Safety Study Report
DOT-FAA-AFS-440-26

Analysis of Area Navigation (RNAV) En Route Separation with Conventional Routes Including Turns and Special Use Airspace

Dr. Richard Greenhaw, AFS-440
Gerry McCartor, AFS-440
Dr. Sherry Avery (ATSI)
Carl Moore (ISI)

January 2007

Flight Operations Simulation
and Analysis Branch, AFS-440
6425 S. Denning, Room 104
Oklahoma City, Oklahoma 73169
Phone: (405) 954-8191

Flight Systems Laboratory

NOTICE

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

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

DOT-FAA-AFS-440-26

Flight Operations Simulation and Analysis Branch
Flight Technologies and Procedures Division
Flight Standards Service

Analysis of Area Navigation (RNAV) En Route Separation with Conventional Routes Including Turns and Special Use Airspace

Reviewed by:

Stephen W. Barnes 1/4/2007

Stephen W. Barnes **Date**
Manager, Flight Operations Simulation and Analysis Branch, AFS-440

Released by:

1/11/07

John W. McGraw **Date**
Manager, Flight Technologies and Procedures Division, AFS-400

January 2007

Technical Report

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT-FAA-AFS-440-26		

4. Title and Subtitle	5. Report Date
Analysis of Area Navigation (RNAV) En Route Separation with Conventional Routes Including Turns and Special Use Airspace	January 2007
6. Author(s)	**7. Performing Organization Code**
Dr. Richard Greenhaw, AFS-440 Gerry McCartor, AFS-440 Dr. Sherri Avery (ATSI) Carl Moore (ISI)	
8. Performing Organization Name and Address	**9. Type of Report and Period Covered**
Federal Aviation Administration Flight Operations Simulation and Analysis Branch, AFS-440 P.O. Box 25082, Oklahoma City, OK 73125	Technical report

10. Sponsoring Agency Name and Address

Federal Aviation Administration
Flight Operations Simulation and Analysis Branch, AFS-440
P.O. Box 25082, Oklahoma City, OK 73125

11. Supplementary Notes

12. Abstract

Developed by AFS-440, this study provides a risk assessment of lateral en route separation between Area Navigation (RNAV) routes with separation for both opposite-direction and same-direction traffic and conventional Very High Frequency (VHF) Omnidirectional Range (VOR) routes, with and without turns. The study estimates the risk of collision of en route RNAV aircraft flying adjacent to conventional VOR routes (in the cases of both opposite-direction and same-direction tracks) when the aircraft of interest is flying adjacent to only one other track (i.e., on an outer track) and when the aircraft of interest is flying between two tracks (i.e., on an inner track). The study also addresses the risk of aircraft on RNAV routes adjacent to Special Use Airspace (SUA) penetrating the SUA.

This study develops risk estimates for scenarios in which the target aircraft's route lies between two other routes and for scenarios in which the target aircraft's route lies adjacent to just one other route. The study shows that the target level of safety of 1.0 E-08 collisions per hour of flight is met for some changeover point (COP) distances from the VOR facility, but not all, when the track-to-track separation is 8 nautical miles (NM). Due to the angular nature of the VOR lateral error and flight technical error (FTE), for larger COP distances from the VOR facility, 10, 12, or 14 NM track-to-track distances are required for the hourly collision rate to meet the target level of safety. The minimum RNAV track distance from a Special Use Airspace was found to be 4 NM.

13. Key Words	14. Distribution Statement
En Route Separation RNAV	
15. Security Classification of This Report	**16. Security Classification of This Page**

Executive Summary

This study[1] provides a risk assessment of lateral en route separation between Area Navigation (RNAV) routes with separation for both opposite-direction and same-direction traffic and conventional Very High Frequency (VHF) Omnidirectional Range (VOR) routes, with and without turns. The study estimates the risk of collision of en route RNAV aircraft flying adjacent to conventional VOR routes (in the cases of both opposite-direction and same-direction tracks) when the aircraft of interest is flying adjacent to only one other track (i.e., on an outer track) and when the aircraft of interest is flying between two tracks (i.e., on an inner track).

The study also addresses the risk of aircraft on RNAV routes that penetrate Special Use Airspace (SUA).

The analysis is based on two previous studies, [1] and [2], and on the United States Standard for Terminal Instrument Procedures (TERPS) [3], Chapter 17 material on conventional route construction criteria.

The study uses the statistical distributions developed in [1] and [2] and the en route turn performance specified for RNAV-equipped aircraft in the Radio Technical Commission for Aeronautics (RTCA) DO-236 [4] to model the likelihood of adjacent aircraft intersecting laterally. It also models and estimates the likelihood of aircraft on parallel, high altitude routes with turns becoming adjacent and thus risking collision. Using those models, it estimates the probability of collision.

The study develops a general risk model that can be used to determine the probability of collision between aircraft on conventional VOR routes and aircraft suitably equipped with a RNAV Flight Management System (FMS) on parallel, adjacent inner or outer routes laterally separated by any track-to-track distance, longitudinally separated by any distance, flying in the opposite or same direction, with straight segments or turns.

This study develops risk estimates for scenarios in which the target aircraft's route lies between two other routes and for scenarios in which the target aircraft's route lies adjacent to just one other route. The study shows that the target level of safety of 1.0 E-08 collisions per hour of flight is met for some (but not all) changeover point (COP) distances from the VOR facility when the track-to-track separation is 8 nautical miles (NM). Due to the angular nature of the VOR lateral error and flight technical error (FTE) for larger COP distances from the VOR facility, 10, 12, or 14 NM track-to-track distances are required for the hourly collision rate to meet the target level of safety.

The minimum RNAV track distance from a Special Use Airspace was found to be 4 NM.

[1] This study is a follow-up study to the study *Analysis of Area Navigation (RNAV) En Route Separation along Adjacent Straight Segments with Radar Surveillance (Phase I)* and utilizes its results.

TABLE OF CONTENTS

1.0	Introduction	1
2.0	Study Methodology	3
3.0	Results and Conclusions	15
Appendices		17
References		39

LIST OF ILLUSTRATIONS

Tables

Table 2.2.1	Scenario 1 Overlap Probabilities	7
Table 2.1.2	Collision Rates, Scenario 1, Same Direction	8
Table 2.1.3	Collision Rates, Scenario 1, Opposite Direction	8
Table 2.1.4	Collision Rates, Scenario 1, Two Adjacent Tracks	8
Table 2.1.5	RNAV SUA Risk (No Turns)	12
Table 2.1.6	RNAV Anticipated Track/SUA Distance for Various Angles of Turn	13
Table 2.1.7	RNAV SUA Penetration Risk (Various Turn Angles, 95% Containment)	14
Table 2.1.8	RNAV SUA Hourly Penetration Rate (Various Turn Angles, 95% Containment	14

Figures

Figure 1.1.1	Parallel Routes: RNAV with Conventional Tracks	1
Figure 2.1.1	Scenario 1	5
Figure 2.1.1	Conventional Route Boundaries (COP ≤ 51 NM)	5
Figure 2.1.3	Conventional Route Boundaries (COP > 51 NM)	6
Figure 2.1.4	RNAV Track Inside Conventional Track on Turn	9
Figure 2.1.5	RNAV Track Outside Conventional Track on Turn	9
Figure 2.1.6	RNAV and Conventional Nominal Paths on Turn	10
Figure 2.1.7	RNAV Route Turn Inside Concave SUA	12
Figure 2.1.8	RNAV Route Turn Outside Convex SUA	13

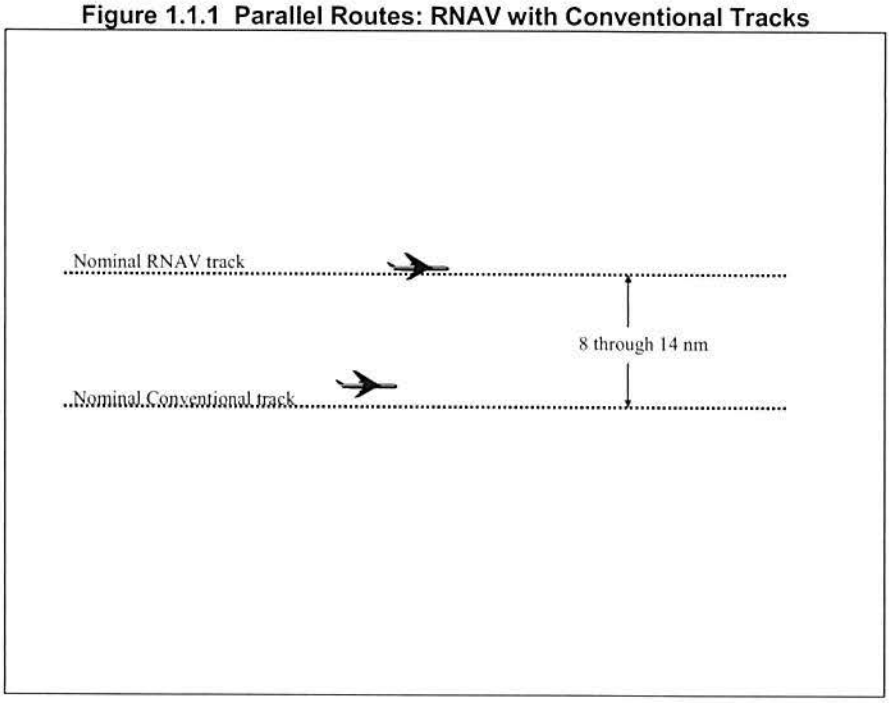
1.0 Introduction

This section of the report describes the purpose and structure of this document, and provides a description of the problem.

1.1 Purpose and Structure of This Document

The purpose of this study is to provide a risk assessment of lateral en route separation between conventional Very High Frequency (VHF) Omnidirectional Range (VOR) routes and parallel Area Navigation (RNAV) routes with both opposite-direction and same-direction traffic under radar surveillance. The study estimates the risk of collision between aircraft on conventional routes and RNAV routes flying adjacent, parallel straight tracks and tracks with turns (in the case of both opposite-direction and same-direction turns). The study examines the case when the aircraft of interest is flying adjacent to only one other track (i.e., on an outer track) and when the aircraft of interest is flying between two tracks (i.e., on an inner track). See Figure 1.1.1.

Figure 1.1.1 Parallel Routes: RNAV with Conventional Tracks



1.2 Statement of the Problem

Specifically, this study seeks to use the lateral track deviation of typical RNAV-equipped aircraft on en route segments with turns greater than 15° and aircraft on conventional tracks to determine the probability of collision of two aircraft with given track-to-track

separation distances of 8 through 12 nautical miles (NM) under radar surveillance, with both inner and outer tracks, and with the aircraft flying in the same or opposite direction.

This analysis assumes the following turn completion performance for RNAV aircraft authorized for Q-routes. The Flight Management System (FMS) or similar equipment, e.g., Flight Management Computer (FMC), computes a turn radius based on ground speed and a software-determined bank angle (typically a function of amount of turn, altitude, and aircraft characteristics). From the computed turn radius, a turn initiation start point is then determined to provide a smooth, seamless transition between route segments. Throughout the turn, the FMS provides guidance to an autopilot or a flight director to automatically affect the turn transition. Radio Technical Commission for Aeronautics (RTCA) DO-236 [4], paragraph 3.2.5.4 provides a performance boundary for the fly-by transition area based upon maximum ground speed assumptions and typical bank angle assumptions for RNAV aircraft for both high (above flight level [FL] 195) and low altitude transitions. While DO-236 relates primarily to Required Navigation Performance (RNP) systems, the fly-by turn transition boundaries are considered and assumed to be representative of RNAV systems which provide command guidance throughout a turn transition. Furthermore, this study assumes that all RNAV aircraft approved for Q-route operation can comply with the DO-236 fly-by turn performance, regardless if they are FMS-equipped.

This analysis assumes that conventional aircraft follow routes whose boundaries are described in the United States Standard for Terminal Instrument Procedures (TERPS) [3].

For suitably equipped RNAV aircraft, as referenced in AC 90-100 [5] and DO-236 [4], flying RNAV routes and aircraft flying conventional VOR routes, this study answers the following general question:

What is the risk of an RNAV aircraft flying a high altitude (i.e., FL 180 and above) en route track segment colliding with an aircraft flying a conventional, parallel, adjacent, VOR-based en route track, as a function of the following variables:

- Track-to-track route separation
- Longitudinal separation within a route
- Angle of turn
- Density of turns along a route
- Whether adjacent aircraft are flying in the same or opposite direction as the aircraft at risk[2]
- Whether the aircraft at risk is flying an inner route or an outer route[3]

[2] The aircraft at risk is the one for which we are assessing the risk of collision with another aircraft.
[3] On an outer track, the aircraft at risk flies a route adjacent to only one other route. On an inner track, it flies between two other routes.

We answer this general question by looking at this specific question:

What turn angles and turn densities (if any) would allow the target level of safety to be met at 8 NM, 10 NM, 12 NM, and 14 NM separation between the RNAV and conventional routes?

2.0 Study Methodology

This section of the report provides a description of all of the scenarios used in the study, and summarizes the data used in this study.

2.1 Model Description

We describe the risk model in terms of four scenarios: Scenario 1, straight tracks (i.e., with turns of no more than 15°); Scenario 2, tracks with turns greater than 15° and RNAV tracks inside VOR-based tracks; Scenario 3, tracks with turns greater than 15° and VOR-based tracks inside RNAV tracks; and Scenario 4, RNAV tracks adjacent to Special Use Airspace (SUA).

Scenario 1 (Straight Tracks)

This scenario addresses straight en route track segments with turns of no more than 15°. There can be parallel, adjacent straight tracks with aircraft on those tracks flying either opposite-direction or same-direction routes. The aircraft at risk can be on an outer track or an inner track, and can be on either the conventional route or the RNAV route. The aircraft are assumed to be under radar surveillance. The calculations for this scenario are based on various changeover point[4] (COP) distances from the VOR. See Figures 2.1.1 through 2.1.3.

