Federal Aviation Administration

Analysis of Area Navigation (RNAV/RNP-1) En Route Separation Along Adjacent Straight Segments with Radar Surveillance Including Impromptu Routes (Phase III)

Flight Systems Laboratory
DOT-FAA-AFS-450-50

March 2009

Flight Systems Laboratory
6500 S. MacArthur Blvd.
Systems Training Building Annex, RM 217
Oklahoma City, Oklahoma 73169
Phone: (405) 954-8191

OK-09-2848

NOTICE

DOT-FAA-AFS-450-50

Flight Systems Laboratory
Flight Technologies and Procedures Division
Flight Standards Service

Analysis of Area Navigation (RNAV/RNP-1) En Route Separation Along Adjacent Straight Segments with Radar Surveillance Including Impromptu Routes (Phase III)

Released by:

Michael J. Zenkovich **Date**
Manager, Flight Technologies and Procedures Division, AFS-400

March 2009

Technical Report

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**
DOT-FAA-AFS-450-50		
4. Title and Subtitle Analysis of Area Navigation (RNAV/RNP-1) En Route Separation Along Adjacent Straight Segments with Radar Surveillance Including Impromptu Routes (Phase III)		**5. Report Date** March 2009
6. Author(s) Dr. Richard Greenhaw, AFS-450 Gerry McCartor, AFS-450 Stephen Barnes, AFS-450		**7. Performing Organization Code**
8. Performing Organization Name and Address Department of Transportation/Federal Aviation Administration Flight Systems Laboratory, AFS-450 Systems Training Annex Bldg. 26 6500 S. MacArthur Blvd. Oklahoma City, OK 73169		**9. Type of Report and Period Covered** Technical report
10. Sponsoring Agency Name and Address Department of Transportation/Federal Aviation Administration Flight Systems Laboratory, AFS-450 Systems Training Annex Bldg. 26 6500 S. MacArthur Blvd. Oklahoma City, OK 73169		
11. Supplementary Notes		

12. Abstract

The purpose of this study is to provide a risk assessment of lateral en route separation between parallel Area Navigation (RNAV) routes (including impromptu routes), such as Q-routes, with separation for both opposite and same direction traffic under radar surveillance and RNP-1 protection. The results of this analysis showed that the hourly rate of collision for suitably equipped RNAV RNP-1 and RNP-2 aircraft on parallel adjacent routes under radar surveillance flying the same or opposite directions (with turns of less than 15°), laterally separated by a track-to-track distance of at least 8 NM (and for RNP-1 aircraft adjacent to other RNP-1 aircraft, 6 NM), longitudinally separated by at least 5 NM on average meets the acceptable level of risk established for this study (5.0 E-09 collisions per hour). This was true for a target aircraft adjacent to just one other track (outer track) or for a target aircraft between two other tracks (inner track).

13. Key Words	**14. Distribution Statement**
Lateral separation, Area Navigation (RNAV), en route	Controlled by AFS-450
15. Security Classification of This Report Unclassified	**16. Security Classification of This Page** Unclassified

Executive Summary

The purpose of this study was to provide a risk assessment of lateral en route separation[1] between parallel Area Navigation (RNAV) routes (including impromptu routes), such as Q-routes, with separation for both opposite and same direction traffic under radar surveillance and Required Navigation Performance Level 1(RNP-1) protection. As such, this is a follow-on to the study [7] which examined en route separation risk for Required Navigation Performance Level 2 (RNP-2) protection only.

This study estimated the risk of RNAV/RNP-1 aircraft flying straight tracks (tracks with turns of less than 15°) deviating from the nominal track laterally by more than 2, 3, or 4 nautical miles (NM). It also estimated the risk of collision of en route RNAV aircraft (RNP-1 and RNP-2) flying adjacent, parallel, straight tracks (both opposite and same directions cases) when the aircraft of interest was flying adjacent to only one other track (on an outer track) and when the aircraft of interest was flying between two tracks (on an inner track) and both were under radar surveillance.

