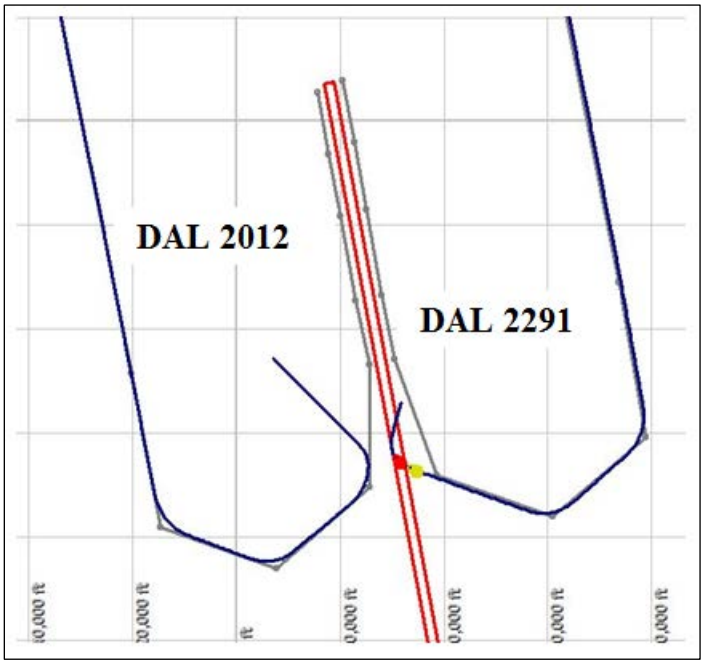

Figure C-7: Example D-1

Example D-2: SKW 6188 overshoots the approach course and is issued a cancellation for their approach clearance to runway 35 right. ASA 12 is given an immediate left turn and issued instructions to maintain 7000 ft.

Table C-8: Deviating aircraft: SKW 6188 | Evading aircraft: ASA 12

Time	Direction
13:20:23	"SKW 6188, cancel approach clearance. Turn right heading 360."
13:20:26	**NTZ WARNING SKW 6188**
13:20:27	"ASA 12, final monitor. Turn left immediately heading 040."
13:20:28	"Right 360, SKW 6188."
13:20:34	"Heading left 040, ASA 12."
13:20:36	**NTZ ALERT SKW 6188**
13:20:36	"ASA 12, turn left heading 320. Maintain 7 thousand. Traffic 2 o'clock, 2 miles turning northbound at 6 thousand and descending, 6700 and descending CRJ."
13:20:43	"SKW 6188, maintain 6 thousand, turn right heading 030."
13:20:46	"Heading 320, 7 thousand, looking for traffic, ASA 12."
13:20:48	"Maintain 6 thousand. Further right to 030, SKW 6188."
13:20:59	"ASA 12, traffic no factor. Descend and maintain 5 thousand. Fly heading 330. Contact departure."
13:21:05	"Roger, traffic no factor. 5 thousand, 330, ASA 12."

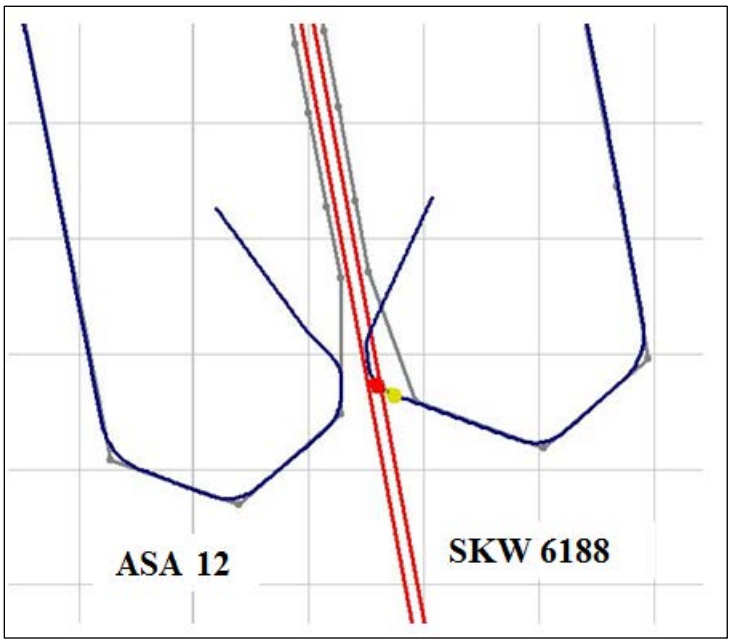

Figure C-8: Example D-2

Example D-3: DAL 2676 overshoots the approach course for runway 35 left and is issued instructions to turn left immediately to intercept the final approach course. After receiving an NTZ warning for DAL 2676, the controller issues a traffic alert, a heading of 320 climbing instructions. SWA 745 is issued a traffic alert and instructed to turn right immediately with climbing instructions.

Table C-9: Deviating aircraft: DAL 2676 | Evading aircraft: SWA 745

Time	Direction
12:54:32	"DAL 2676, turn left to intercept final approach course immediately."
12:54:38	"Turn left to intercept, DAL 2676."
12:54:40	**NTZ WARNING DAL 2676**
12:54:42	"Traffic alert, DAL 2676. Turn left immediately, heading 320. Climb and maintain 8 thousand."
12:54:50	**NTZ ALERT DAL 2676**
12:54:50	"SWA 745, traffic alert. Turn right heading 020 immediately. Climb and maintain 7 thousand."
12:54:52	"Turn left 320, climb and maintain 8 thousand, DAL 2676."
12:54:55	"Immediate right to 020, climbing to 7 thousand, SWA 745."
12:55:14	"DAL 2676 contact departure."
12:55:38	"SWA 745, contact departure."

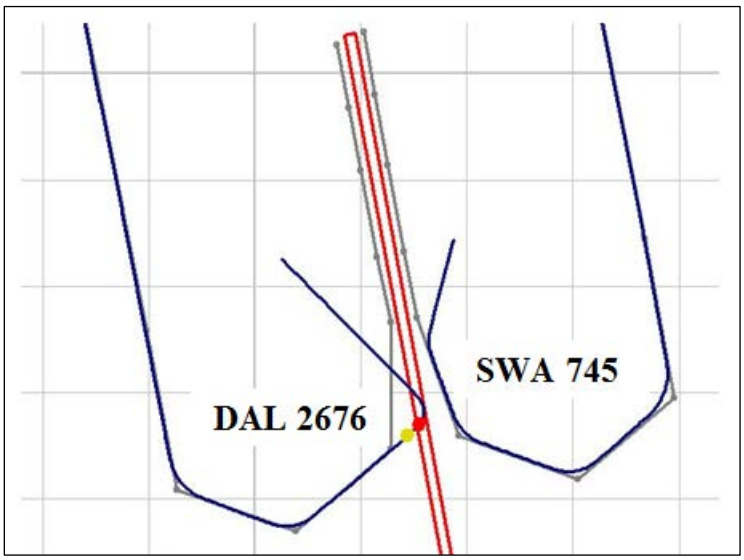

Figure C-9: Example D-3

Example D-4: SKW 6952 overshoots the approach course for runway 35 right and is issued instructions to turn right and cancel the approach clearance. FFT 510 is issued left turn instructions and cancel approach clearance for runway 35 left.