The specific Test Criterion Violation (TCV) for this scenario is the combined lateral, longitudinal, and vertical conjunction of the two aircraft. This conjunction is modeled by centers of gravity of the aircraft converging within their mean wingspan laterally, within their mean lengths longitudinally, and within their mean heights vertically.

[4] A changeover point is a point between navigation facilities along en route segments at which the pilot using the route should "change over" the navigation equipment to receive course guidance from the facility ahead instead of the one behind. See Figures 2.1.2 and 2.1.3.

In the previous studies ([1] and [2]), we made several assumptions about the RNAV aircraft:

- The aircraft lateral, longitudinal, and vertical deviations are independent.
- The aircraft length and width are both approximately 0.03 NM (182 feet).
- The probability of aircraft on adjacent tracks being at the same altitude is 1.
- The aircraft is contained laterally within 2 NM of the straight track 95% of the time.

This last assumption is based on the AC 90-100 en route requirement. We used a statistical distribution to model the lateral track deviation that would provide 95% containment. The specific distribution used is a mixed Johnson S_B/Double-Exponential distribution. This distribution satisfies both theoretical and empirical reasonableness tests. Theoretically, the distribution models a combination of core (typical) lateral deviation behavior and tail (atypical) lateral deviation behavior. Empirically, the distribution is conservative as compared to the results of the three empirical studies ([6], [7], and [8]).

For conventional routes, we add two more assumptions:

- The aircraft is contained laterally within a given angular projection initiating from the VOR facility 95% of the time. See Figure 2.1.2.
- Because of radar surveillance intended to prevent adjacent en route aircraft from approaching closer than 5 NM, the aircraft are assumed to fly within 4 NM of their nominal tracks 95% of the time while in the vicinity of aircraft on adjacent RNAV routes.

The probability of a TCV for this scenario is the sum of the probabilities of three mutually exclusive events: side-to-side (C_s), top-to-bottom (C_t), or nose-to-nose[5] (C_n) collision between aircraft on adjacent tracks.

[5] Or nose-to-tail for same-direction adjacent aircraft

Figure 2.1.1 Scenario 1

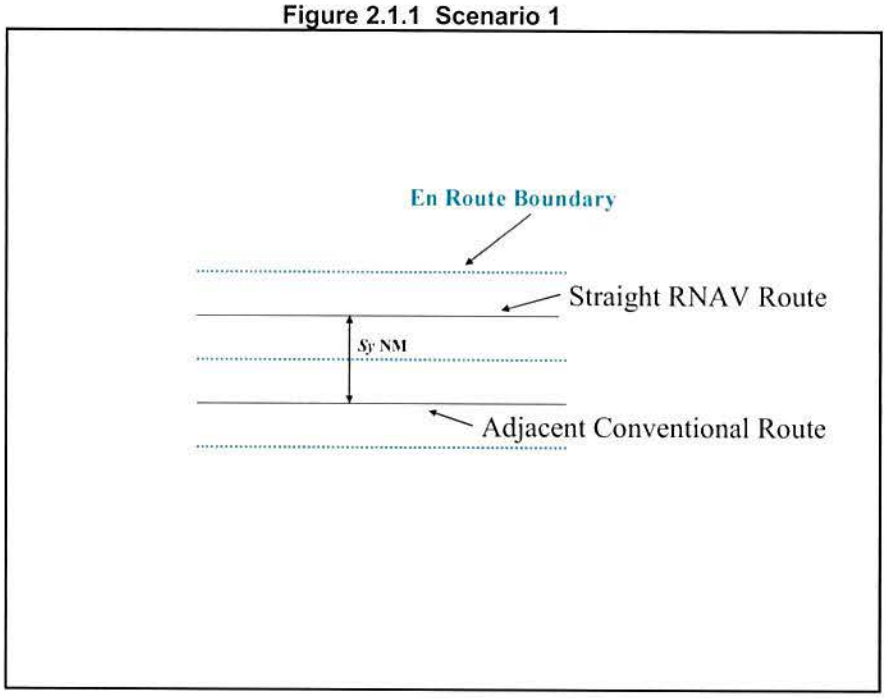


Figure 2.1.2 Conventional Route Boundaries (COP ≤ 51 NM)

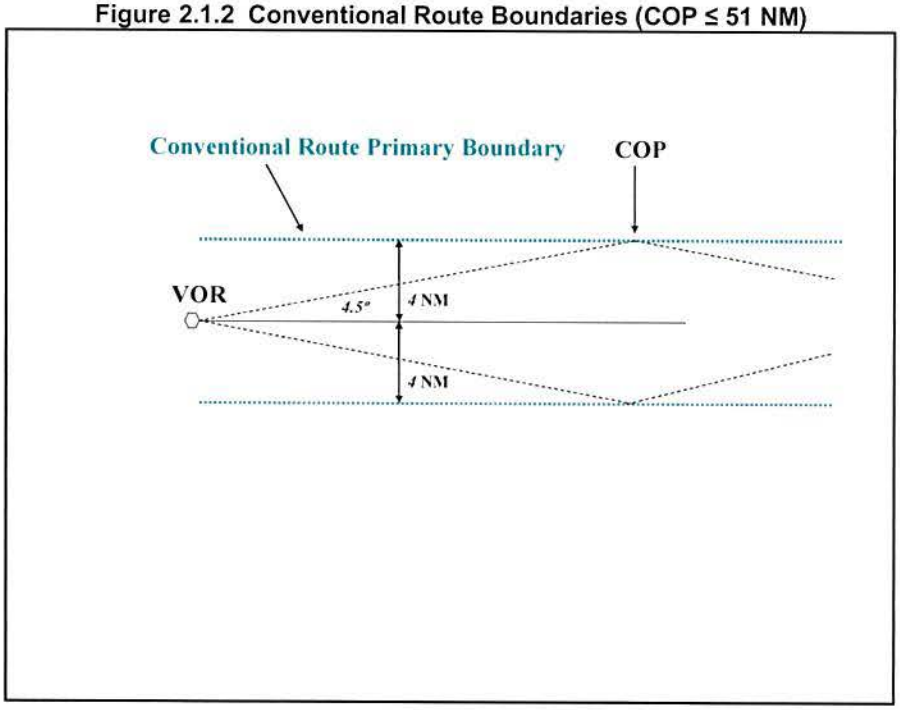
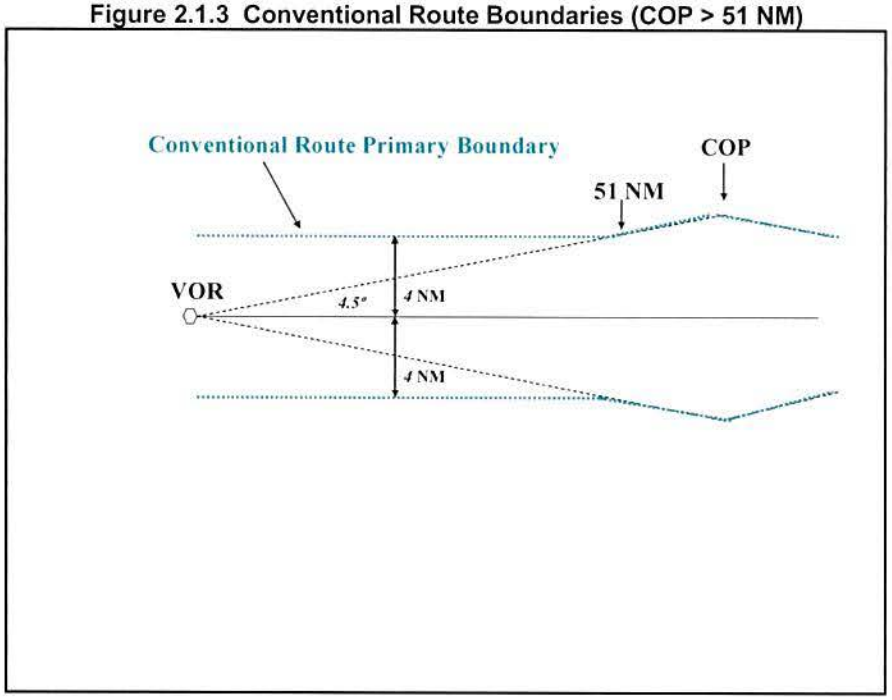


Figure 2.1.3 Conventional Route Boundaries (COP > 51 NM)



That is,

$$P(TCV) = P(C_s) + P(C_t) + P(C_n). \tag{1}$$

In the previous study [1], this TCV probability was shown to have a value given by the equation,

$$P(TCV) = P_y(S_y)\left[\frac{1}{\sqrt{2}} + 1\right], \tag{2}$$

where $P_y(S_y)$ is the probability of a lateral overlap of the two aircraft on the two routes, and S_y is the track-to-track distance assumed.

To find $P_y(S_y)$, let the lateral positions of the aircraft be given by the variables y_1 and y_2 respectively. The aircraft are assumed to be in lateral overlap when their centers of gravity are within λ. That is, when $|y_2 - y_1| < \lambda$. Therefore, the probability of lateral overlap,

$$P_y(S_y) = \mathrm{P}(|y_2 - y_1| < \lambda). \tag{3}$$

But, $P(|y_2 - y_1| < \lambda) = P(-\lambda < y_2 - y_1 < \lambda)$. This probability can be found by integrating the Probability Density Function (PDF) describing $(y_2 - y_1)$ between $-\lambda$ and λ.

The PDF describing (y_2 - y_1) is the convolution of the two PDFs of the two variables, y_2 and -y_1. The PDF for the variable y_1 is that of the criterion-based distribution for RNAV route lateral deviation developed in [1]. The PDF for the variable y_2 is that of the conventional route lateral deviation and is developed in Appendix A, Conventional Route Lateral Deviation Distribution. Appendix B, Statistical Distributions Used in the Study, gives the details for the convolution of these two PDFs and of the integration that yields the PDF for the lateral overlap probability, $P_y(S_y)$[6]. (See Equation (B4).) Table 2.1.1 gives the lateral overlap probability, $P_y(S_y)$, for each of the values of track-to-track separation, S_y: 8, 10, 12, and 14 NM and COP distances based on this distribution.

Table 2.1.1 Scenario 1 Overlap Probabilities, $P_y(S_y)$, by Track-to-Track Distance and COP

S_y	COP Distance							
(NM)	10	20	30	40	50	60	70	80+
8	8.5E-15	2.3E-14	1.1E-13	1.1E-10	2.0E-08	5.4E-08	1.4E-07	5.9E-07
10	1.1E-17	3.0E-17	1.4E-16	3.8E-15	1.7E-11	5.4E-09	6.4E-08	1.5E-07
12	1.4E-20	3.8E-20	1.7E-19	2.9E-18	2.5E-15	6.4E-12	5.5E-10	1.4E-09
14	1.8E-23	5.0E-23	2.2E-22	3.7E-21	2.5E-19	4.0E-15	2.0E-12	5.4E-12

*The notation E-09 denotes 10^{-9}, that is, ten to the negative ninth power.

Since the target level of safety for these en route operations is specified in terms of the number of collisions per hour of flight, the TCV rate must be converted to the units of collisions per hour of flight. To convert, we multiply the TCV rate by the expected number of encounters of adjacent aircraft per hour of flight. If we assume a mean ground speed of V knots (for opposite-direction aircraft), a mean passing speed of ΔV knots (for same-direction aircraft), and a mean traffic separation of d NM, then in one hour an aircraft will encounter $2V/d$ other aircraft on an opposite-direction track and $\Delta V/d$ aircraft on a same-direction track.

Therefore, the hourly collision rate, C, for this scenario can be determined from the single equation,

$$C(S_y, V, \Delta V, d, n_o, n_s) = \left(\frac{2V}{d} n_o + \frac{\Delta V}{d} n_s\right)\left[\frac{1}{\sqrt{2}} + 1\right] P_y(S_y) \quad (4)$$

where n_o is the number of opposite-direction tracks adjacent to the target aircraft track (the values of n_o can be 0, 1, or 2), and n_s is the number of same-direction tracks adjacent to the target aircraft track (the values of n_s can also be 0, 1, or 2, but subject to $1 \leq n_o + n_s \leq 2$, since the target track cannot be adjacent to more than two other tracks).

Table 2.1.2 gives hourly collision rates, C, for aircraft on adjacent conventional and RNAV tracks for various track-to-track separation values, S_y, and for one same-direction adjacent track. These values are calculated assuming $V = 500$ knots, $\Delta V = 100$ knots, and

[6] $P_y(S_y)$ is actually determined by averaging the values obtained from Equation (B4) for each member of the family of distributions corresponding to the ten distances from the VOR: 0, 5, 10, …, 40, 45 NM.

$d = 5$ NM. The values in bold face are those that meet the more stringent 1.0 E-09 target level of safety.

Table 2.1.2 Hourly Collision Rates, Scenario 1, One Same-Direction Adjacent Track

S_y	COP Distance							
(NM)	10	20	30	40	50	60	70	80+
8	**2.9E-13**	**7.9E-13**	**3.7E-12**	3.6E-09	6.8E-07	1.8E-06		
10	**3.8E-16**	**1.0E-15**	**4.7E-15**	**1.3E-13**	**5.9E-10**	1.8E-07	2.2E-06	5.2E-06
12	**4.8E-19**	**1.3E-18**	**5.9E-18**	**9.9E-17**	**8.6E-14**	**2.2E-10**	1.9E-08	4.7E-08
14	**6.0E-22**	**1.7E-21**	**7.6E-21**	**1.2E-19**	**8.6E-18**	**1.4E-13**	**6.7E-11**	**1.8E-10**

Table 2.1.3 gives hourly collision rates, C, for aircraft on adjacent conventional and RNAV tracks for various track-to-track separation values, S_y, and for one opposite-direction adjacent track. These values are calculated assuming $V = 500$ knots, $\Delta V = 100$ knots, and $d = 5$ NM.