The analysis was based on two types of data: values specified in AC 90-100 and data from radar tracks reported in previous RNAV studies. AC 90-100 specifies a value for track-keeping accuracy for RNAV aircraft. This criterion was the basis for the analysis. There are three studies examined that have used RNAV track data. This study used the data and results from those studies to validate the criterion-based analysis results.

This study fit statistical distributions to the values from the AC 90-100 criteria to model the likelihood of adjacent aircraft intersecting laterally. It also modeled and estimated the likelihood of aircraft on parallel routes becoming adjacent. Using those models, it estimated the hourly rate of collision.

The results of this analysis showed that the hourly rate of collision for suitably equipped RNAV RNP-1 and RNP-2 aircraft on parallel adjacent routes under radar surveillance flying the same or opposite directions (with turns of less than 15°), laterally separated by a track-to-track distance of at least 8 NM (and for RNP-1 aircraft adjacent to other RNP-1 aircraft, 6 NM), longitudinally separated by at least 5 NM on average met the acceptable level of risk established for this study[2] (5.0 E-09 collisions per hour). This was true for a target aircraft adjacent to just one other track (outer track) or for a target aircraft between two other tracks (inner track).

These results were developed using conservative assumptions for lateral and vertical track deviations and conservative assumptions for longitudinal traffic density.

---

[1] That is, track-to-track or centerline-to-centerline separation.
[2] Based on the ICAO target level of safety for en route separation minima established in [6].

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Tables

Figures

1.0 Introduction

This report is one of a group of studies that address RNAV / RNP en route lateral separation[3]. These studies differ as to whether the routes are under radar surveillance, whether turns greater than 15º are allowed, what type of adjacent routes are allowed (RNAV or conventional), and the level of RNP protection required (RNP-1 or RNP-2). The six reports in this group are:

- "Analysis of Area Navigation (RNAV) En Route Separation along Adjacent Straight Segments with Radar Surveillance (Phase I)" DOT-FAA-AFS-440-24, January 2007
- "Analysis of Area Navigation (RNAV) En Route Separation along Adjacent Straight Segments with Radar Surveillance and Turns (Phase II)" DOT-FAA-AFS-440-25, January 2007
- "Analysis of Area Navigation (RNAV) En Route Separation with Conventional Routes Including Turns and Special Use Airspace" DOT-FAA-AFS-440-26, January 2007
- "Analysis of Area Navigation (RNAV/RNP-1) En Route Separation Along Adjacent Straight Segments With Radar Surveillance Including Impromptu Routes (Phase III)" DOT-FAA-AFS-450-50, March 2009
- "Analysis of Area Navigation (RNAV/RNP-1 and RNP-2) En Route Separation Along Adjacent Straight Segments Without Radar Surveillance Including Impromptu Routes (Phase IV)" DOT-FAA-AFS-450-51, March 2009
- Analysis of Area Navigation (RNAV RNP-1 and RNP-2) En Route Separation Along Adjacent Segments With and Without Radar Surveillance and With Turns (Phase V) DOT-FAA-AFS-450-52, March 2009

This report presents the results of a safety study conducted to evaluate the risk of en route lateral separation between parallel Area Navigation (RNAV) routes with RNP-1 protection and radar surveillance and with separation for both opposite and same direction traffic. The safety evaluation was conducted by the Flight Systems Laboratory (AFS-450) of the Federal Aviation Administration (FAA) located at the Mike Monroney Aeronautical Center in Oklahoma City, Oklahoma.

1.1 Purpose and Structure of This Document

The purpose of this study was to provide a risk assessment of en route lateral separation between parallel RNAV routes, such as Q-routes, with separation for both opposite and same direction traffic <u>under radar surveillance and Required Navigation Performance</u>

[3] That is, track-to-track or centerline-to-centerline separation.