Table C-10: Deviating aircraft: SKW 6952 | Evading aircraft: FFT 510

Time	Direction
12:04:36	**NTZ WARNING SKW 6952**
12:04:37	"SKW 6952, cancel approach clearance. Turn right heading 070."
12:04:37	"FFT 510, cancel approach clearance. Turn left 360, maintain 7 thousand."
12:04:44	"Left to 360, maintain 7 thousand, FFT 510."
12:04:54	**NTZ ALERT SKW 6952**
12:04:56	"SKW 6952, maintain 6 thousand. Fly heading 050 now."
12:04:56	"FFT 510, turn left heading 320."
12:05:00	"FFT 510, roger, heading 320."
12:05:01	"6 thousand, heading 050, SKW 6952."
12:05:15	"SKW 6952, turn left heading 010. Maintain 5 thousand, contact departure."
12:05:21	"010, 5 thousand, SKW 6952."
12:05:23	"FFT 510, contact departure."
12:05:25	"FFT 510, roger, switching."

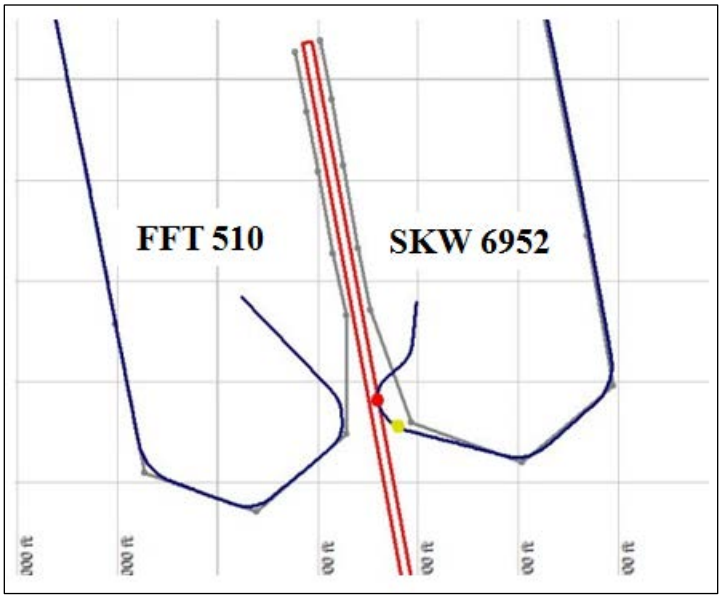

Figure C-10: Example D-4

Example D-5: ASQ 5564 requests a go-around for a landing gear problem on the approach course for runway 35 left. The controller cancels the approach clearance and issues left turn instructions. ASQ 5564 penetrates the NTZ as a left turn is initiated. SKW 6497 on the approach course for runway 35 right is issued a right turn and cancel approach clearance instructions.

Table C-11: Deviating aircraft: ASQ 5564 | Evading aircraft: SKW 6497

Time	Direction
12:26:36	"ASQ 5564, we'd like to go around. Working a gear problem."
12:26:53	"ASQ 5564, cancel approach clearance. Turn left heading 320. Maintain 7 thousand."
12:27:00	"Left to 320, 7 thousand, ASQ 5564."
12:27:02	"SKW 6497, final monitor. Cancel approach clearance. Turn right heading 030. Maintain 5 thousand."
12:27:08	"Right turn 030, maintain 5 thousand, SKW 6497."
12:27:08	"ASQ 5564, traffic alert. Traffic 1 o'clock and 6 miles westbound CRJ at 7 thousand."
12:27:12	**NTZ WARNING ASQ 5564**
12:27:16	"Roger, looking, ASQ 5564."
12:27:26	**NTZ ALERT ASQ 5564**
12:27:29	"ASQ 5564, confirm you are in your turn now."
12:27:32	"ASQ 5564, affirmative. We are in our turn to 320."

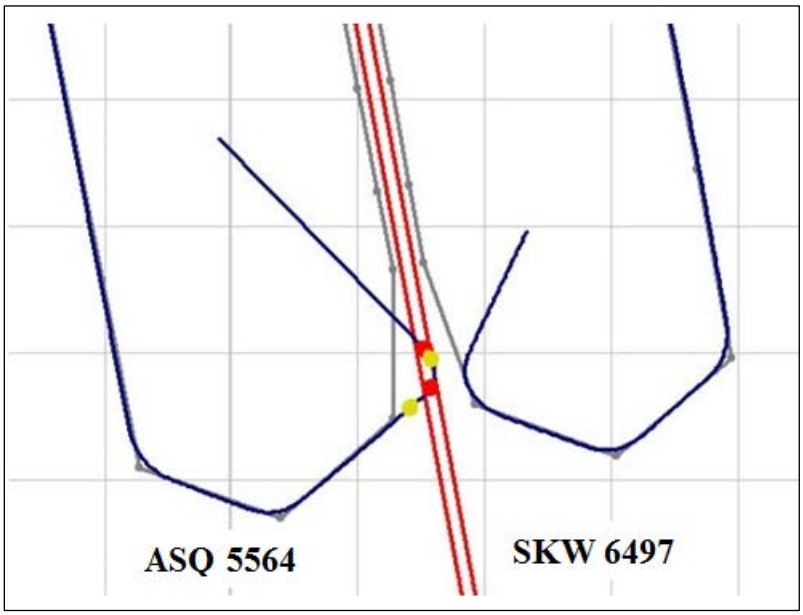

Figure C-11: Example D-5

Category E: Significant Maneuvering by Both Aircraft Executing Evasive Maneuvers

Example E-1: TRS 538 overshoots the approach course to runway 35 right and is given an immediate right turn to rejoin the course. In close proximity, TRS 850 on the approach course for runway 35 left is issued instructions to turn right and maintain 7000 ft, passing behind TRS 538. TRS 538 is then issued instructions to immediately descend to 5000 ft, turn right and the approach clearance is canceled. The controller attempts to save the approach for TRS 850 by turning the aircraft back onto the approach course for runway 35 left but ends up canceling the approach clearance.

Table C-12: Deviating aircraft: TRS 538 | Evading aircraft: TRS 850

Time	Direction
11:56:56	"TRS 538, looks like you overshot the final approach course. Turn right immediately and rejoin arrival."
11:56:59	**NTZ WARNING TRS 538**
11:57:00	"TRS 850, turn right, heading 110. Maintain 7 thousand."
11:57:04	"TRS 538, roger, turn right to rejoin."
11:57:08	"Heading right 110, 7 thousand, TRS 850."
11:57:08	**NTZ ALERT TRS 538**
11:57:11	"TRS 538, descend immediately. Maintain 5 thousand."
11:57:16	"TRS 538, roger."
11:57:24	"TRS 538, maintain 5 thousand. Cancel approach clearance. Fly heading 030."
11:57:27	"TRS 850, turn left now heading 330. Intercept the localizer. Maintain 7 thousand."
11:57:29	"Heading 030, TRS 538."
11:57:33	"Turn left 320 to intercept, TRS 850."
11:57:46	"TRS 538, fly heading 020. Contact departure."
11:57:51	"Heading 020, 5 thousand, contact departure, TRS 538."
11:58:12	"TRS 850, turn left heading 280. Descend and maintain 6 thousand."
11:58:19	"Descending to 6 thousand, heading 280, TRS 850."
11:58:40	"TRS 850, turn right heading 350. 3 from the marker. Maintain 6 thousand until established. Cleared ILS 35 left approach."
11:58:53	"TRS 850, roger, will do our best."
11:59:32	"TRS 850, cancel approach clearance. Maintain 6 thousand and present heading. Contact departure."
11:59:39	"Roger, present heading, 6 thousand. Contact departure, TRS 850."