Table 2.1.3 Hourly Collision Rates, Scenario 1, One Opposite-Direction Adjacent Track

S_y	COP Distance							
(NM)	10	20	30	40	50	60	70	80+
8	**2.9E-12**	**7.9E-12**	**3.7E-11**	3.6E-08	6.8E-06	1.8E-05		
10	**3.8E-15**	**1.0E-14**	**4.7E-14**	**1.3E-12**	5.9E-09	1.8E-06	2.2E-05	5.2E-05
12	**4.8E-18**	**1.3E-17**	**5.9E-17**	**9.9E-16**	**8.6E-13**	2.2E-09	1.9E-07	4.7E-07
14	**6.0E-21**	**1.7E-20**	**7.6E-20**	**1.2E-18**	**8.6E-17**	**1.4E-12**	**6.7E-10**	1.8E-09

Table 2.1.4 gives hourly collision rates, C, for aircraft on adjacent conventional and RNAV tracks for various track-to-track separation values, S_y, and for two same-direction adjacent tracks. These values are calculated assuming $V = 500$ knots, $\Delta V = 100$ knots, and $d = 5$ NM.

Table 2.1.4 Hourly Collision Rates, Scenario 1, Two Same-Direction Adjacent Tracks

S_y	COP Distance							
(NM)	10	20	30	40	50	60	70	80+
8	**5.8E-13**	**1.6E-12**	**7.4E-12**	7.3E-09	1.4E-06	3.7E-06		
10	**7.5E-16**	**2.0E-15**	**9.4E-15**	**2.6E-13**	1.2E-09	3.7E-07	4.4E-06	1.0E-05
12	**9.6E-19**	**2.6E-18**	**1.2E-17**	**2.0E-16**	**1.7E-13**	**4.4E-10**	3.8E-08	9.4E-08
14	**1.2E-21**	**3.4E-21**	**1.5E-20**	**2.5E-19**	**1.7E-17**	**2.8E-13**	**1.3E-10**	**3.7E-10**

The values in the tables in bold face type indicate where the target level of safety of 1.0 E-08 collisions per hour of flight is met.

Scenario 2 (Tracks with Turns Greater than 15°, RNAV Track Inside Conventional)

As in the previous study [2], we assume that the degree of turn lies between 15° and 70°. For adjacent RNAV and conventional en route tracks there are two cases: RNAV inside and RNAV outside (see Figures 2.1.4 and 2.1.5).

This scenario treats the case in which the RNAV track lies inside the conventional track on the turn.

Figure 2.1.4 RNAV Track Inside Conventional Track on Turn

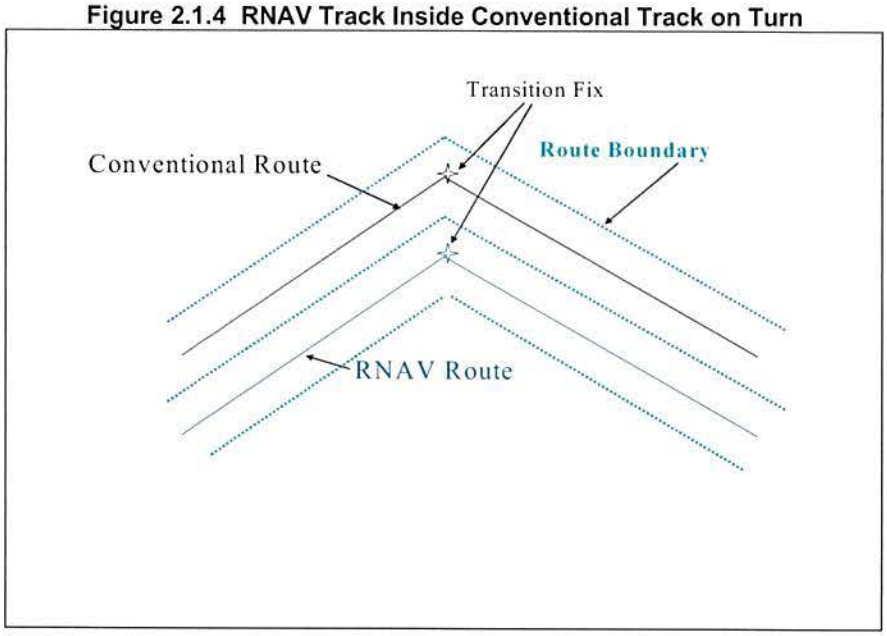
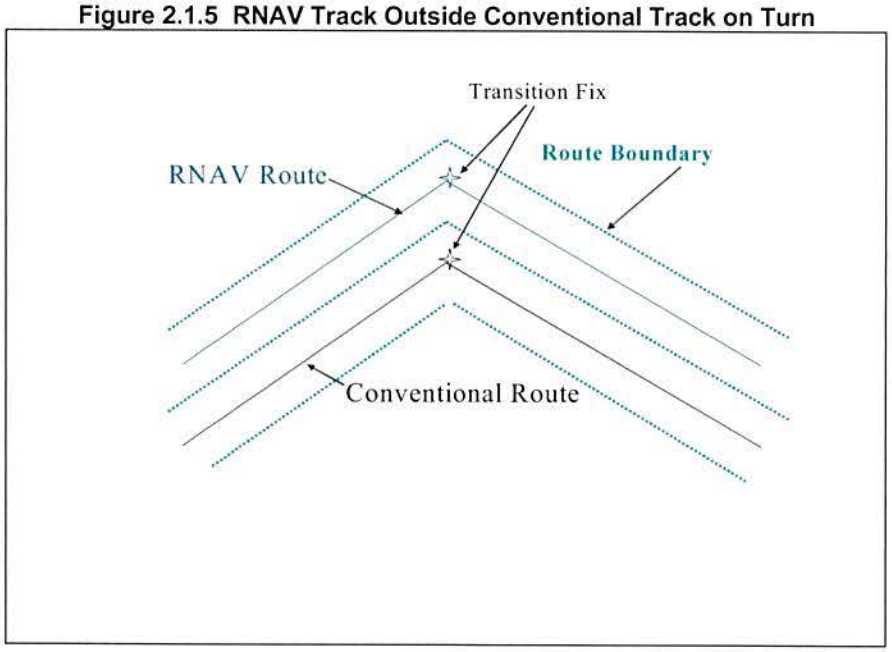


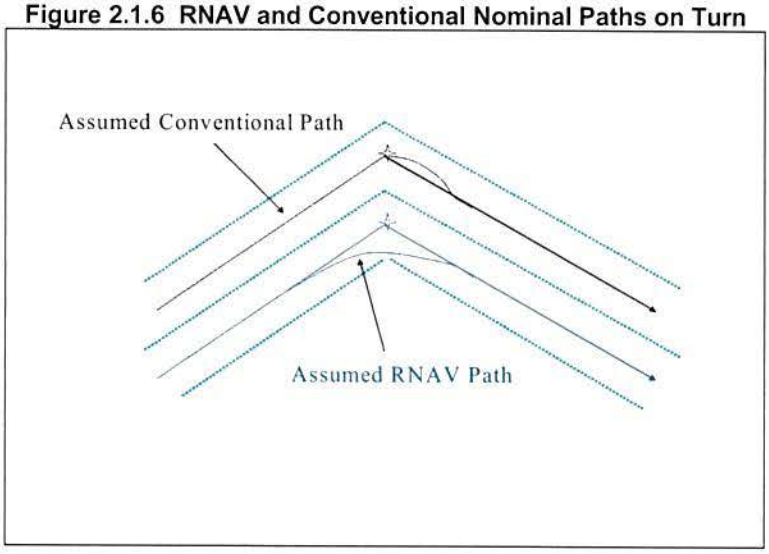
Figure 2.1.5 RNAV Track Outside Conventional Track on Turn



In this case, the turning area protection for conventional en route turns lies exclusively to the outside of the turn (see [3]) and the protection area for RNAV en route turns lies exclusively to the inside of the turn (see [2]). As Figure 2.1.6 indicates, since the

conventional turn is based on a fix interception and the RNAV turn is based on a fly-by fix, the nominal paths for aircraft flying these tracks are, even in the worst case, no closer together laterally than the corresponding straight tracks.

Figure 2.1.6 RNAV and Conventional Nominal Paths on Turn



However, in some cases, the conventional aircraft may not fly the nominal interception fix path, but may start the turn early. We have only anecdotal information concerning this situation, but no objective data. As a result, we assume that there is not significant risk from conventional track aircraft turning early because the well-established conventional turn areas do not protect only the outside of the turn. As a conservative approach, however, we apply the methodology of [2] assuming that the conventional aircraft treat the fix as a fly-by transition similar to that of RNAV aircraft. We also assume that any extreme early turns on the conventional track are mitigated by radar surveillance.

The tables in Appendix C, Collision Rates by Turn Angle, Track Separation, COP Distance, Track Direction, and Number of Turns per Hour of Flight (RNAV Track Inside Conventional), summarize the estimated collision rates for turns (per hour of flight) of track-to-track separation of 8, 10, 12, and 14 NM; COP distances of 10, 20, 30, 40, 50, 60, 70, and 80 or more NM; turn angles of 20°, 30°, 45°, 60°, and 70°; and same-direction or opposite-direction adjacent track configuration. In each table, the RNAV track is assumed to lie *inside* the conventional track (see Figure 2.1.6). The values in bold face are those that meet the more stringent 1.0 E-09 target level of safety.

These results are summarized in Section 3, Results and Conclusions.

Scenario 3 (Tracks with Turns Greater than 15°, RNAV Track Outside Conventional)

This scenario treats the case in which the RNAV track lies outside the conventional track on the turn. Since the conventional turn relies on a fix, we estimate the probability of aircraft overlap on this type of turn by assuming that the conventional aircraft turns above the expected DO-236 track by 1 NM. That is, because we lack specific data, we conservatively calculate the probability of aircraft overlap as in Scenario 2, except that we assume during the turn the conventional aircraft is 1 NM closer to the RNAV aircraft than when the RNAV aircraft is on the inside of the turn (Scenario 2). The assumption used here is that the use of the RNAV turn geometry together with the extra 1 NM buffer provides a reasonably accurate model of the techniques used by the majority of pilots executing conventional en route turns (in which, in fact, the turn is typically anticipated by the pilot).

The tables in Appendix D, Collision Rates by Turn Angle, Track Separation, COP Distance, Track Direction, and Number of Turns per Hour of Flight (RNAV Track Outside Conventional), summarize the estimated collision rates for turns (per hour of flight) of track-to-track separation of 8, 10, 12, and 14 NM; COP distances of 10, 20, 30, 40, 50, 60, 70, and 80 or more NM; turn angles of 20°, 30°, 45°, 60°, and 70°; and same-direction or opposite-direction adjacent track configuration. In each table, the RNAV track is assumed to lie *outside* the conventional track. The values in bold face are those that meet the more stringent 1.0 E-09 target level of safety.

These results are summarized in Section 3, Results and Conclusions.

Scenario 4 (RNAV Tracks Adjacent to Special Use Airspace)

Based on FAA Order 7110.65, Section 3 "Special Use and ATC Assigned Airspace" [11], paragraph 9-3-2 Separation Minima (b), air traffic controllers are to provide radar separation of three miles from a peripheral boundary of Special Use Airspace. This separation applies to aircraft on conventional and RNAV routes under radar surveillance.

Suppose an RNAV route was placed along the boundary of an SUA. How far should the nominal route track be set from the boundary?

Table 2.1.5 summarizes two cases: 95% and 90% containment assumed within 1 NM of the nominal flight path with the lateral deviations following a normal distribution, similar to that of the Q-route data [8], about the nominal path[7]. To compute the hourly rate of boundary penetration, we assume a typical ground speed of 500 knots and that the aircraft lateral error behavior becomes independent every 5 NM (a conservative assumption).

[7] The Q-route data show a tighter lateral error distribution than these assumptions. Therefore, we take these assumptions to be conservative. Also, we assume that the radar surveillance will typically prevent the traffic on the route from flying closer than 3 NM to the boundary, so that the aircraft are contained with 1 NM of the nominal flight path most of the time (say, 90% or 95% of the time).

The values in bold face are those that meet the more stringent 1.0 E-09 target level of safety.

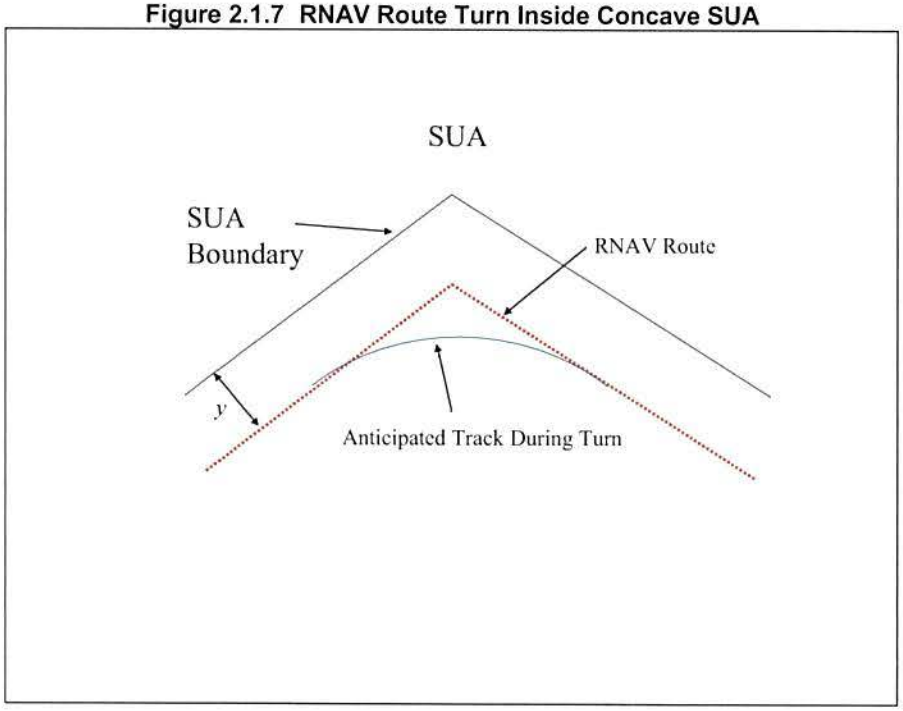
Table 2.1.5 RNAV SUA Risk (No Turns)

Separation: RNAV Track to SUA (NM)	95% Containment within 1 NM of Nominal Flight Path		90% Containment within 1 NM of Nominal Flight Path	
	Probability of a Boundary Penetration	Hourly Rate of Boundary Penetration	Probability of a Boundary Penetration	Hourly Rate of Boundary Penetration
3	9.9 E-10	9.9 E-08	4.4 E-07	4.4 E-05
4	2.2 E-15	**2.2 E-13**	2.4 E-11	2.4 E-09
5	0	**0.0 E+00**	7.3 E-17	**7.3 E-15**

These calculations indicate that, under the assumptions given, a 4 NM lateral separation between the SUA boundary and the nominal RNAV flight path without turns results in fewer than 2.70 E-09 penetrations per hour of flight.