Level 1 (RNP-1) protection[4]. As such, this study is a follow-on to the study [7] which examined en route separation risk for Required Navigation Performance Level 2 (RNP-2) protection only.

This study estimated the risk of RNAV/RNP-1 aircraft flying straight tracks (tracks with turns of less than 15°) deviating from the nominal track laterally by more than 2, 3, or 4 nautical miles (NM). It also estimated the risk of collision of en route RNAV aircraft (both RNP-1 and RNP-2) flying adjacent, parallel, straight tracks (both opposite and same directions cases) when the aircraft of interest was flying adjacent to only one other track (on an outer track) and when the aircraft of interest was flying between two tracks (on an inner track) and both were under radar surveillance.

This study did not estimate the risk of wake exposures.

1.2 Statement of the Problem

Specifically, this study quantified the lateral track deviation[5] of typical RNAV/RNP-1 equipped aircraft[6] on straight en route segments—segments with no turns, or turns of at most 15°—with radar surveillance. This lateral track deviation was used to determine the probability that a typical RNAV/RNP-1 en route operation deviated laterally from the track by more than certain given distances (each of 2, 3, or 4 NM).

This lateral track deviation was also used to determine the probability of collision of two aircraft (either RNP-1 or RNP-2) flying parallel, adjacent en route tracks under radar surveillance, with given track-to-track separation distances (4, 6, or 8 NM), with both inner and outer tracks, and with the two cases: flying in the same direction or in the opposite direction.

For suitably equipped RNAV aircraft, as referenced in AC 90-100, this study answered the following questions:

1. What is the probability of an RNP-1 aircraft flying a straight en route track segment under radar surveillance deviating laterally from that track by more than 2 NM (or 3 NM or 4 NM)?

2. What is the risk of an RNP-1 aircraft flying a straight en route outer track segment under radar surveillance colliding with an aircraft (either RNP-1 or RNP-2) flying a parallel, adjacent en route track, in a direction opposite that of the other aircraft,

[4] This study assumes that, because of common navigation requirements, RNP and RNAV risk will be equivalent under radar surveillance. Later studies, which address separation without radar surveillance, focus on RNP aircraft.
[5] This study addressed collision risk between aircraft on laterally parallel RNAV routes, it did not attempt to address collision risk between aircraft on vertical parallel routes, that is, routes one above the other.
[6] As defined in [4], ICAO Document 9689-AN/953, First edition, 1998

with given track-to-track separation distance of 4 NM (or 6 NM or 8 NM)?

3. What is the risk of an RNP-1 aircraft flying a straight en route outer track segment under radar surveillance colliding with an aircraft (either RNP-1 or RNP-2) flying a parallel, adjacent en route track, in a direction the same as that of the other aircraft, with given track-to-track separation distance of 4 NM (or 6 NM or 8 NM)?

4. What is the risk of an RNP-1 aircraft flying a straight en route inner track segment under radar surveillance colliding with an aircraft (either RNP-1 or RNP-2) flying a parallel, adjacent en route track, in a direction opposite that of the other aircraft, with given track-to-track separation distance of 4 NM (or 6 NM or 8 NM) assuming aircraft on either side of the inner track aircraft are flying in an opposite direction to that of the inner aircraft?

5. What is the risk of an RNP-1 aircraft flying a straight en route inner track segment under radar surveillance colliding with an aircraft (either RNP-1 or RNP-2) flying a parallel, adjacent en route track, in a direction the same as that of the other aircraft, with given track-to-track separation distance of 4 NM (or 6 NM or 8 NM) assuming aircraft on either side of the inner track aircraft are flying in the same direction to that of the inner aircraft?

6. What is the risk of an RNP-1 aircraft flying a straight en route inner track segment under radar surveillance colliding with an aircraft (either RNP-1 or RNP-2) flying a parallel, adjacent en route track, in a direction the same as or opposite to that of the other aircraft, with given track-to-track separation distance of 4 NM (or 6 NM or 8 NM) assuming the aircraft on one side of the inner track aircraft is flying in the same direction as and the aircraft on the other side is flying in the opposite direction to that of the inner aircraft?