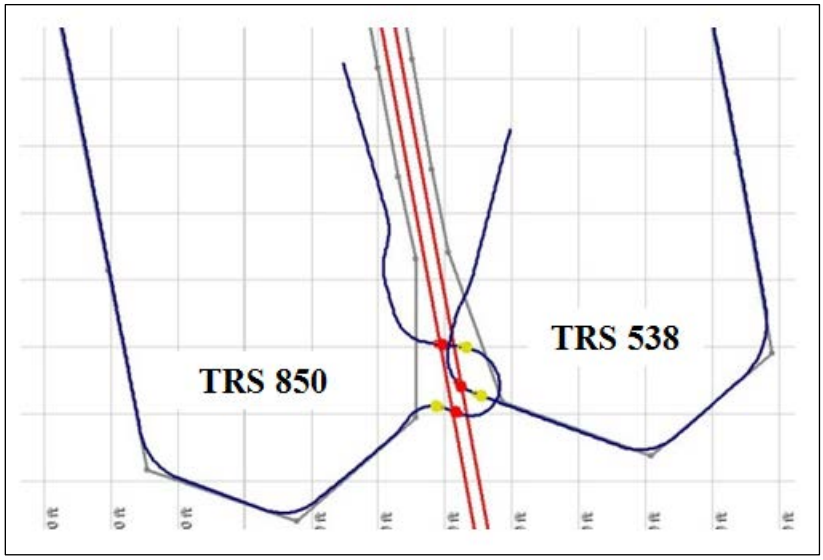

Figure C-12: Example E-1

Example E-2: UAL 283 is right of the approach course for runway 35 left and is issued instructions to turn left to heading 300. FFT 234 is issued instructions to maintain 7000 ft and cancel the approach clearance. Once UAL 283 is established on heading 330, FFT 234 is instructed to turn left to pass behind UAL 283 and head back out for re-sequencing into the arrival traffic pattern.

Table C-13: Deviating aircraft: UAL 283 | Evading aircraft: FFT 234

Time	Direction
11:53:52	**NTZ WARNING UAL 283**
11:53:52	"UAL 283, turn left heading 300."
11:53:53	"FFT 234, final monitor. Maintain 7 thousand. Cancel approach clearance."
11:53:57	"Left to 300, UAL 283."
11:53:58	"7 thousand, FFT 234, roger."
11:54:05	"FFT 234, turn left heading 220."
11:54:07	**NTZ ALERT UAL 283**
11:54:10	"Left 220, FFT 234."
11:54:12	"UAL 283, traffic alert. Traffic 2 o'clock and 3 miles, westbound Airbus 319."
11:54:17	"UAL 283, roger traffic, we're looking."
11:54:29	"UAL 283, fly heading 320. Contact departure."
11:54:33	"320, contact departure, UAL 283."
11:54:40	**NTZ WARNING FFT 234**
11:54:45	**NTZ ALERT FFT 234**
11:54:52	"FFT 234, turn left heading 190."
11:54:58	"Left turn 190, FFT 234."
11:55:01	"FFT 234, descend and maintain 5 thousand. Contact departure."

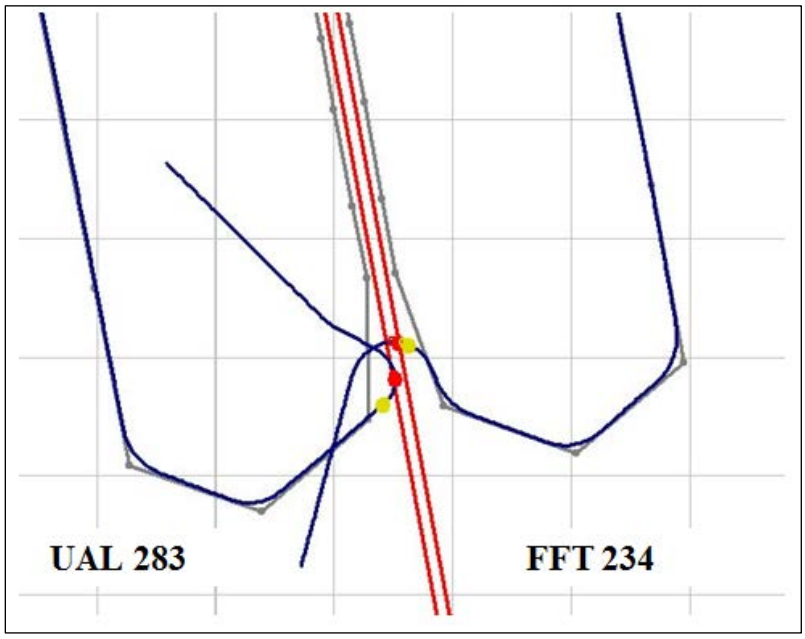

Figure C-13: Example E-2

Example E-3: ASA 142 overshoots the approach course for runway 35 right and is issued a traffic alert and right turn instructions. SWA 161, having been cleared for the approach, is directed to turn left and fly a new heading of 320 and maintain 7000 ft. ASA 142 is directed to climb to 9000 ft and is issued a traffic alert for SWA 161 directly 1 mile ahead at 7000 ft. Then the controller issues instructions to maintain present altitude of 6500 ft. ASA 142 in a right turn back to the approach course for runway 35 right passes behind SWA 161. The controller attempts to return SWA 161 to the approach course for runway 35 left.

Table C-14: Deviating aircraft: ASA 142 | Evading aircraft: SWA 161

Time	Direction
13:37:14	"SWA 161, runway 35 left. Cleared to land."
13:37:19	"Runway 35 left, cleared to land, SWA 161."
13:37:39	**NTZ WARNING ASA 142**
13:37:40	"ASA 142, turn right heading 040. Maintain 7 thousand. Traffic alert. 12 o'clock and 5 miles 7 thousand. Boeing 737 for the parallel runway."
13:37:41	"SWA 161, final monitor. Turn left heading 320. Maintain 7 thousand."
13:37:46	"Turn left 320, maintain 7 thousand, SWA 161."
13:37:49	**NTZ ALERT ASA 142**
13:38:00	"ASA 142, climb and maintain 9 thousand. Traffic alert, 12 o'clock and 1 mile northbound, 6700 descending."
13:38:16	"ASA 142, turn right heading 070. Maintain present altitude. Traffic just ahead and to your left, 800 and climbing. Maintain 6500."
13:38:26	"Roger, right to 070. Maintain 6500, ASA 142."
13:39:03	"ASA 142, turn left heading 030. Maintain 6500."
13:39:07	"SWA 161, turn left heading 330."
13:39:10	"Left to 030, 6500, ASA 142."
13:39:12	"Heading left 330, SWA 161."
13:39:28	"ASA 142, climb and maintain 8 thousand."
13:39:30	"8 thousand, ASA 142."
13:39:33	"SWA 161, turn right heading 250. Maintain 8 thousand."
13:39:40	"SWA 161, heading right 250, 8 thousand."