For RNAV routes adjacent to SUA with geometry requiring turns, there are two cases. The first case treats a concavity in the SUA with an adjacent RNAV route (see Figure 2.1.7). In this case, the anticipated track during the turn lies at the greater distance from the SUA boundary than the track before or after the turn. Therefore, the risk of penetration of the SUA is no greater than if there were no turn. In this case, Table 2.1.5 may be used as a set of upper bounds on the hourly rate of penetration with concave SUA turns.

Figure 2.1.7 RNAV Route Turn Inside Concave SUA



The second case treats a convexity in the SUA with an adjacent RNAV route (see Figure 2.1.8). In this case, the anticipated track during the turn lies at the smaller distance from the SUA boundary than the track before or after the turn. Table 2.1.6 gives the average value of this smaller distance between the SUA boundary and the anticipated RNAV track, y_{avg}, for various turn angles assuming the initial distance between the RNAV route and the SUA is 4 NM.

Table 2.1.6 RNAV Anticipated Track/SUA Distance for Various Angles of Turn

Angle	y_{avg}
0°	4.00 NM
15°	3.74 NM
20°	3.54 NM
30°	3.18 NM
45°	2.82 NM
60°	2.50 NM
70°	2.31 NM

Figure 2.1.8 RNAV Route Turn Outside Convex SUA

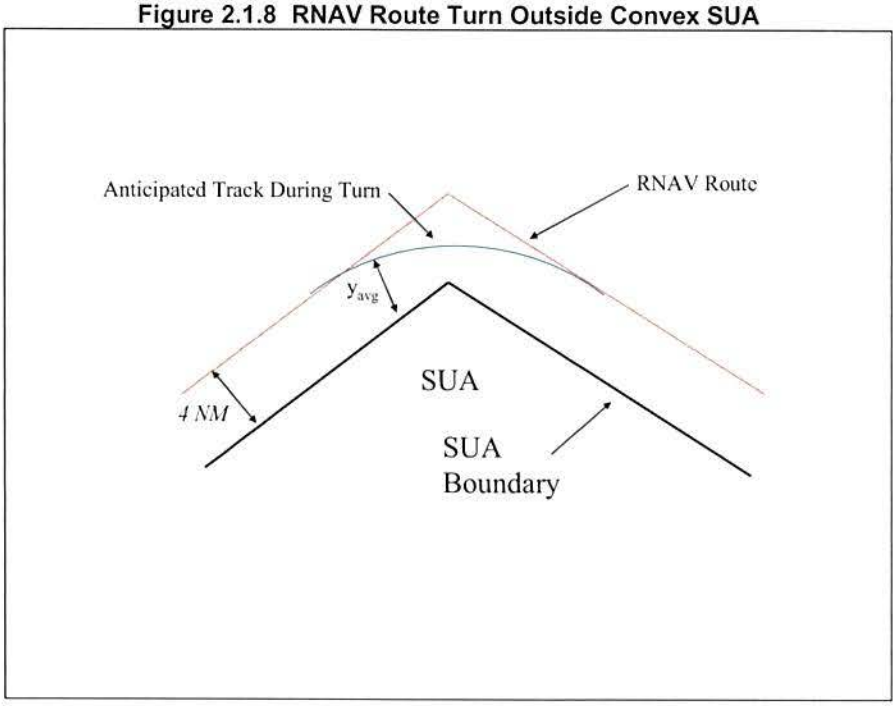


Table 2.1.7 summarizes the case of 95% containment assumed within 1 NM of the nominal flight path with the lateral deviations following a normal distribution about the nominal path for convex SUA turns of various angles.

Table 2.1.7 RNAV SUA Penetration Risk (Various Turn Angles, 95% Containment)

	Number of Turns per Hour of Flight					
Angle	**0**	**1**	**2**	**3**	**4**	**5**
15	2.2E-15	2.8E-15	3.3E-15	4.1E-15	5.0E-15	6.0E-15
20	2.2E-15	3.7E-15	5.8E-15	9.2E-15	1.5E-14	2.3E-14
30	2.2E-15	6.2E-15	1.7E-14	4.5E-14	1.2E-13	3.1E-13
45	2.2E-15	9.8E-15	4.1E-14	1.6E-13	6.4E-13	2.4E-12
60	2.2E-15	1.4E-14	8.6E-14	4.9E-13	2.7E-12	1.4E-11
70	2.2E-15	1.8E-14	1.3E-13	9.2E-13	5.9E-12	3.6E-11

Table 2.1.8 summarizes the hourly rate of boundary penetration based on the values found in Table 2.1.7 (95% containment). To compute the hourly rate of boundary penetration, we assume a typical ground speed of 500 knots and that the aircraft lateral error behavior becomes independent every 5 NM (a conservative assumption). The values in bold face are those that meet the more stringent 1.0 E-09 target level of safety.

Table 2.1.8 RNAV SUA Hourly Penetration Rate (Various Turn Angles, 95% Containment)

	Number of Turns per Hour of Flight					
Angle	**0**	**1**	**2**	**3**	**4**	**5**
15	**2.2E-13**	**2.8E-13**	**3.3E-13**	**4.1E-13**	**5.0E-13**	**6.0E-13**
20	**2.2E-13**	**3.7E-13**	**5.8E-13**	**9.2E-13**	**1.5E-12**	**2.3E-12**
30	**2.2E-13**	**6.2E-13**	**1.7E-12**	**4.5E-12**	**1.2E-11**	**3.1E-11**
45	**2.2E-13**	**9.8E-13**	**4.1E-12**	**1.6E-11**	**6.4E-11**	**2.4E-10**
60	**2.2E-13**	**1.4E-12**	**8.6E-12**	**4.9E-11**	**2.7E-10**	1.4E-09
70	**2.2E-13**	**1.8E-12**	**1.3E-11**	**9.2E-11**	**5.9E-10**	3.6E-09

2.2 Summary of Data Used

This section provides a description of the data used on aircraft traveling on both RNAV routes and conventional routes.

Data on RNAV Route Aircraft

The RNAV route aircraft data for this study are used to validate the risk models, but the models themselves are based on values specified in the documents AC 90-100 and DO-236.

AC 90-100 specifies a value for track-keeping accuracy for RNAV aircraft approved for Q-route operations. This criterion is the basis for the lateral deviation model used in the

present study. DO-236 specifies worst-case boundaries for turns. These criteria are the bases for this study's turn path definition model.

We used three empirical studies, [6], [7], and [8], to validate the RNAV aircraft track-keeping accuracy distributions developed.

Data on Conventional Route Aircraft

We based the distributions for conventional aircraft track-keeping accuracy on two studies:

- [9] A study that quantified a conventional flight technical error (FTE) using a family of Johnson S_U distributions (for lateral deviations at various distances from the VOR facility)
- [10] A study that quantified conventional navigational system error (NSE) (using VOR facilities and aircraft sensors) using normal distributions

We combined the distributions from these two studies to arrive at a total system error for lateral deviation of conventional en route aircraft. This provided a family of distributions, one member for each of several distances from the VOR facility.

These combined conventional lateral error distributions were used together with the RNAV lateral error distribution to arrive at a probability of lateral overlap between an aircraft on a conventional route and an aircraft on an adjacent RNAV route.

3.0 Results and Conclusions

This section summarizes the key results of the scenario risk evaluations, and the conclusions of the study.

In Scenario 1, we compared the risk of hourly collision of aircraft on RNAV and conventional routes with the target level of safety established for the study (1.0 E-08 collisions per hour of flight) and for the more stringent target level of safety from the FAA Safety Management System Manual, v 1.1. Since the lateral navigational and flight technical errors of the conventional route depend on the distance of the COP from the VOR facility, the risk of collision must be given in terms of this COP distance.

For Scenarios 2 and 3, the results are more difficult to summarize. Appendices C and D describe the results of various combinations of turn angle, track separation, COP distance, track direction, and number of turns per hour of flight. Appendix C addresses the configuration with the RNAV track on the inside; Appendix D addresses the configuration with the RNAV track on the outside.

For Scenario 4, the probability of SUA penetration by an aircraft on an adjacent RNAV route is estimated to be less than 1.0 E-08 when the RNAV track is 4 NM or more from the SUA boundary. It is less than 1.0 E-09 when the RNAV track is 4 NM or more from the SUA boundary assuming 95% containment within 1 NM of the nominal flight path and when the RNAV track is 5 NM or more from the SUA boundary assuming 90% containment within 1 NM of the nominal flight path. (See Table 2.1.5.)

Appendix A: Conventional Route Lateral Deviation Distribution

The random variable y_2 that represents the conventional route lateral deviation is itself the sum of two random variables: the lateral error due to FTE, y_{2F}, and the lateral error due to NSE, y_{2N}.

The distribution PDF for the random variable, y_{2F}, the conventional lateral FTE, is taken from the study [9]. In that paper, the PDF was found to be from a Johnson S_U distribution:

$$f_{2F}(x) = \frac{\eta}{\sqrt{2\pi}} \frac{1}{\sqrt{(x-\varepsilon)^2 + \lambda^2}} \exp\left[-\frac{1}{2} \left(\gamma + \eta \ln\left\{ \left(\frac{x-\varepsilon}{\lambda} \right) + \left[\left(\frac{x-\varepsilon}{\lambda} \right)^2 + 1 \right]^{\frac{1}{2}} \right\} \right)^2 \right], \quad \text{(A1)}$$

where $-\infty < x < \infty$, $-\infty < \gamma < \infty$, $-\infty < \varepsilon < \infty$, $\eta > 0$, $\lambda > 0$. The location parameter is ε. The scale parameter is λ. The shape (including skewness) parameters are γ and η. Since the FTE is angular, the parameter values change as the aircraft moves away from the VOR. At 40 NM, the values (for lateral distances in meters) are: $\gamma = -0.28539$, $\eta = 1.6796$, $\varepsilon = -300.094$, and $\lambda = 1893.1183$.

The distribution PDF for the random variable, y_{2N}, the conventional lateral NSE, is taken from the study [10]. In that paper, the PDF was found to be from a normal distribution:

$$f_{2N}(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{x-\mu}{\sigma} \right)^2 \right]. \quad \text{(A2)}$$

At 40 NM, the values (for lateral distances in meters) are: $\mu = 0$ and $\sigma = 1939.8$.

Therefore, the PDF for the total lateral deviation is the convolution of these two PDFs. That is,

$$f_2(u) = \int_{-\infty}^{\infty} f_{2F}(y) f_{2N}(u-y)\,dy. \quad \text{(A3)}$$

This function, $f_2(u)$, is actually a family of distributions whose members are found by evaluating the parameters at appropriate distances from the VOR.

Appendix B: Statistical Distributions Used in the Study

RNAV Route Lateral Deviation Distribution

(The Mixed Johnson S_B and Double-Exponential Distribution PDF from [1])

$$f_1(x) = \begin{cases} \frac{\alpha}{2\delta}\exp\left[-\frac{|x|}{\lambda}\right] + (1-\alpha)\frac{\eta\lambda}{\sqrt{2\pi}}\frac{1}{(x-\varepsilon)(-x+\varepsilon+\lambda)}\exp\left[-\frac{1}{2}\left(\eta^2\ln\left\{\left(\frac{x-\varepsilon}{-x+\varepsilon+\lambda}\right)^2\right\}\right)\right], \varepsilon < x < \varepsilon+\lambda \\ \frac{\alpha}{2\delta}\exp\left[-\frac{|x|}{\lambda}\right], x \le \varepsilon . or . x \ge \varepsilon+\lambda \end{cases} \quad \text{(B1)}$$

The Convolution of Variables y_2 and y_1 and the Probability of $|y_2 - y_1| < W$

The PDF describing $(y_2 - y_1)$ is the convolution of the two PDFs of the two variables, y_2 and $-y_1$. The convolution of two variables y_2 and $+y_1$ is defined as the integral

$$f(u) = \int_{-\infty}^{\infty} f_1(y_1) f_2(u - y_1)\, dy_1, \quad \text{(B2)}$$

where $u = y_1 + y_2$. If f_1 and f_2 are PDFs of y_1 and y_2, then f is the PDF of $u = y_1 + y_2$.

Also, if the PDF of y_1 is symmetric about zero, then the convolution of y_2 and y_1 is equivalent to the convolution of y_2 and $-y_1$. Therefore, f is also the PDF of $u = y_2 - y_1$.

This means that the probability of $|y_2 - y_1| < W$ is the integral of f between $-W$ and W. That is,

$$P(\,|y_2 - y_1| < W\,) = \int_{-W}^{W} f(x)\, dx. \quad \text{(B3)}$$

But $f(x)$ is defined in (2) where f_1 is the Mixed Johnson S_B and Double-Exponential distribution PDF defined in (B1). That is, the PDF for the RNAV en route lateral deviations from [1] and f_2 is the PDF for the conventional route lateral deviations derived in Appendix A. Therefore,

$$P(\,|y_2 - y_1| < W\,) = \int_{-W}^{W}\int_{-\infty}^{\infty} f_1(y_1) f_2(x - y_1)\, dy_1\, dx \quad \text{(B4)}$$

where f_1 and f_2 are defined above.