What differences in risk (if any) are obtained if the routes are impromptu routes? By "impromptu routes," we mean unpublished, controller-initiated, point-to-point routes. "Point-to-point" here means from established, published waypoints. That is, for such impromptu routes, points were defined as navigational aids (NAVAIDs), airports, or named and published waypoints, intersections or fixes. So the route must begin and end with charted points.

2.0 Study Methodology

This study contained 22 scenarios involving RNP-1 and RNP-2 aircraft. For each scenario, we defined a specific Test Criteria Violation (TCV), and we used statistical distributions to determine the probability of the TCVs in each scenario.

2.1 Model Description

We described the models in terms of their scenarios and the associated hazards. The study contained 22 scenarios of interest. The first six scenarios involved RNP-1 aircraft only. The final 16 scenarios involved combinations of RNP-1 and RNP-2 aircraft.

Scenario 1

In this scenario, a typical RNP-1 aircraft flew a straight en route track segment (possibly, an impromptu route) under radar surveillance with turns of no more than 15º. The hazard in this scenario was the aircraft deviating laterally from that track by more than 2 NM (or 3 NM or 4 NM) during one hour of flight (Figure 1). The severity of this hazard was major. (See Appendix A: Severity Definitions Based on the Perspective of the Flying Public for a description of this severity.)

The specific TCV for this hazard was the deviation of the center of gravity of the aircraft from the nominal track by a lateral distance of 2 NM or more (or 3 NM or more, or 4 NM or more). We estimated the probabilities of these TCVs, but did not assess their risk since no actual collision was involved.

We modeled this scenario by using a statistical distribution of lateral aircraft deviations. This distribution was used to determine the probability of a TCV.

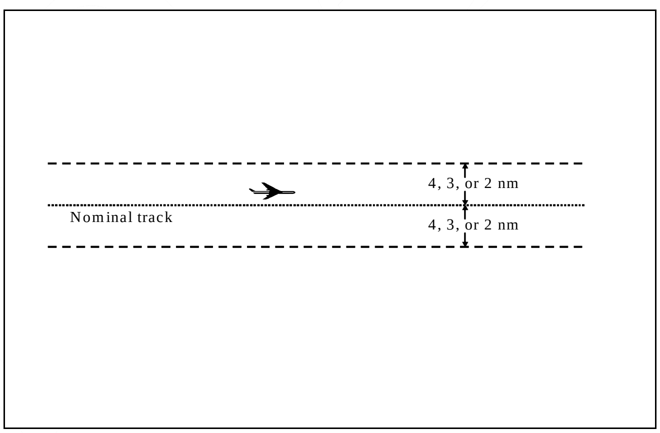
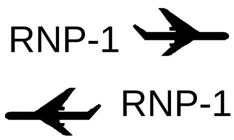


Figure 1: Scenario 1 Hazards

Scenario 2



In this scenario, two RNP-1 aircraft flew in opposite directions (see Figure 2b) on parallel, adjacent, straight en route track segments (possibly impromptu routes) under radar surveillance with turns of no more than 15°. The parallel tracks were separated by 4 NM (or 6 NM or 8 NM). The hazard in this scenario was the collision of the aircraft. The severity of this hazard was catastrophic (see Appendix A).

The specific TCV for this hazard was the combined lateral, longitudinal, and vertical conjunction of the two aircraft (i.e., a collision). This conjunction was modeled by centers of gravity of the aircraft converging to within their mean wingspan laterally, within their mean lengths longitudinally, and within their mean heights vertically.