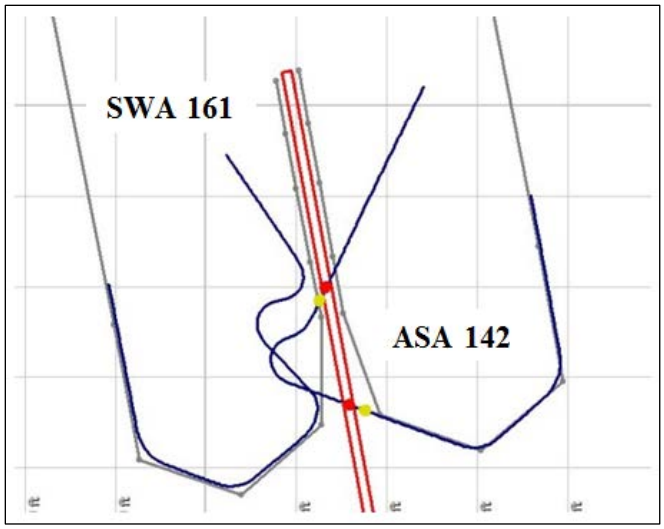

Figure C-14: Example E-3

Example E-4: TRS 55 overshoots the approach course for runway 35 right and is given a heading to 030. SKW 6878 is cleared for the approach to runway 35 left but is kept at 7000 ft. TRS 55 is instructed to turn right for vectors to final approach course. SKW 6878's clearance is canceled and issued a left turn to heading 320.

Table C-15: Deviating aircraft: TRS 55 | Evading aircraft: SKW 6878

Time	Direction
12:08:18	**NTZ WARNING TRS 55**
12:08:21	"TRS 55, final monitor. Turn right heading 030."
12:08:25	"Right to 030, TRS 55."
12:08:32	**NTZ ALERT TRS 55**
12:08:34	"SKW 6878, stop your descent. Maintain 7 thousand."
12:08:37	"Roger, will stop at 7 thousand, SKW 6878."
12:08:39	"SKW 6878, traffic, 2 o'clock and 3 miles, northwest bound 737 at 6300 descending."
12:08:47	"SKW 6878, roger. Looking."
12:09:00	"SKW 6878, cleared to land runway 35 left."
12:09:07	"SKW 6878, you are 5 and ½ miles from the final approach fix. Cross the final approach fix at above 4500. Cleared ILS 35 left approach."
12:09:17	"SKW 6878, roger."
12:09:20	"SKW 6878, maintain 190 knots until final approach fix."
12:09:54	**NTZ WARNING SKW 6878**
12:09:55	"SKW 6878, cancel approach clearance. Turn left heading 320. Climb and maintain 5 thousand."
12:10:01	"Heading 320. Maintain 5 thousand, SKW 6878."
12:10:35	"TRS 55, turn right heading 190. Vectors to final approach course."
12:10:39	"Right to 190, TRS 55."
12:11:11	"TRS 55, descend and maintain 5 thousand."
12:11:14	"5 thousand, TRS 55."

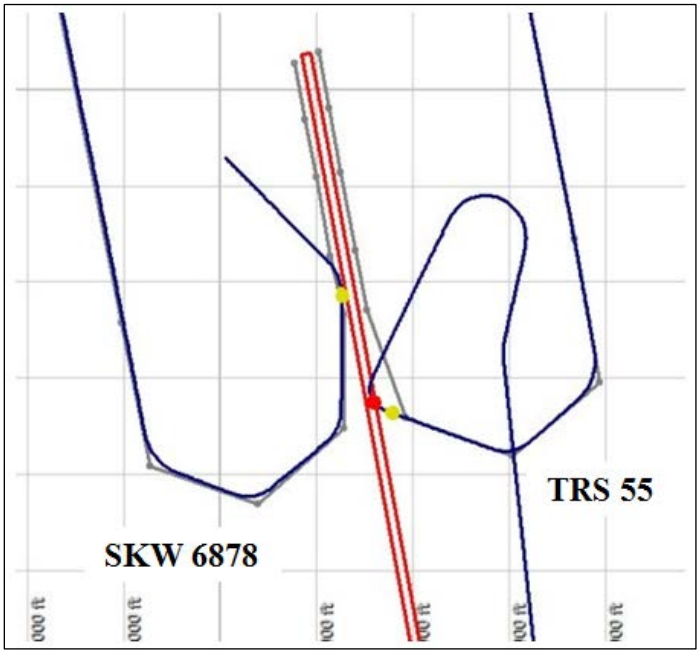

Figure C-15: Example E-4

Category F: Both Aircraft Experience NTZ Warnings/Alerts During Evasive Maneuvers

Example F-1: Both aircraft in this example have their approach clearances canceled as they overshoot their designated runways. SWA 20 is instructed to expedite down to 6000 ft for altitude separation.

Table C-16: Deviating aircraft: ASA 702 | Evading aircraft: SWA 20

Time	Direction
1:09:00	"ASA 702, turn right, heading 040, cancel approach clearance. Maintain 7 thousand."
1:09:07	"Right to 040, 7 thousand, ASA 702."
1:09:08	**NTZ WARNING ASA 702**
1:09:11	"SWA 20, expedite down to 6 thousand."
1:09:16	"6 thousand expedite, SWA 20."
1:09:18	"ASA 702, crossing the NTZ. Cancel approach clearance. Maintain 7 thousand, heading 050."
1:09:23	**NTZ ALERT ASA 702**
1:09:59	"ASA 702, contact departure."
1:10:06	"Switching, ASA 702."
1:10:16	"SWA 20, turn left to rejoin."
1:10:20	"Left to rejoin, SWA 20."
1:10:23	"SWA 20 expedite descent to 4 thousand now."
1:10:25	**NTZ WARNING SWA 20**
1:10:26	"SWA 20, down to 4 thousand."
1:10:28	"SWA 20, turn left heading 320. You're going through the localizer and final approach course."
1:10:35	**NTZ ALERT SWA 20**
1:10:35	"Heading now 320, SWA 20."
1:11:11	"SWA 20 climb and maintain 5 thousand. Fly heading 340."
1:11:15	"Fly heading 340, 5 thousand. SWA 20."