Appendix C: Collision Rates by Turn Angle, Track Separation, COP Distance, Track Direction, and Number of Turns per Hour of Flight (RNAV Track Inside Conventional)

20° Turns

Collision Rates for 20° Turns RNAV Inside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	3.2E-13	3.4E-13	3.7E-13	3.9E-13	4.2E-13
8	Opposite	2.9E-12	3.2E-12	3.5E-12	3.8E-12	4.1E-12	4.3E-12
10	Same	3.8E-16	4.1E-16	4.4E-16	4.7E-16	5.0E-16	5.3E-16
10	Opposite	3.8E-15	4.1E-15	4.5E-15	4.8E-15	5.2E-15	5.6E-15

Collision Rates for 20° Turns RNAV Inside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	8.7E-13	9.3E-13	1.0E-12	1.1E-12	1.1E-12
8	Opposite	8.0E-12	8.8E-12	9.5E-12	1.0E-11	1.1E-11	1.2E-11
10	Same	1.0E-15	1.1E-15	1.2E-15	1.3E-15	1.4E-15	1.4E-15
10	Opposite	1.0E-14	1.1E-14	1.2E-14	1.3E-14	1.4E-14	1.5E-14

Collision Rates for 20° Turns RNAV Inside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	4.0E-12	4.3E-12	4.6E-12	5.0E-12	5.3E-12
8	Opposite	3.7E-11	4.0E-11	4.4E-11	4.8E-11	5.1E-11	5.5E-11
10	Same	4.7E-15	5.1E-15	5.5E-15	5.9E-15	6.3E-15	6.7E-15
10	Opposite	4.7E-14	5.2E-14	5.6E-14	6.1E-14	6.5E-14	6.7E-14

Collision Rates for 20° Turns RNAV Inside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	4.6E-09	5.5E-09	6.5E-09	7.4E-09	8.3E-09
8	Opposite	3.6E-08	4.8E-08	5.9E-08	7.0E-08	8.2E-08	9.3E-08
10	Same	1.3E-13	1.4E-13	1.6E-13	1.8E-13	1.9E-13	2.1E-13
10	Opposite	1.3E-12	1.5E-12	1.6E-12	1.8E-12	2.0E-12	2.2E-12

Collision Rates for 20° Turns RNAV Inside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	7.3E-07	7.7E-07	8.2E-07	8.6E-07	9.0E-07
8	Opposite	6.8E-06	7.3E-06	7.8E-06	8.3E-06	8.8E-06	9.3E-06
10	Same	**6.1E-10**	**6.8E-10**	**7.5E-10**	**8.2E-10**	**8.9E-10**	**9.6E-10**
10	Opposite	6.1E-09	6.9E-09	7.7E-09	8.5E-09	9.3E-09	1.0E-08
12	Same	**8.6E-14**	**9.8E-14**	**1.1E-13**	**1.2E-13**	**1.3E-13**	**1.5E-13**
12	Opposite	**8.6E-13**	**1.0E-12**	**1.1E-12**	**1.3E-12**	**1.4E-12**	**1.4E-12**

Collision Rates for 20° Turns RNAV Inside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	**8.6E-14**	**9.8E-14**	**1.1E-13**	**1.2E-13**	**1.3E-13**	**1.4E-13**
8	Opposite	**8.6E-13**	**1.0E-12**	**1.1E-12**	**1.3E-12**	**1.4E-12**	**1.5E-12**
10	Same	1.8E-07	1.9E-07	2.0E-07	2.1E-07	2.2E-07	2.4E-07
10	Opposite	1.8E-06	2.0E-06	2.1E-06	2.2E-06	2.3E-06	2.4E-06
12	Same	**2.2E-10**	**2.4E-10**	**2.6E-10**	**2.8E-10**	**3.1E-10**	**3.3E-10**
12	Opposite	2.2E-09	2.4E-09	2.7E-09	2.9E-09	3.2E-09	3.5E-09

Collision Rates for 20° Turns RNAV Inside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	2.3E-06	2.4E-06	2.5E-06	2.6E-06	2.7E-06
10	Opposite	2.2E-05	2.3E-05	2.4E-05	2.5E-05	2.7E-05	2.8E-05
12	Same	1.9E-08	2.0E-08	2.1E-08	2.2E-08	2.3E-08	2.4E-08
12	Opposite	1.9E-07	2.0E-07	2.1E-07	2.2E-07	2.4E-07	2.5E-07
14	Same	**6.7E-11**	**7.1E-11**	**7.6E-11**	**8.0E-11**	**8.5E-11**	**9.0E-11**
14	Opposite	**6.7E-10**	**7.2E-10**	**7.7E-10**	**8.3E-10**	**8.8E-10**	**9.3E-10**

Collision Rates for 20° Turns RNAV Inside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	5.5E-06	5.7E-06	6.0E-06	6.2E-06	6.5E-06
10	Opposite	5.2E-05	5.5E-05	5.8E-05	6.1E-05	6.4E-05	6.6E-05
12	Same	4.7E-08	5.0E-08	5.2E-08	5.5E-08	5.8E-08	6.0E-08
12	Opposite	4.7E-07	5.0E-07	5.3E-07	5.6E-07	5.9E-07	6.2E-07
14	Same	**1.9E-10**	**2.0E-10**	**2.1E-10**	**2.2E-10**	**2.3E-10**	**2.4E-10**
14	Opposite	1.9E-09	2.0E-09	2.1E-09	2.2E-09	2.3E-09	2.4E-09

30° Turns

Collision Rates for 30° Turns RNAV Inside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	5.4E-13	7.9E-13	1.0E-12	1.3E-12	1.5E-12
8	Opposite	2.9E-12	5.7E-12	8.4E-12	1.1E-11	1.4E-11	1.7E-11
10	Same	3.8E-16	6.8E-16	9.8E-16	1.3E-15	1.6E-15	1.9E-15
10	Opposite	3.8E-15	7.1E-15	1.0E-14	1.4E-14	1.7E-14	2.0E-14

Collision Rates for 30° Turns RNAV Inside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	1.5E-12	2.2E-12	2.9E-12	3.5E-12	4.2E-12
8	Opposite	8.0E-12	1.6E-11	2.3E-11	3.1E-11	3.8E-11	4.6E-11
10	Same	1.0E-15	1.8E-15	2.7E-15	3.5E-15	4.3E-15	5.1E-15
10	Opposite	1.0E-14	1.9E-14	2.8E-14	3.8E-14	4.7E-14	5.6E-14

Collision Rates for 30° Turns RNAV Inside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	6.8E-12	1.0E-11	1.3E-11	1.6E-11	1.9E-11
8	Opposite	3.7E-11	7.2E-11	1.1E-10	1.4E-10	1.8E-10	2.1E-10
10	Same	4.7E-15	8.5E-15	1.2E-14	1.6E-14	2.0E-14	2.4E-14
10	Opposite	4.7E-14	8.9E-14	1.3E-13	1.7E-13	2.2E-13	2.6E-13

Collision Rates for 30° Turns RNAV Inside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	5.2E-08	1.0E-07	1.5E-07	2.0E-07	2.5E-07
8	Opposite	3.6E-08	6.3E-07	1.2E-06	1.8E-06	2.4E-06	3.0E-06
10	Same	1.3E-13	3.7E-13	6.2E-13	8.6E-13	1.1E-12	1.3E-12
10	Opposite	1.3E-12	4.1E-12	6.9E-12	9.7E-12	1.3E-11	1.5E-11

Collision Rates for 30° Turns RNAV Inside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	9.7E-07	1.3E-06	1.5E-06	1.8E-06	2.1E-06
8	Opposite	6.8E-06	9.9E-06	1.3E-05	1.6E-05	1.9E-05	2.2E-05
10	Same	6.1E-10	1.4E-09	2.2E-09	2.9E-09	3.7E-09	4.5E-09
10	Opposite	6.1E-09	1.5E-08	2.4E-08	3.2E-08	4.1E-08	5.0E-08
12	Same	8.6E-14	2.5E-13	4.1E-13	5.8E-13	7.4E-13	9.0E-13
12	Opposite	8.6E-13	2.7E-12	4.6E-12	6.5E-12	8.4E-12	1.0E-11

Collision Rates for 30° Turns RNAV Inside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	2.8E-06	3.0E-06	3.3E-06	3.5E-06	3.9E-06
8	Opposite	1.9E-05	2.8E-05	3.0E-05	3.3E-05	3.5E-05	3.9E-05
10	Same	1.8E-07	2.4E-07	2.9E-07	3.5E-07	4.0E-07	4.5E-07
10	Opposite	1.8E-06	2.4E-06	3.0E-06	3.6E-06	4.1E-06	4.7E-06
12	Same	**2.2E-10**	**4.4E-10**	**6.6E-10**	**8.8E-10**	1.1E-09	1.3E-09
12	Opposite	2.2E-09	4.7E-09	7.2E-09	9.6E-09	1.2E-08	1.5E-08

Collision Rates for 30° Turns RNAV Inside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	2.8E-06	3.4E-06	4.1E-06	4.7E-06	5.3E-06
10	Opposite	2.2E-05	2.9E-05	3.5E-05	4.2E-05	4.9E-05	5.5E-05
12	Same	1.9E-08	2.6E-08	3.3E-08	4.0E-08	4.8E-08	5.5E-08
12	Opposite	1.9E-07	2.7E-07	3.4E-07	4.2E-07	5.0E-07	5.8E-07
14	Same	**6.7E-11**	**1.0E-10**	**1.3E-10**	**1.7E-10**	**2.0E-10**	**2.4E-10**
14	Opposite	**6.7E-10**	**1.0E-09**	1.4E-09	1.8E-09	2.2E-09	2.6E-09

Collision Rates for 30° Turns RNAV Inside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	6.7E-06	8.2E-06	9.7E-06	1.1E-05	1.3E-05
10	Opposite	5.2E-05	6.8E-05	8.4E-05	1.0E-04	1.2E-04	1.3E-04
12	Same	4.7E-08	6.5E-08	8.2E-08	1.0E-07	1.2E-07	1.3E-07
12	Opposite	4.7E-07	6.6E-07	8.5E-07	1.0E-06	1.2E-06	1.4E-06
14	Same	**1.9E-10**	**2.8E-10**	**3.7E-10**	**4.6E-10**	**5.5E-10**	**6.4E-10**
14	Opposite	1.9E-09	2.8E-09	3.8E-09	4.8E-09	5.8E-09	6.8E-09

45° Turns

Collision Rates for 45° Turns RNAV Inside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	9.7E-13	1.7E-12	2.3E-12	3.0E-12	3.7E-12
8	Opposite	2.9E-12	1.1E-11	1.9E-11	2.7E-11	3.5E-11	4.3E-11
10	Same	3.8E-16	1.1E-15	1.9E-15	2.6E-15	3.3E-15	4.1E-15
10	Opposite	3.8E-15	1.2E-14	2.1E-14	3.0E-14	3.8E-14	4.7E-14

Collision Rates for 45° Turns RNAV Inside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	2.7E-12	4.5E-12	6.4E-12	8.3E-12	1.0E-11
8	Opposite	8.0E-12	3.0E-11	5.1E-11	7.3E-11	9.5E-11	1.2E-10
10	Same	1.0E-15	3.0E-15	5.1E-15	7.1E-15	9.1E-15	1.1E-14
10	Opposite	1.0E-14	3.4E-14	5.8E-14	8.1E-14	1.0E-13	1.3E-13

Collision Rates for 45° Turns RNAV Inside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	1.2E-11	2.1E-11	2.9E-11	3.8E-11	4.7E-11
8	Opposite	3.7E-11	1.4E-10	2.4E-10	3.4E-10	4.3E-10	5.3E-10
10	Same	4.7E-15	1.4E-14	2.3E-14	3.3E-14	4.2E-14	5.2E-14
10	Opposite	4.7E-14	1.6E-13	2.7E-13	3.8E-13	4.9E-13	5.9E-13

Collision Rates for 45° Turns RNAV Inside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	4.4E-07	8.9E-07	1.3E-06	1.8E-06	2.2E-06
8	Opposite	3.6E-08	6.3E-06	1.2E-05	1.9E-05	2.5E-05	3.1E-05
10	Same	1.3E-13	1.0E-12	1.9E-12	2.8E-12	3.6E-12	4.5E-12
10	Opposite	1.3E-12	1.2E-11	2.3E-11	3.5E-11	4.6E-11	5.7E-11

Collision Rates for 45° Turns RNAV Inside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	1.2E-06	1.8E-06	2.3E-06	2.8E-06	3.4E-06
8	Opposite	6.8E-06	1.3E-05	1.9E-05	2.5E-05	3.0E-05	3.6E-05
10	Same	6.1E-10	2.6E-09	4.7E-09	6.7E-09	8.7E-09	1.1E-08
10	Opposite	6.1E-09	3.0E-08	5.4E-08	7.8E-08	1.0E-07	1.3E-07
12	Same	8.6E-14	5.5E-13	1.0E-12	1.5E-12	1.9E-12	2.4E-12
12	Opposite	8.6E-13	6.6E-12	1.2E-11	1.8E-11	2.4E-11	2.9E-11

Collision Rates for 45° Turns RNAV Inside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	2.2E-06	2.4E-06	2.7E-06	3.0E-06	3.2E-06
8	Opposite	1.9E-05	2.2E-05	2.4E-05	2.7E-05	3.0E-05	3.2E-05
10	Same	1.8E-07	2.7E-07	3.5E-07	4.4E-07	5.2E-07	6.1E-07
10	Opposite	1.8E-06	2.7E-06	3.6E-06	4.6E-06	5.5E-06	6.4E-06
12	Same	**2.2E-10**	**7.3E-10**	1.2E-09	1.7E-09	2.3E-09	2.8E-09
12	Opposite	2.2E-09	8.2E-09	1.4E-08	2.0E-08	2.6E-08	3.2E-08
14	Same	**1.4E-13**	**3.5E-13**	**5.7E-13**	**7.8E-13**	**1.0E-12**	**1.2E-12**
14	Opposite	**1.4E-12**	**4.0E-12**	**6.6E-12**	**9.2E-12**	**1.2E-11**	**1.4E-11**