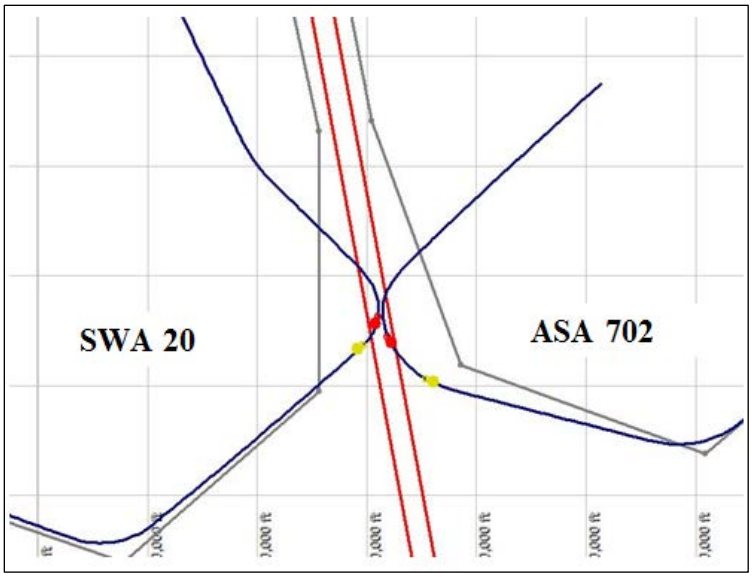

Figure C-16: Example F-1

Appendix D: Pilot Reaction Data from the TF turn study HITL Experiment

The following information was collected in a pilot human-in-the-loop experiment conducted from January 12 through January 30, 2015.

The runs selected for determination of pilot response times to execute an evasion were those where the controller issued a breakout instruction to the evading aircraft, and the flight crew did not make visual contact with the deviating aircraft during the approach. There were 18 test runs that met these criteria.

In previous CSPO studies, the pilot response time for executing an evasion was calculated from "the instant the controller pressed the push-to-talk button, until the pilot made an input to either the roll or throttle control."[31] The roll control input was used to simulate the turn initiation. In the EoR TF HITL experiment, however, the aircraft was on the 10° intercept leg in a quartering crosswind, either in a bank or about to bank in order to transition to the final approach course. This made it impossible to apply the CSPO algorithm. In the EoR TF study, therefore, we used an algorithm based on previous work for the Multiple Parallel Approach Program which determined pilot response using the change in heading from the final approach course.[32, 33] However, due to the position of the aircraft at the time of the evasion command, we determined that these reactions were extremely conservative. For this study, we calculated the pilot response using a technique used in later studies in the Multiple Parallel Approach Program, which used the bank angle of the aircraft.[34]

For this study, the pilot response time for evasion was the time elapsed from the controller pressing the push-to-talk button to the time the aircraft corrected by achieving a bank angle of 7.5° for the B737 or 12.5° for the A330. These values were selected to be certain the evaluated bank angle was the result of pilot compliance with the breakout instruction, and not due to bank angles commanded during nominal flight of the approach. Once the maximum was identified, the point in time prior to the maximum bank angle where the target bank angle was achieved was identified as the time for aircraft correction.

In all but one evaluated case, the target bank angle was determined to be the first occurrence of the bank angle following the breakout instruction. Figure D-1 depicts a representative example.

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[31] Flight Systems Laboratory. *DOT-FAA-AFS-450-67, Report on Pilot Response Times from the March 2010 Human in the Loop Data Collection Effort* (Flight Technologies and Procedures Division, Federal Aviation Administration, June 2011).

[32] Flight Technologies and Procedures Division, *DOT/FAA/AFS400/2016/R/01*.

[33] ATC Simulation Team. *DOT/FAA/CT-92/16, I, Evaluation of Triple Simultaneous Parallel ILS Approaches Spaced 4300 Feet Apart, Final Monitor Aid with Simulated Radar 4.8 Second Update Rate* (FAA Technical Center, Federal Aviation Administration, November 1993).

[34] Ozmore, Richard E. and Sherri L. Morrow. *DOT/FAA/CT-96/2, Evaluation of Dual Simultaneous Instrument Landing System Approaches to Runways Spaced 3000 Feet Apart with One Localizer Offset Using a Precision Runway Monitor System* (William J. Hughes Technical Center, Federal Aviation Administration, September 1996).

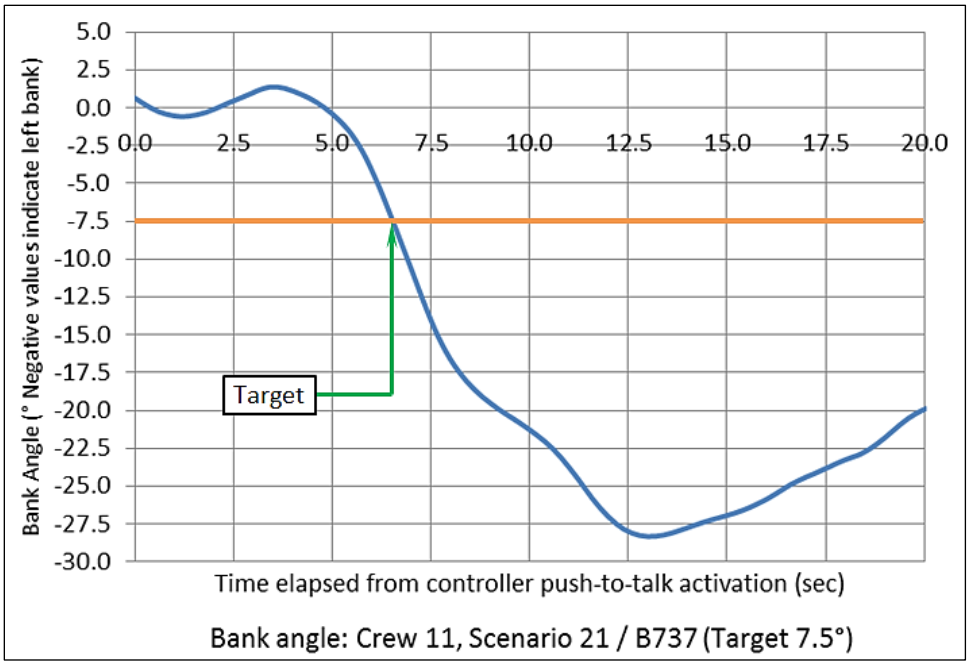


Figure D-1: Representative Bank Angle after Controller Instruction

In one instance, the test aircraft initially achieved the target bank angle, but rolled back to wings level before initiating the turn for the controller instruction compliance. In this case, the latest incident of target bank angle prior to maximum bank was utilized as the point for reaction time determination. From a review of flight track data for this particular test, it would appear likely the turn shortly after the controller initiated the breakout instruction was a correction back to the approach path after a slight overshoot during a turn. Figure D-2 depicts the bank angle data for this flight.

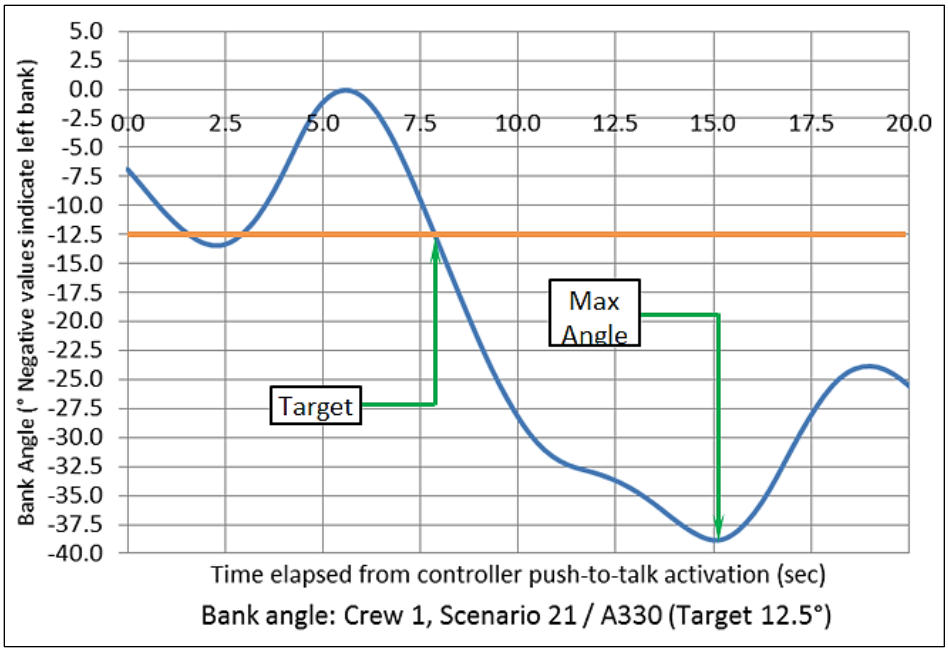


Figure D-2: Bank Angle after Controller Instruction with Turn Prior to Target Angle

Summary of Results

The summary of results for the 18 test scenarios evaluated to determine pilot reaction time is shown in table D-1.

Table D-1: Time from Controller Breakout Instruction to Achieve Target Bank Angle

Crew	Scenario	Aircraft	Elapsed Time (sec)
1	21	A330	7.919
5	21	A330	20.789
8	9	A330	7.721
8	21	A330	5.742
8	22	A330	10.098
9	21	A330	10.889
11	21	B737	6.599
13	21	B737	8.999
14	9	B737	12.198
15	9	B737	5.000
16	21	B737	5.200
17	9	B737	11.398
17	21	B737	9.199
17	22	B737	6.399
18	9	B737	6.399
20	9	B737	5.999
20	21	B737	3.999
20	22	B737	7.199

Appendix E: Supporting Tables

This appendix contains numerical results that may be relevant to some readers or that were used to generate the visualizations seen throughout the report.

Table E-1: Time Available for Air Traffic Intervention before Wake Separation Violation

Runway spacing	Groundspeed	Turn radius	Available time
3600	180	2	12.79361
3600	180	3	13.08735
3600	180	4	13.28112
3600	210	2	12.69644
3600	210	3	12.97694
3600	210	4	13.13289
3600	260	2	12.60006
3600	260	3	12.9044
3600	260	4	13.02773
3600	310	2	12.52659
3600	310	3	12.89684
3600	310	4	13.01493
4100	180	2	13.97425
4100	180	3	14.53563
4100	180	4	14.95477
4100	210	2	13.68569
4100	210	3	14.19946
4100	210	4	14.55099
4100	260	2	13.36566
4100	260	3	13.86322
4100	260	4	14.14775
4100	310	2	13.13902
4100	310	3	13.67455
4100	310	4	13.93029
4600	180	2	15.11912
4600	180	3	15.93522
4600	180	4	16.5694
4600	210	2	14.64624
4600	210	3	15.38207
4600	210	4	15.92016
4600	260	2	14.11079
4600	260	3	14.79245
4600	260	4	15.23073
4600	310	2	13.7365
4600	310	3	14.42974
4600	310	4	14.81684

Runway spacing	Groundspeed	Turn radius	Available time
5100	180	2	16.23214
5100	180	3	17.29142
5100	180	4	18.13144
5100	210	2	15.58115
5100	210	3	16.52901
5100	210	4	17.24564
5100	260	2	14.83752
5100	260	3	15.69509
5100	260	4	16.2805
5100	310	2	14.32045
5100	310	3	15.16458
5100	310	4	15.67744
5600	180	2	17.31663
5600	180	3	18.60867
5600	180	4	19.64625
5600	210	2	16.49302
5600	210	3	17.64384
5600	210	4	18.53181
5600	260	2	15.54762
5600	260	3	16.57368
5600	260	4	17.30029
5600	310	2	14.8921
5600	310	3	15.88094
5600	310	4	16.51451
6100	180	2	18.37543
6100	180	3	19.89073
6100	180	4	21.11837
6100	210	2	17.38406
6100	210	3	18.72961
6100	210	4	19.78238
6100	260	2	16.2426
6100	260	3	17.43043
6100	260	4	18.29284
6100	310	2	15.45251
6100	310	3	16.58044
6100	310	4	17.33013
6600	180	2	19.41097
6600	180	3	21.14082
6600	180	4	22.55169
6600	210	2	18.25621
6600	210	3	19.78892
6600	210	4	21.00056

Runway spacing	Groundspeed	Turn radius	Available time
6600	260	2	16.92382
6600	260	3	18.26723
6600	260	4	19.26053
6600	310	2	16.00264
6600	310	3	17.26447
6600	310	4	18.12611
7100	180	2	20.42536
7100	180	3	22.36173
7100	180	4	23.94955
7100	210	2	19.11116
7100	210	3	20.82404
7100	210	4	22.18908
7100	260	2	17.59244
7100	260	3	19.08572
7100	260	4	20.20541
7100	310	2	16.54332
7100	310	3	17.93426
7100	310	4	18.90402
7600	180	2	21.42048
7600	180	3	23.55587
7600	180	4	25.31484
7600	210	2	19.95038
7600	210	3	21.83695
7600	210	4	23.35036
7600	260	2	18.24952
7600	260	3	19.88735
7600	260	4	21.12928
7600	310	2	17.0753
7600	310	3	18.5909
7600	310	4	19.66523
8100	180	2	22.39796
8100	180	3	24.72539
8100	180	4	26.65013
8100	210	2	20.77519
8100	210	3	22.82939
8100	210	4	24.48648
8100	260	2	18.89597
8100	260	3	20.67341
8100	260	4	22.03371
8100	310	2	17.59926
8100	310	3	19.23535
8100	310	4	20.41099

Runway spacing	Groundspeed	Turn radius	Available time
8600	180	2	23.35927
8600	180	3	25.87216
8600	180	4	27.95766
8600	210	2	21.58676
8600	210	3	23.8029
8600	210	4	25.59931
8600	260	2	19.53264
8600	260	3	21.44504
8600	260	4	22.92012
8600	310	2	18.11581
8600	310	3	19.86849
8600	310	4	21.14236

Table E-2: Conservative Times Required for Successful Controller-Induced Pilot Evasion

Delay	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/10,000 threshold	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/1000 threshold	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/100 threshold	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/10 threshold
2.2	51.6	41.7	31.7	21.4
3.2	52.6	42.7	32.7	22.4
4.2	53.6	43.7	33.7	23.4
5.2	54.6	44.7	34.7	24.4
6.2	55.6	45.7	35.7	25.4
7.2	56.6	46.7	36.7	26.4
8.2	57.6	47.7	37.7	27.4
9.2	58.6	48.7	38.7	28.4
10.2	59.6	49.7	39.7	29.4
11.2	60.6	50.7	40.7	30.4
12.2	61.6	51.7	41.7	31.4
13.2	62.6	52.7	42.7	32.4
14.2	63.6	53.7	43.7	33.4
15.2	64.6	54.7	44.7	34.4
16.2	65.6	55.7	45.7	35.4
17.2	66.6	56.7	46.7	36.4
Model	62.7	52.8	42.8	32.4