Collision Rates for 45° Turns RNAV Inside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	3.3E-06	4.5E-06	5.7E-06	6.8E-06	8.0E-06
10	Opposite	2.2E-05	3.5E-05	4.8E-05	6.0E-05	7.3E-05	8.6E-05
12	Same	1.9E-08	3.2E-08	4.6E-08	5.9E-08	7.2E-08	8.6E-08
12	Opposite	1.9E-07	3.4E-07	4.9E-07	6.4E-07	8.0E-07	9.5E-07
14	Same	**6.7E-11**	**1.3E-10**	**1.9E-10**	**2.6E-10**	**3.2E-10**	**3.8E-10**
14	Opposite	**6.7E-10**	1.4E-09	2.1E-09	2.9E-09	3.6E-09	4.3E-09

Collision Rates for 45° Turns RNAV Inside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	8.0E-06	1.1E-05	1.3E-05	1.6E-05	1.9E-05
10	Opposite	5.2E-05	8.3E-05	1.1E-04	1.4E-04	1.7E-04	2.0E-04
12	Same	4.7E-08	8.0E-08	1.1E-07	1.4E-07	1.8E-07	2.1E-07
12	Opposite	4.7E-07	8.4E-07	1.2E-06	1.6E-06	1.9E-06	2.3E-06
14	Same	**1.9E-10**	**3.5E-10**	**5.2E-10**	**6.8E-10**	**8.4E-10**	**1.0E-09**
14	Opposite	1.9E-09	3.8E-09	5.7E-09	7.6E-09	9.5E-09	1.0E-08

60° Turns

Collision Rates for 60° Turns RNAV Inside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	1.5E-12	2.6E-12	3.8E-12	5.0E-12	6.2E-12
8	Opposite	2.9E-12	2.0E-11	3.7E-11	5.4E-11	7.1E-11	8.8E-11
10	Same	3.8E-16	1.4E-15	2.5E-15	3.6E-15	4.7E-15	5.7E-15
10	Opposite	3.8E-15	2.0E-14	3.6E-14	5.2E-14	6.8E-14	8.4E-14

Collision Rates for 60° Turns RNAV Inside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	4.0E-12	7.2E-12	1.0E-11	1.4E-11	1.7E-11
8	Opposite	8.0E-12	5.5E-11	1.0E-10	1.5E-10	1.9E-10	2.4E-10
10	Same	1.0E-15	4.0E-15	6.9E-15	9.8E-15	1.3E-14	1.6E-14
10	Opposite	1.0E-14	5.4E-14	9.8E-14	1.4E-13	1.9E-13	2.3E-13

Collision Rates for 60° Turns RNAV Inside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	1.8E-11	3.3E-11	4.8E-11	6.3E-11	7.7E-11
8	Opposite	3.7E-11	2.5E-10	4.6E-10	6.8E-10	8.9E-10	1.1E-09
10	Same	4.7E-15	1.8E-14	3.2E-14	4.5E-14	5.9E-14	7.3E-14
10	Opposite	4.7E-14	2.5E-13	4.5E-13	6.6E-13	8.6E-13	1.1E-12

Collision Rates for 60° Turns RNAV Inside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	1.6E-06	3.2E-06	4.8E-06	6.4E-06	8.0E-06
8	Opposite	3.6E-08	4.0E-05	8.0E-05	1.2E-04	1.6E-04	2.0E-04
10	Same	1.3E-13	1.7E-12	3.2E-12	4.7E-12	6.3E-12	7.8E-12
10	Opposite	1.3E-12	3.0E-11	5.8E-11	8.7E-11	1.2E-10	1.4E-10

Collision Rates for 60° Turns RNAV Inside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	1.4E-06	2.1E-06	2.9E-06	3.6E-06	4.3E-06
8	Opposite	6.8E-06	1.6E-05	2.4E-05	3.3E-05	4.2E-05	5.1E-05
10	Same	6.1E-10	3.6E-09	6.6E-09	9.6E-09	1.3E-08	1.6E-08
10	Opposite	6.1E-09	5.1E-08	9.7E-08	1.4E-07	1.9E-07	2.3E-07
12	Same	8.6E-14	6.8E-13	1.3E-12	1.9E-12	2.4E-12	3.0E-12
12	Opposite	8.6E-13	1.1E-11	2.2E-11	3.2E-11	4.3E-11	5.3E-11

Collision Rates for 60° Turns RNAV Inside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	2.2E-06	2.4E-06	2.7E-06	3.0E-06	3.2E-06
8	Opposite	1.9E-05	2.2E-05	2.4E-05	2.7E-05	3.0E-05	3.2E-05
10	Same	1.8E-07	2.8E-07	3.8E-07	4.8E-07	5.8E-07	6.8E-07
10	Opposite	1.8E-06	3.0E-06	4.1E-06	5.2E-06	6.3E-06	7.5E-06
12	Same	**2.2E-10**	**8.4E-10**	1.5E-09	2.1E-09	2.7E-09	3.3E-09
12	Opposite	2.2E-09	1.2E-08	2.2E-08	3.1E-08	4.1E-08	5.1E-08
14	Same	**1.4E-13**	**3.5E-13**	**5.7E-13**	**7.8E-13**	**1.0E-12**	**1.2E-12**
14	Opposite	**1.4E-12**	**5.1E-12**	**8.8E-12**	**1.3E-11**	**1.6E-11**	**2.0E-11**

Collision Rates for 60° Turns RNAV Inside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	3.7E-06	5.1E-06	6.6E-06	8.1E-06	9.6E-06
10	Opposite	2.2E-05	4.1E-05	6.0E-05	7.9E-05	9.8E-05	1.2E-04
12	Same	1.9E-08	3.4E-08	5.0E-08	6.5E-08	8.1E-08	9.6E-08
12	Opposite	1.9E-07	4.0E-07	6.2E-07	8.3E-07	1.0E-06	1.3E-06
14	Same	**6.7E-11**	**1.3E-10**	**1.9E-10**	**2.6E-10**	**3.2E-10**	**3.8E-10**
14	Opposite	**6.7E-10**	1.6E-09	2.6E-09	3.6E-09	4.5E-09	5.5E-09

Collision Rates for 60° Turns RNAV Inside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	8.7E-06	1.2E-05	1.6E-05	1.9E-05	2.3E-05
10	Opposite	5.2E-05	9.7E-05	1.4E-04	1.9E-04	2.3E-04	2.8E-04
12	Same	4.7E-08	8.5E-08	1.2E-07	1.6E-07	2.0E-07	2.3E-07
12	Opposite	4.7E-07	9.9E-07	1.5E-06	2.0E-06	2.6E-06	3.1E-06
14	Same	**1.9E-10**	**3.5E-10**	**5.2E-10**	**6.8E-10**	**8.4E-10**	**1.0E-09**
14	Opposite	1.9E-09	4.4E-09	6.9E-09	9.4E-09	1.2E-08	1.4E-08

70° Turns

Collision Rates for 70° Turns RNAV Inside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	1.5E-12	2.8E-12	4.0E-12	5.2E-12	6.5E-12
8	Opposite	2.9E-12	2.7E-11	5.0E-11	7.4E-11	9.8E-11	1.2E-10
10	Same	3.8E-16	1.3E-15	2.3E-15	3.2E-15	4.2E-15	5.1E-15
10	Opposite	3.8E-15	2.3E-14	4.3E-14	6.3E-14	8.2E-14	1.0E-13

Collision Rates for 70° Turns RNAV Inside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	4.2E-12	7.6E-12	1.1E-11	1.4E-11	1.8E-11
8	Opposite	8.0E-12	7.3E-11	1.4E-10	2.0E-10	2.7E-10	3.3E-10
10	Same	1.0E-15	3.6E-15	6.2E-15	8.8E-15	1.1E-14	1.4E-14
10	Opposite	1.0E-14	6.4E-14	1.2E-13	1.7E-13	2.2E-13	2.8E-13

Collision Rates for 70° Turns RNAV Inside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	1.9E-11	3.5E-11	5.0E-11	6.6E-11	8.1E-11
8	Opposite	3.7E-11	3.3E-10	6.3E-10	9.2E-10	1.2E-09	1.5E-09
10	Same	4.7E-15	1.7E-14	2.9E-14	4.1E-14	5.3E-14	6.5E-14
10	Opposite	4.7E-14	3.0E-13	5.4E-13	7.9E-13	1.0E-12	1.3E-12

Collision Rates for 70° Turns RNAV Inside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	1.8E-06	3.6E-06	5.5E-06	7.3E-06	9.1E-06
8	Opposite	3.6E-08	9.3E-05	1.9E-04	2.8E-04	3.7E-04	4.6E-04
10	Same	1.3E-13	1.4E-12	2.7E-12	3.9E-12	5.2E-12	6.4E-12
10	Opposite	1.3E-12	4.0E-11	8.0E-11	1.2E-10	1.6E-10	2.0E-10

Collision Rates for 70° Turns RNAV Inside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	1.4E-06	2.2E-06	2.9E-06	3.7E-06	4.4E-06
8	Opposite	6.8E-06	1.7E-05	2.7E-05	3.8E-05	4.8E-05	5.8E-05
10	Same	6.1E-10	3.2E-09	5.9E-09	8.5E-09	1.1E-08	1.4E-08
10	Opposite	6.1E-09	6.1E-08	1.2E-07	1.7E-07	2.3E-07	2.8E-07
12	Same	8.6E-14	4.7E-13	8.6E-13	1.2E-12	1.6E-12	2.0E-12
12	Opposite	8.6E-13	1.2E-11	2.4E-11	3.5E-11	4.7E-11	5.8E-11

Collision Rates for 70° Turns RNAV Inside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06		2.4E-06	2.7E-06	3.0E-06	3.2E-06
8	Opposite	1.9E-05	2.2E-05	2.4E-05	2.7E-05	3.0E-05	3.2E-05
10	Same	1.8E-07	2.8E-07	3.7E-07	4.7E-07	5.6E-07	6.5E-07
10	Opposite	1.8E-06	3.0E-06	4.2E-06	5.4E-06	6.6E-06	7.8E-06
12	Same	**2.2E-10**	**6.6E-10**	1.1E-09	1.5E-09	2.0E-09	2.4E-09
12	Opposite	2.2E-09	1.3E-08	2.3E-08	3.3E-08	4.4E-08	5.4E-08
14	Same	**1.4E-13**	**2.5E-13**	**3.7E-13**	**4.9E-13**	**6.0E-13**	**7.2E-13**
14	Opposite	**1.4E-12**	**4.8E-12**	**8.2E-12**	**1.2E-11**	**1.5E-11**	**1.8E-11**

Collision Rates for 70° Turns RNAV Inside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	3.6E-06	4.9E-06	6.3E-06	7.6E-06	9.0E-06
10	Opposite	2.2E-05	4.3E-05	6.5E-05	8.6E-05	1.1E-04	1.3E-04
12	Same	1.9E-08	3.1E-08	4.3E-08	5.5E-08	6.7E-08	7.9E-08
12	Opposite	1.9E-07	4.1E-07	6.4E-07	8.6E-07	1.1E-06	1.3E-06
14	Same	**6.7E-11**	**1.1E-10**	**1.4E-10**	**1.8E-10**	**2.2E-10**	**2.6E-10**
14	Opposite	**6.7E-10**	1.6E-09	2.5E-09	3.4E-09	4.3E-09	5.2E-09

Collision Rates for 70° Turns RNAV Inside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	8.4E-06	1.2E-05	1.5E-05	1.8E-05	2.1E-05
10	Opposite	5.2E-05	1.0E-04	1.5E-04	2.0E-04	2.6E-04	3.1E-04
12	Same	4.7E-08	7.7E-08	1.1E-07	1.4E-07	1.6E-07	1.9E-07
12	Opposite	4.7E-07	1.0E-06	1.6E-06	2.1E-06	2.7E-06	3.2E-06
14	Same	**1.9E-10**	**2.9E-10**	**3.9E-10**	**4.9E-10**	**5.9E-10**	**6.9E-10**
14	Opposite	1.9E-09	4.2E-09	6.6E-09	8.9E-09	1.1E-08	1.4E-08

Appendix D: Collision Rates by Turn Angle, Track Separation, COP Distance, Track Direction, and Number of Turns per Hour of Flight (RNAV Track Outside Conventional)

20° Turns

Collision Rates for 20° Turns RNAV Outside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	1.6E-12	2.9E-12	4.3E-12	5.6E-12	2.9E-11
8	Opposite	2.9E-12	1.7E-11	3.1E-11	4.6E-11	6.0E-11	3.0E-10
10	Same	3.8E-16	2.1E-15	3.8E-15	5.5E-15	7.2E-15	1.8E-14
10	Opposite	3.8E-15	2.2E-14	4.0E-14	5.9E-14	7.7E-14	1.9E-13

Collision Rates for 20° Turns RNAV Outside,10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	4.4E-12	8.0E-12	1.2E-11	1.5E-11	1.8E-11
8	Opposite	8.0E-12	4.7E-11	8.6E-11	1.2E-10	1.6E-10	1.8E-10
10	Same	1.0E-15	5.7E-15	1.0E-14	1.5E-14	2.0E-14	2.4E-14
10	Opposite	1.0E-14	6.0E-14	1.1E-13	1.6E-13	2.1E-13	2.4E-13

Collision Rates for 20° Turns RNAV Outside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	2.0E-11	3.7E-11	5.3E-11	7.0E-11	8.3E-11
8	Opposite	3.7E-11	2.1E-10	3.9E-10	5.7E-10	7.5E-10	8.7E-10
10	Same	4.7E-15	2.6E-14	4.8E-14	6.9E-14	9.1E-14	1.3E-13
10	Opposite	4.7E-14	2.8E-13	5.1E-13	7.5E-13	9.8E-13	1.4E-12

Collision Rates for 20° Turns RNAV Outside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	2.1E-06	4.3E-06	6.4E-06	8.5E-06	9.6E-06
8	Opposite	3.6E-08	2.6E-05	5.1E-05	7.7E-05	1.0E-04	1.6E-04
10	Same	1.3E-13	3.3E-12	6.4E-12	9.5E-12	1.3E-11	3.3E-11
10	Opposite	1.3E-12	3.7E-11	7.2E-11	1.1E-10	1.4E-10	3.5E-10

Collision Rates for 20° Turns RNAV Outside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	1.5E-06	2.2E-06	3.0E-06	3.8E-06	4.4E-06
8	Opposite	6.8E-06	1.5E-05	2.3E-05	3.1E-05	3.9E-05	4.5E-05
10	Same	**6.1E-10**	5.4E-09	1.0E-08	1.5E-08	2.0E-08	2.4E-08
10	Opposite	6.1E-09	5.8E-08	1.1E-07	1.6E-07	2.1E-07	2.4E-07
12	Same	**8.6E-14**	**1.8E-12**	**3.5E-12**	**5.2E-12**	**6.9E-12**	**8.6E-12**
12	Opposite	**8.6E-13**	**2.0E-11**	**3.9E-11**	**5.8E-11**	**7.7E-11**	**8.6E-11**

Collision Rates for 20° Turns RNAV Outside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	1.7E-06	1.6E-06	1.4E-06	1.3E-06	1.9E-06
8	Opposite	1.9E-05	1.7E-05	1.6E-05	1.4E-05	1.3E-05	1.9E-05
10	Same	1.8E-07	3.0E-07	4.1E-07	5.3E-07	6.4E-07	1.8E-07
10	Opposite	1.8E-06	3.0E-06	4.2E-06	5.4E-06	6.5E-06	1.8E-06
12	Same	**2.2E-10**	1.6E-09	3.0E-09	4.5E-09	5.9E-09	7.2E-09
12	Opposite	2.2E-09	1.7E-08	3.3E-08	4.8E-08	6.3E-08	2.2E-09

Collision Rates for 20° Turns RNAV Outside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	4.2E-06	6.1E-06	8.1E-06	1.0E-05	2.2E-05
10	Opposite	2.2E-05	4.3E-05	6.3E-05	8.4E-05	1.0E-04	2.2E-04
12	Same	1.9E-08	4.7E-08	7.5E-08	1.0E-07	1.3E-07	1.9E-07
12	Opposite	1.9E-07	4.9E-07	7.9E-07	1.1E-06	1.4E-06	1.9E-06
14	Same	**6.7E-11**	**2.4E-10**	**4.1E-10**	**5.9E-10**	**7.6E-10**	**9.7E-10**
14	Opposite	**6.7E-10**	2.5E-09	4.4E-09	6.2E-09	8.1E-09	9.6E-09

Collision Rates for 20° Turns RNAV Outside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	9.9E-06	1.5E-05	1.9E-05	2.4E-05	3.2E-05
10	Opposite	5.2E-05	1.0E-04	1.5E-04	2.0E-04	2.5E-04	3.2E-04
12	Same	4.7E-08	1.2E-07	1.8E-07	2.5E-07	3.2E-07	4.7E-07
12	Opposite	4.7E-07	1.2E-06	1.9E-06	2.6E-06	3.4E-06	4.7E-06
14	Same	**1.9E-10**	**6.3E-10**	1.1E-09	1.5E-09	2.0E-09	2.6E-09
14	Opposite	1.9E-09	6.7E-09	1.1E-08	1.6E-08	2.1E-08	2.7E-08

30° Turns

Collision Rates for 30° Turns RNAV Outside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	8.1E-12	1.6E-11	2.4E-11	3.1E-11	3.9E-11
8	Opposite	2.9E-12	8.8E-11	1.7E-10	2.6E-10	3.4E-10	4.3E-10
10	Same	3.8E-16	9.9E-15	1.9E-14	2.9E-14	3.8E-14	4.8E-14
10	Opposite	3.8E-15	1.1E-13	2.1E-13	3.2E-13	4.2E-13	5.3E-13

Collision Rates for 30° Turns RNAV Outside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	2.2E-11	4.3E-11	6.4E-11	8.6E-11	1.1E-10
8	Opposite	8.0E-12	2.4E-10	4.7E-10	7.0E-10	9.4E-10	1.2E-09
10	Same	1.0E-15	2.7E-14	5.3E-14	7.9E-14	1.1E-13	1.3E-13
10	Opposite	1.0E-14	3.0E-13	5.8E-13	8.7E-13	1.2E-12	1.4E-12

Collision Rates for 30° Turns RNAV Outside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	1.0E-10	2.0E-10	2.9E-10	3.9E-10	4.8E-10
8	Opposite	3.7E-11	1.1E-09	2.1E-09	3.2E-09	4.2E-09	5.3E-09
10	Same	4.7E-15	1.3E-13	2.5E-13	3.7E-13	4.9E-13	6.1E-13
10	Opposite	4.7E-14	1.4E-12	2.7E-12	4.0E-12	5.4E-12	6.7E-12

Collision Rates for 30° Turns RNAV Outside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	1.8E-06	3.6E-06	5.5E-06	7.3E-06	9.1E-06
8	Opposite	3.6E-08	9.3E-05	1.9E-04	2.8E-04	3.7E-04	4.6E-04
10	Same	1.3E-13	5.7E-11	1.1E-10	1.7E-10	2.3E-10	2.8E-10
10	Opposite	1.3E-12	6.7E-10	1.3E-09	2.0E-09	2.7E-09	3.4E-09

Collision Rates for 30° Turns RNAV Outside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	2.3E-06	3.9E-06	5.6E-06	7.2E-06	8.8E-06
8	Opposite	6.8E-06	2.4E-05	4.0E-05	5.7E-05	7.4E-05	9.0E-05
10	Same	**6.1E-10**	2.6E-08	5.1E-08	7.6E-08	1.0E-07	1.3E-07
10	Opposite	6.1E-09	2.8E-07	5.5E-07	8.2E-07	1.1E-06	1.4E-06
12	Same	**8.6E-14**	**1.5E-11**	**2.9E-11**	**4.4E-11**	**5.9E-11**	**7.3E-11**
12	Opposite	**8.6E-13**	**1.7E-10**	**3.3E-10**	**5.0E-10**	**6.6E-10**	**8.3E-10**

Collision Rates for 30° Turns RNAV Outside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	2.3E-06	2.6E-06	2.9E-06	3.3E-06	3.7E-06
8	Opposite	1.9E-05	2.3E-05	2.6E-05	3.0E-05	3.3E-05	3.8E-05
10	Same	1.8E-07	3.3E-07	4.8E-07	6.2E-07	7.7E-07	9.2E-07
10	Opposite	1.8E-06	3.3E-06	4.8E-06	6.2E-06	7.7E-06	9.1E-06
12	Same	**2.2E-10**	6.8E-09	1.3E-08	2.0E-08	2.7E-08	3.3E-08
12	Opposite	2.2E-09	7.4E-08	1.5E-07	2.2E-07	2.9E-07	3.6E-07

Collision Rates for 30° Turns RNAV Outside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	7.7E-06	1.3E-05	1.9E-05	2.4E-05	3.0E-05
10	Opposite	2.2E-05	8.0E-05	1.4E-04	2.0E-04	2.5E-04	3.1E-04
12	Same	1.9E-08	1.1E-07	2.0E-07	2.9E-07	3.8E-07	4.7E-07
12	Opposite	1.9E-07	1.2E-06	2.1E-06	3.1E-06	4.1E-06	5.0E-06
14	Same	**6.7E-11**	**7.2E-10**	1.4E-09	2.0E-09	2.7E-09	3.3E-09
14	Opposite	**6.7E-10**	7.7E-09	1.5E-08	2.2E-08	2.9E-08	3.6E-08

Collision Rates for 30° Turns RNAV Outside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	1.8E-05	3.1E-05	4.4E-05	5.7E-05	7.0E-05
10	Opposite	5.2E-05	1.9E-04	3.3E-04	4.6E-04	6.0E-04	7.3E-04
12	Same	4.7E-08	2.6E-07	4.8E-07	7.0E-07	9.2E-07	1.1E-06
12	Opposite	4.7E-07	2.8E-06	5.1E-06	7.4E-06	9.8E-06	1.2E-05
14	Same	**1.9E-10**	1.8E-09	3.5E-09	5.1E-09	6.8E-09	8.4E-09
14	Opposite	1.9E-09	2.0E-08	3.8E-08	5.5E-08	7.3E-08	9.1E-08

45° Turns

Collision Rates for 45° Turns RNAV Outside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	2.1E-11	4.2E-11	6.4E-11	8.5E-11	1.1E-10
8	Opposite	2.9E-12	2.5E-10	4.9E-10	7.3E-10	9.7E-10	1.2E-09
10	Same	3.8E-16	2.4E-14	4.7E-14	7.1E-14	9.4E-14	1.2E-13
10	Opposite	3.8E-15	2.7E-13	5.5E-13	8.2E-13	1.1E-12	1.4E-12

Collision Rates for 45° Turns RNAV Outside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	5.8E-11	1.2E-10	1.7E-10	2.3E-10	2.9E-10
8	Opposite	8.0E-12	6.7E-10	1.3E-09	2.0E-09	2.6E-09	3.3E-09
10	Same	6.5E-14	1.3E-13	1.9E-13	2.6E-13	3.2E-13	6.5E-14
10	Opposite	7.5E-13	1.5E-12	2.2E-12	3.0E-12	3.7E-12	7.5E-13

Collision Rates for 45° Turns RNAV Outside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	2.6E-10	5.2E-10	7.8E-10	1.0E-09	1.3E-09
8	Opposite	3.7E-11	3.0E-09	6.0E-09	9.0E-09	1.2E-08	1.5E-08
10	Same	4.7E-15	3.0E-13	6.0E-13	8.9E-13	1.2E-12	1.5E-12
10	Opposite	4.7E-14	3.5E-12	6.9E-12	1.0E-11	1.4E-11	1.7E-11

Collision Rates for 45° Turns RNAV Outside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	*3.6E-09*	1.8E-06	3.6E-06	5.5E-06	7.3E-06	9.1E-06
8	Opposite	*3.6E-08*	9.3E-05	1.9E-04	2.8E-04	3.7E-04	4.6E-04
10	Same	**1.3E-13**	**3.0E-10**	**6.0E-10**	**8.9E-10**	1.2E-09	1.5E-09
10	Opposite	**1.3E-12**	3.9E-09	7.9E-09	1.2E-08	1.6E-08	2.0E-08

Collision Rates for 45° Turns RNAV Outside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	2.8E-06	4.9E-06	7.0E-06	9.1E-06	1.1E-05
8	Opposite	6.8E-06	2.8E-05	5.0E-05	7.2E-05	9.3E-05	1.2E-04
10	Same	**6.1E-10**	5.6E-08	1.1E-07	1.7E-07	2.2E-07	2.8E-07
10	Opposite	6.1E-09	6.3E-07	1.2E-06	1.9E-06	2.5E-06	3.1E-06
12	Same	**8.6E-14**	**4.0E-11**	**7.9E-11**	**1.2E-10**	**1.6E-10**	**2.0E-10**
12	Opposite	**8.6E-13**	**4.8E-10**	**9.6E-10**	1.4E-09	1.9E-09	2.4E-09

Collision Rates for 45° Turns RNAV Outside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	2.3E-06	2.6E-06	2.9E-06	3.3E-06	3.7E-06
8	Opposite	1.9E-05	2.3E-05	2.6E-05	3.0E-05	3.3E-05	3.8E-05
10	Same	1.8E-07	3.2E-07	4.5E-07	5.8E-07	7.2E-07	8.5E-07
10	Opposite	1.8E-06	3.1E-06	4.4E-06	5.7E-06	7.0E-06	8.3E-06
12	Same	**2.2E-10**	1.3E-08	2.6E-08	3.9E-08	5.1E-08	6.4E-08
12	Opposite	2.2E-09	1.5E-07	2.9E-07	4.4E-07	5.8E-07	7.2E-07
14	Same	**1.4E-13**	**1.2E-11**	**2.3E-11**	**3.5E-11**	**4.6E-11**	**5.8E-11**
14	Opposite	**1.4E-12**	**1.4E-10**	**2.8E-10**	**4.2E-10**	**5.6E-10**	**7.0E-10**

Collision Rates for 45° Turns RNAV Outside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	1.1E-05	2.0E-05	2.9E-05	3.8E-05	4.8E-05
10	Opposite	2.2E-05	1.2E-04	2.2E-04	3.2E-04	4.2E-04	5.1E-04
12	Same	1.9E-08	1.7E-07	3.3E-07	4.8E-07	6.4E-07	7.9E-07
12	Opposite	1.9E-07	1.9E-06	3.6E-06	5.3E-06	7.1E-06	8.8E-06
14	Same	**6.7E-11**	1.2E-09	2.3E-09	3.4E-09	4.6E-09	5.7E-09
14	Opposite	**6.7E-10**	1.3E-08	2.6E-08	3.9E-08	5.2E-08	6.5E-08

Collision Rates for 45° Turns RNAV Outside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	2.7E-05	4.8E-05	6.9E-05	9.1E-05	1.1E-04
10	Opposite	5.2E-05	2.8E-04	5.2E-04	7.5E-04	9.8E-04	1.2E-03
12	Same	4.7E-08	4.2E-07	7.9E-07	1.2E-06	1.5E-06	1.9E-06
12	Opposite	4.7E-07	4.6E-06	8.7E-06	1.3E-05	1.7E-05	2.1E-05
14	Same	**1.9E-10**	3.0E-09	5.9E-09	8.7E-09	1.2E-08	1.4E-08
14	Opposite	1.9E-09	3.4E-08	6.6E-08	9.8E-08	1.3E-07	1.6E-07

60° Turns

Collision Rates for 60° Turns RNAV Outside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	3.9E-11	7.8E-11	1.2E-10	1.6E-10	1.9E-10
8	Opposite	2.9E-12	5.5E-10	1.1E-09	1.7E-09	2.2E-09	2.8E-09
10	Same	3.8E-16	3.7E-14	7.3E-14	1.1E-13	1.5E-13	1.8E-13
10	Opposite	3.8E-15	5.4E-13	1.1E-12	1.6E-12	2.1E-12	2.7E-12