Table E-3: Optimistic Times Required for Successful Controller-Induced Pilot Evasion

Delay	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/10,000 threshold	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/1000 threshold	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/100 threshold	Number of seconds that the aircraft continues to be at risk after FMA caution, with a 1/10 threshold
2.2	41.2	33.4	25.5	16.9
3.2	42.2	34.4	26.5	17.9
4.2	43.2	35.4	27.5	18.9
5.2	44.2	36.4	28.5	19.9
6.2	45.2	37.4	29.5	20.9
7.2	46.2	38.4	30.5	21.9
8.2	47.2	39.4	31.5	22.9
9.2	48.2	40.4	32.5	23.9
10.2	49.2	41.4	33.5	24.9
11.2	50.2	42.4	34.5	25.9
12.2	51.2	43.4	35.5	26.9
13.2	52.2	44.4	36.5	27.9
14.2	53.2	45.4	37.5	28.9
15.2	54.2	46.4	38.5	29.9
16.2	55.2	47.4	39.5	30.9
17.2	56.2	48.4	40.5	31.9
Model	52.6	44.8	36.8	27.9

Table E-4: Standard Deviation Probability Exceptions

Number of standard deviations	0	1	2	3	4	5	6
Probability of exceeding N standard deviations	0.50	0.16	2.3E-2	1.3E-3	3.2E-5	2.9E-7	9.9E-10

Table E-5: Probability of Wake Separation Violation

Runway spacing (ft)	Probability of wake separation violation
3600	0.99792
3900	0.987616
4200	0.96629
4500	0.933775
4800	0.891091
5100	0.839697
5400	0.781118
5700	0.716774
6000	0.647907
6300	0.575614
6600	0.50292
6900	0.43418
7200	0.371662
7500	0.316205
7800	0.267837
8100	0.226147
8400	0.190517
8700	0.16025
9000	0.134656

Table E-6: In-Trail Spacing at 2 NM

Groundspeed	Turn Radius	Collision Risk
150	1	0.310976
150	2	0.3232
150	3	0.332609
150	4	0.34055
150	5	0.347551
180	1	0.259146
180	2	0.269333
180	3	0.277174
180	4	0.283792
180	5	0.289626
210	1	0.222126
210	2	0.230857
210	3	0.237578
210	4	0.24325
210	5	0.248251
240	1	0.19436
240	2	0.202
240	3	0.207881
240	4	0.212844
240	5	0.21722
270	1	0.172764
270	2	0.179556
270	3	0.184783
270	4	0.189195
270	5	0.193084
300	1	0.155488
300	2	0.1616
300	3	0.166304
300	4	0.170275
300	5	0.173776

Table E-7: In-Trail Spacing at 2.5 NM

Groundspeed	Turn Radius	Collision Risk
150	1	0.248781
150	2	0.25856
150	3	0.266087
150	4	0.27244
150	5	0.278041
180	1	0.207317
180	2	0.215467
180	3	0.221739
180	4	0.227034
180	5	0.231701
210	1	0.1777
210	2	0.184686
210	3	0.190062
210	4	0.1946
210	5	0.198601
240	1	0.155488
240	2	0.1616
240	3	0.166304
240	4	0.170275
240	5	0.173776
270	1	0.138211
270	2	0.143644
270	3	0.147826
270	4	0.151356
270	5	0.154467
300	1	0.12439
300	2	0.12928
300	3	0.133044
300	4	0.13622
300	5	0.139021

Table E-8: In-Trail Spacing at 3 NM

Groundspeed	Turn Radius	Collision Risk
150	1	0.207317
150	2	0.215467
150	3	0.221739
150	4	0.227034
150	5	0.231701
180	1	0.172764
180	2	0.179556
180	3	0.184783
180	4	0.189195
180	5	0.193084
210	1	0.148084
210	2	0.153905
210	3	0.158385
210	4	0.162167
210	5	0.165501
240	1	0.129573
240	2	0.134667
240	3	0.138587
240	4	0.141896
240	5	0.144813
270	1	0.115176
270	2	0.119704
270	3	0.123189
270	4	0.12613
270	5	0.128723
300	1	0.103659
300	2	0.107733
300	3	0.11087
300	4	0.113517
300	5	0.11585

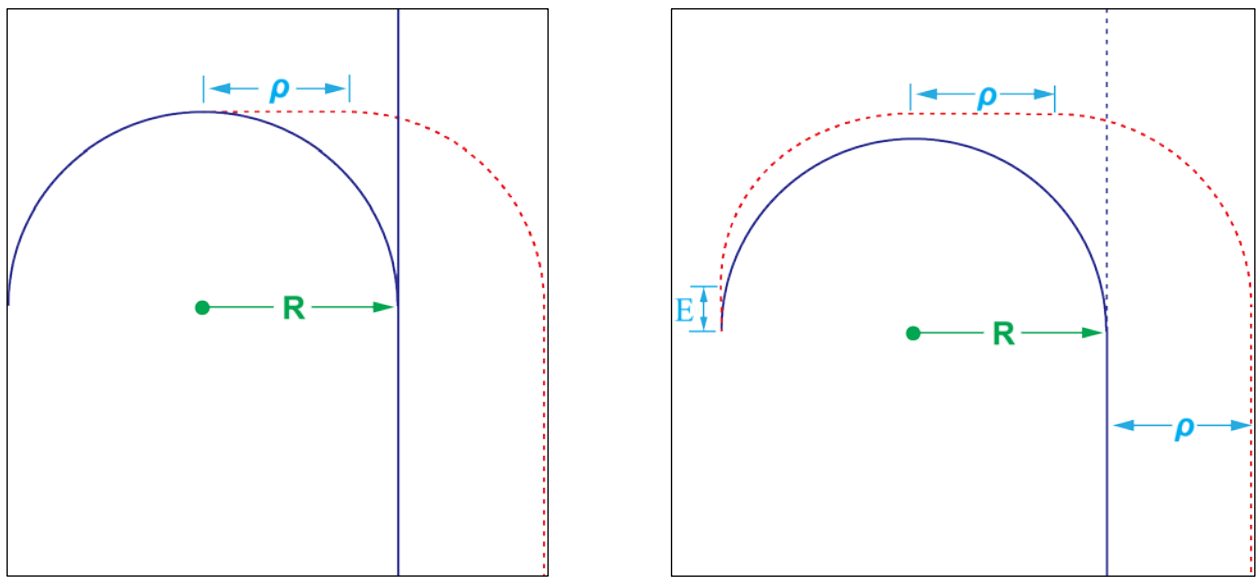
Table E-9: In-Trail Spacing 3.5 NM

Groundspeed	Turn Radius	Collision Risk
150	1	0.1777
150	2	0.184686
150	3	0.190062
150	4	0.1946
150	5	0.198601
180	1	0.148084
180	2	0.153905
180	3	0.158385
180	4	0.162167
180	5	0.165501
210	1	0.126929
210	2	0.131918
210	3	0.135759
210	4	0.139
210	5	0.141858
240	1	0.111063
240	2	0.115429
240	3	0.118789
240	4	0.121625
240	5	0.124126
270	1	0.098722
270	2	0.102603
270	3	0.10559
270	4	0.108111
270	5	0.110334
300	1	0.08885
300	2	0.092343
300	3	0.095031
300	4	0.0973
300	5	0.0993

Appendix F: Case 1 Approach Design Assumption Generalization

Although the analysis for case 1 collision risk only considered two flight procedure designs, the results need to inform any possible design. The conclusion that paths diverging at the apex introduce case 2 wake vortex concerns and case 3 collision risk implies that controller mitigation will need to prevent case 1 risk. This discussion is not geometry specific and can be found in section 3.4. Additionally, this appendix demonstrates that the two cases examined can be used to bound any expected approach construction.