Collision Rates for 60° Turns RNAV Outside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	1.1E-10	2.1E-10	3.2E-10	4.2E-10	5.3E-10
8	Opposite	8.0E-12	1.5E-09	3.0E-09	4.5E-09	6.0E-09	7.5E-09
10	Same	1.0E-15	1.0E-13	2.0E-13	3.0E-13	4.0E-13	5.0E-13
10	Opposite	1.0E-14	1.5E-12	2.9E-12	4.4E-12	5.9E-12	7.3E-12

Collision Rates for 60° Turns RNAV Outside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	4.8E-10	9.5E-10	1.4E-09	1.9E-09	2.4E-09
8	Opposite	3.7E-11	6.7E-09	1.3E-08	2.0E-08	2.7E-08	3.4E-08
10	Same	4.7E-15	4.7E-13	9.3E-13	1.4E-12	1.9E-12	2.3E-12
10	Opposite	4.7E-14	6.8E-12	1.4E-11	2.0E-11	2.7E-11	3.4E-11

Collision Rates for 60° Turns RNAV Outside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	1.8E-06	3.6E-06	5.5E-06	7.3E-06	9.1E-06
8	Opposite	3.6E-08	9.3E-05	1.9E-04	2.8E-04	3.7E-04	4.6E-04
10	Same	1.3E-13	7.0E-10	1.4E-09	2.1E-09	2.8E-09	3.5E-09
10	Opposite	1.3E-12	1.5E-08	3.0E-08	4.5E-08	6.0E-08	7.5E-08

Collision Rates for 60° Turns RNAV Outside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	3.0E-06	5.3E-06	7.7E-06	1.0E-05	1.2E-05
8	Opposite	6.8E-06	3.1E-05	5.5E-05	8.0E-05	1.0E-04	1.3E-04
10	Same	**6.1E-10**	8.0E-08	1.6E-07	2.4E-07	3.2E-07	4.0E-07
10	Opposite	6.1E-09	1.1E-06	2.1E-06	3.2E-06	4.3E-06	5.3E-06
12	Same	**8.6E-14**	**5.5E-11**	**1.1E-10**	**1.7E-10**	**2.2E-10**	**2.8E-10**
12	Opposite	**8.6E-13**	**9.1E-10**	1.8E-09	2.7E-09	3.7E-09	4.6E-09

Collision Rates for 60° Turns RNAV Outside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	2.3E-06	2.6E-06	2.9E-06	3.3E-06	3.7E-06
8	Opposite	1.9E-05	2.3E-05	2.6E-05	3.0E-05	3.3E-05	3.8E-05
10	Same	1.8E-07	3.0E-07	4.2E-07	5.4E-07	6.6E-07	7.8E-07
10	Opposite	1.8E-06	2.9E-06	3.9E-06	5.0E-06	6.0E-06	7.1E-06
12	Same	**2.2E-10**	1.6E-08	3.2E-08	4.8E-08	6.3E-08	7.9E-08
12	Opposite	2.2E-09	2.2E-07	4.3E-07	6.5E-07	8.6E-07	1.1E-06
14	Same	**1.4E-13**	**1.3E-11**	**2.6E-11**	**3.9E-11**	**5.1E-11**	**6.4E-11**
14	Opposite	**1.4E-12**	**2.2E-10**	**4.3E-10**	**6.5E-10**	**8.6E-10**	1.1E-09

Collision Rates for 60° Turns RNAV Outside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	1.4E-05	2.5E-05	3.7E-05	4.8E-05	6.0E-05
10	Opposite	2.2E-05	1.6E-04	3.1E-04	4.5E-04	5.9E-04	7.3E-04
12	Same	1.9E-08	2.0E-07	3.9E-07	5.8E-07	7.6E-07	9.5E-07
12	Opposite	1.9E-07	2.6E-06	5.0E-06	7.5E-06	9.9E-06	1.2E-05
14	Same	**6.7E-11**	1.3E-09	2.5E-09	3.7E-09	4.9E-09	6.1E-09
14	Opposite	**6.7E-10**	1.8E-08	3.5E-08	5.2E-08	6.9E-08	8.7E-08

Collision Rates for 60° Turns RNAV Outside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	3.3E-05	6.0E-05	8.7E-05	1.1E-04	1.4E-04
10	Opposite	5.2E-05	3.9E-04	7.2E-04	1.1E-03	1.4E-03	1.7E-03
12	Same	4.7E-08	4.9E-07	9.3E-07	1.4E-06	1.8E-06	2.3E-06
12	Opposite	4.7E-07	6.2E-06	1.2E-05	1.8E-05	2.4E-05	2.9E-05
14	Same	**1.9E-10**	3.2E-09	6.3E-09	9.3E-09	1.2E-08	1.5E-08
14	Opposite	1.9E-09	4.5E-08	8.8E-08	1.3E-07	1.7E-07	2.2E-07

70° Turns

Collision Rates for 70° Turns RNAV Outside, 0-10 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	2.9E-13	4.5E-11	8.9E-11	1.3E-10	1.8E-10	2.2E-10
8	Opposite	2.9E-12	8.2E-10	1.6E-09	2.5E-09	3.3E-09	4.1E-09
10	Same	3.8E-16	3.6E-14	7.1E-14	1.1E-13	1.4E-13	1.8E-13
10	Opposite	3.8E-15	7.0E-13	1.4E-12	2.1E-12	2.8E-12	3.5E-12

Collision Rates for 70° Turns RNAV Outside, 10-20 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	8.0E-13	1.2E-10	2.4E-10	3.6E-10	4.8E-10	6.0E-10
8	Opposite	8.0E-12	2.2E-09	4.4E-09	6.6E-09	8.8E-09	1.1E-08
10	Same	1.0E-15	9.8E-14	1.9E-13	2.9E-13	3.9E-13	4.9E-13
10	Opposite	1.0E-14	1.9E-12	3.8E-12	5.7E-12	7.6E-12	9.5E-12

Collision Rates for 70° Turns RNAV Outside, 20-30 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.7E-12	5.4E-10	1.1E-09	1.6E-09	2.2E-09	2.7E-09
8	Opposite	3.7E-11	9.9E-09	2.0E-08	3.0E-08	4.0E-08	4.9E-08
10	Same	4.7E-15	4.5E-13	9.0E-13	1.3E-12	1.8E-12	2.2E-12
10	Opposite	4.7E-14	8.8E-12	1.8E-11	2.6E-11	3.5E-11	4.4E-11

Collision Rates for 70° Turns RNAV Outside, 30-40 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	3.6E-09	1.8E-06	3.6E-06	5.5E-06	7.3E-06	9.1E-06
8	Opposite	3.6E-08	9.3E-05	1.9E-04	2.8E-04	3.7E-04	4.6E-04
10	Same	1.3E-13	6.6E-10	1.3E-09	2.0E-09	2.6E-09	3.3E-09
10	Opposite	1.3E-12	2.5E-08	5.1E-08	7.6E-08	1.0E-07	1.3E-07

Collision Rates for 70° Turns RNAV Outside, 40-50 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	6.8E-07	3.1E-06	5.4E-06	7.8E-06	1.0E-05	1.3E-05
8	Opposite	6.8E-06	3.2E-05	5.7E-05	8.1E-05	1.1E-04	1.3E-04
10	Same	**6.1E-10**	7.8E-08	1.5E-07	2.3E-07	3.1E-07	3.9E-07
10	Opposite	6.1E-09	1.3E-06	2.6E-06	3.9E-06	5.2E-06	6.5E-06
12	Same	**8.6E-14**	**4.3E-11**	**8.5E-11**	**1.3E-10**	**1.7E-10**	**2.1E-10**
12	Opposite	**8.6E-13**	1.1E-09	2.1E-09	3.2E-09	4.3E-09	5.3E-09

Collision Rates for 70° Turns RNAV Outside, 50-60 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
8	Same	1.9E-06	2.3E-06	2.6E-06	2.9E-06	3.3E-06	3.7E-06
8	Opposite	1.9E-05	2.3E-05	2.6E-05	3.0E-05	3.3E-05	3.8E-05
10	Same	1.8E-07	3.0E-07	4.3E-07	5.5E-07	6.7E-07	7.9E-07
10	Opposite	1.8E-06	2.8E-06	3.7E-06	4.7E-06	5.6E-06	6.6E-06
12	Same	**2.2E-10**	1.4E-08	2.7E-08	4.0E-08	5.4E-08	6.7E-08
12	Opposite	2.2E-09	2.4E-07	4.7E-07	7.1E-07	9.4E-07	1.2E-06
14	Same	**1.4E-13**	**8.1E-12**	**1.6E-11**	**2.4E-11**	**3.2E-11**	**4.0E-11**
14	Opposite	**1.4E-12**	**2.2E-10**	**4.3E-10**	**6.4E-10**	**8.6E-10**	1.1E-09

Collision Rates for 70° Turns RNAV Outside, 60-70 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	2.2E-06	1.4E-05	2.5E-05	3.6E-05	4.8E-05	5.9E-05
10	Opposite	2.2E-05	1.8E-04	3.5E-04	5.1E-04	6.7E-04	8.4E-04
12	Same	1.9E-08	1.8E-07	3.4E-07	5.0E-07	6.6E-07	8.2E-07
12	Opposite	1.9E-07	2.8E-06	5.5E-06	8.1E-06	1.1E-05	1.3E-05
14	Same	**6.7E-11**	**9.4E-10**	1.8E-09	2.7E-09	3.6E-09	4.4E-09
14	Opposite	**6.7E-10**	1.8E-08	3.5E-08	5.2E-08	6.9E-08	8.6E-08

Collision Rates for 70° Turns RNAV Outside, 70-80 NM COP		Number of Turns					
Track-to-Track Separation (NM)	Track Direction	0	1	2	3	4	5
10	Same	5.2E-06	3.2E-05	5.9E-05	8.6E-05	1.1E-04	1.4E-04
10	Opposite	5.2E-05	4.4E-04	8.2E-04	1.2E-03	1.6E-03	2.0E-03
12	Same	4.7E-08	4.3E-07	8.2E-07	1.2E-06	1.6E-06	2.0E-06
12	Opposite	4.7E-07	6.7E-06	1.3E-05	1.9E-05	2.6E-05	3.2E-05
14	Same	**1.9E-10**	2.4E-09	4.6E-09	6.8E-09	9.0E-09	1.1E-08
14	Opposite	1.9E-09	4.5E-08	8.8E-08	1.3E-07	1.7E-07	2.2E-07

References

[1] "Analysis of Area Navigation (RNAV) En Route Separation Along Adjacent Straight Segments with Radar Surveillance."

AFS-400 Safety Study Report number DOT-FAA-AFS-440-24

This paper by the FAA's Flight Technologies and Procedures Division (AFS-400) was published in November 2006. The paper's analysis was confined to RNAV en route segments with no turns greater than 15° (and therefore assumed to be straight).

[2] "Analysis of Area Navigation (RNAV) En Route Separation Along Adjacent Straight Segments with Radar Surveillance and Turns."

AFS-400 Safety Study Report number DOT-FAA-AFS-440-25

This paper by the FAA's Flight Technologies and Procedures Division (AFS-400) was published in November 2006. The paper's analysis includes RNAV en route segments with turns greater than 15°.

[3] United States Standard for Terminal Instrument Procedures (TERPS), 3rd Ed.

Change 19, June 2002

Chapter 17, especially pages 173 through 180 on en route spacing.

[4] Radio Technical Commission for Aeronautics (RTCA) DO-236.

[5] FAA AC 90-100.

[6] "Preliminary Re-evaluation of the Probability of Lateral Overlap, $P_y(0)$, Based on non-Global Positioning Satellite (GPS) and GPS-Equipped Aircraft Performance at Entry into North Atlantic Reduced Vertical Separation Minimum Airspace."

North Atlantic Mathematicians' Implementation Group
NAT MIG/5-WP/18
Atlantic City, April 1999

This paper was published by the North Atlantic Mathematicians' Implementation Group as NAT MIG/5-WP/18 in April 1999. The paper's analysis was based on data collected in 1995 from 11 aircraft flights by five operators with three aircraft types (B747-200, B747-400, A340). Each aircraft was using GPS navigation on an oceanic route—five flights were North Atlantic routes, five were Pacific Oceanic airspace, and one was a South Atlantic route.

[7] "Estimating the Well-Fit Model for the Distribution of Cross Track Deviations of GPS-Equipped Aircraft on a North Pacific Route."

Separation and Airspace Safety Panel (SASP)
SASP-WG/WHL/4-WP/23
Honolulu, United States, 10-21 November 2003

This paper was published by the Separation and Airspace Safety Panel (SASP) as SASP-WG/WHL/4-WP/23 in November 2003. The paper's analysis was based on data collected between December 2001 and 23 May 2002, from 3,150 flights on the North Pacific route R220. Each aircraft, types B747-400, B777, A340, was using GPS navigation on the route.

[8] "Analysis of Lateral Track Deviation along Two Q-Routes."

AFS-400 Safety Study

This paper was published by the FAA's Flight Technologies and Procedures Division (AFS-400) in October 2005. The paper's analysis was based on data collected between February 19 and March 6, 2003, from 865 flights on Q-routes 100 and 102 in the Gulf of Mexico. Each aircraft was using some type of RNAV navigation, typically GPS or Distance Measuring Equipment/Distance Measuring Equipment (DME/DME) on the route.

[9] "Analysis of VOR En Route Flight Technical Error (FTE) based on Data Collected by FAA Flight Inspection Aircraft," Don P. Pate, FAA Flight Inspection National Field Office, Operations Research Staff, AFS-512, December, 1975.

[10] "An Analysis of Radio Navigation Sensor Accuracies Associated with Area Navigation (RNAV)," Thomas V. Logue, FAA Systems Research and Development Service, August 1978.

Report Number FAA-RD-78-85

[11] "FAA Order 7110.65, Section 3 Special Use and ATC Assigned Airspace."

Paragraph 9-3-2, Separation Minima (b)