The two approach designs used in the analysis were: (a) an approach with a constant radius turn from the downwind to a common apex followed by a straight segment to traverse from the intended runway to the final approach course of the landing runway using an additional constant radius turn (of the same size) to align with the final approach course, and (b) an approach with the same construction described above, but with a different length on the downwind leg, resulting in a divergence on the downwind leg instead of the apex of the turn. Figure F-1 displays these two designs.



(a) Common Apex **(b) Varied Downwind Lengths**

Figure F-1: Approach Designs Considered

The analysis considered whether a non-normal aircraft would pass through the airspace intended for the EoR aircraft sequencing with the straight-in traffic. This was presented as whether the intersection position was an element of a defined interval. In practice, however, the concern is that the EoR aircraft which incorrectly selected the approach could threaten a trailing straight-in aircraft. Generalizing the terms and defining the gap as an inequality (instead of the interval), we derive the following:

$$\begin{aligned} &Intended\ Separation - Intersection\ Position \\ &\quad + \big(Speed\ Ratio \times (Distance\ Backwards - Distance\ Forwards)\big) > 0 \end{aligned} \tag{12}$$

In equation 12, the intended separation is the separation intended for the EoR aircraft, such as 2.5 or 3 NM. The intersection position is the distance from the location where the incorrectly selected path intersects the extended runway centerline to where the intended path merges with the extended runway centerline of the intended landing runway. The speed ratio is the groundspeed of the straight-in aircraft divided by the groundspeed of the EoR aircraft. Distance backwards is the distance from where the intended track merges with the extended runway centerline to the point where the intended and incorrectly selected paths diverge. Distance forward is the distance from where the paths diverge to where the incorrectly selected path intersects the final approach course.

Intended separation and speed ratio are fixed, meaning that the three main variables to consider for determining approach designs are: intersection position, distance backwards, and distance forwards. The maximum for the left hand side of equation 12 (least likely to erode spacing) occurs when distance backwards is large and intersection position and distance forwards are small. The minimum for the left hand side of equation 12 (most likely to erode spacing) occurs when distance backwards is small and intersection position and distance forwards are large.

The design that diverges at the apex is the maximizing design. For runway spacings greater than the turn radius, the path from the divergence point to the extended runway centerline is a straight line. No other shorter path can be drawn under any circumstances. When runway spacings are greater than the turn radius, one could imagine two possible turning options that result in merging with a final approach course for the same runway separation. First, the turn radius of the second turn could be larger than that of the turn to the nearer runway. In this case, the distance between the divergence point and the intersection would have less of the minimal straight-line orthogonal path and more curved path length, which would increase the distance forward. This can be conceptualized as the turn becoming more similar to the intended path which would result in the intended spacing being more likely to contain the non-normal EoR aircraft. The other option would be to have a smaller turn radius for the second turn. This could result in shortening the path; however, it is unreasonable operationally. RF designs are expected to avoid decreasing turn radii due to concerns with collision risk, TCAS, and FMA nuisance alerts. Furthermore, the turn to the nearer runway is likely to demand something close to the smallest turn radius for alignment with the downwind. This implies that in this case the distance forward is the smallest possible for the distance backwards.

On the other hand, the downwind divergence design can be considered to be minimizing. Any divergence after the apex of the turn approaches something closer to the EoR aircraft merging where anticipated, resulting in low chances of eroded spacing. Divergence before the apex would always result in an increase in the distance between the apex of the turn and the runway threshold projected along the extended runway centerline. For any such design, the downwind path extension with the same increase in distance is worst. The intercept position would be no shorter, but the distance forward may convert any diagonal distance into its x-direction and y-direction components. By the triangle inequality with a Euclidean distance metric, this means that the distance forward of the downwind extension case will always be longer than that in the equivalent diagonal extension design, see figure F-2.

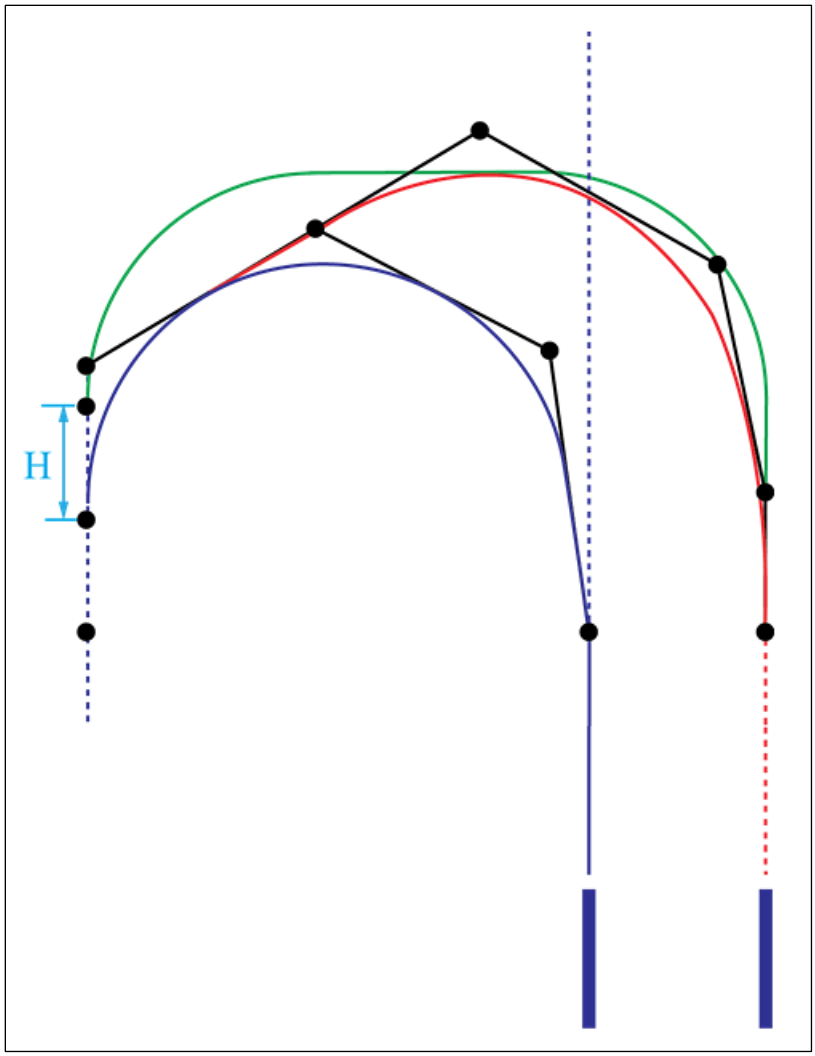


Figure F-2: Downwind Extension Equivalence to Diagonal Extension Approach Designs