Assumption 1 (Independence)

We modeled this scenario by statistical distributions for lateral aircraft deviations and by probabilities for longitudinal and vertical convergence (or overlap) of the two aircraft. We assumed that the lateral deviation, the vertical deviation, and the longitudinal exposure to the other aircraft were independent events. This was a conservative assumption because for these to be dependent would imply that the two aircraft were either trying to avoid each other or trying to collide. For aircraft operating under normal conditions we eliminated this latter possibility. Therefore, under normal operating conditions dependence implied avoidance. But we assumed (conservatively) non-avoidance (the effects of the Traffic Alert and Collision Avoidance System [TCAS] were neglected for this study) and therefore independence.

Assumption 2 (Mutual Exclusivity)

We also assumed that for aircraft flying in opposite directions a collision could occur in only one of three ways: side-to-side, top-to-bottom, or nose-to-nose.

Under the assumption of event mutual exclusivity the probability of a TCV for this scenario, $P(TCV_2)$, is the sum of the probabilities of collision for each way:

$$P(TCV_2) = P(C_s) + P(C_t) + P(C_n), \tag{1}$$

where $P(C_s)$ represents the probability of a side-to-side collision, $P(C_t)$ represents the probability of a top-to-bottom collision, and $P(C_n)$ represents the probability of a nose-to-nose collision.

Figure 2a Same Direction

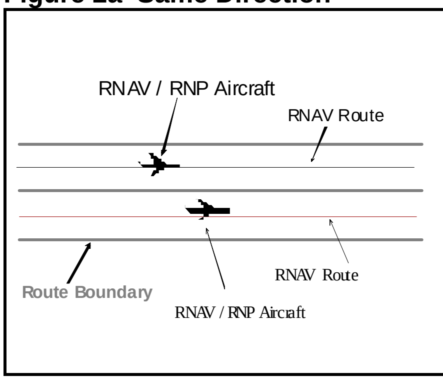
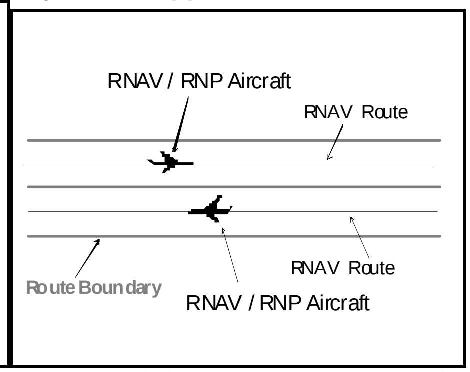
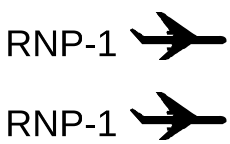


Figure 2b Opposite Direction



Scenario 3



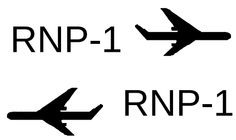
This scenario was the same as Scenario 2 except the two RNP-1 aircraft were flying in the same direction (see Figure 2a) on parallel, adjacent, straight en route track segments under radar surveillance with turns of no more than 15°. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 2. We assumed both independence and mutual exclusivity.

Under the assumption of mutual exclusivity the probability of a TCV for this scenario, $P(TCV_3)$, was the sum of the probabilities of collision for each way:

$$P(TCV_3) = P(D_s) + P(D_t) + P(D_n), \qquad (2)$$

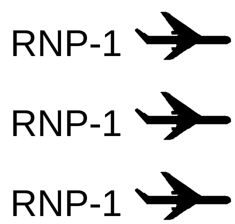
where $P(D_s)$ represents the probability of a side-to-side collision, $P(D_t)$ represents the probability of a top-to-bottom collision, and $P(D_n)$ represents the probability of a nose-to-tail collision.

Scenario 4



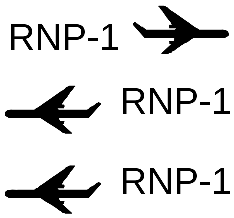
This scenario was the same as Scenario 2 except there were three RNP-1 aircraft rather than two. The aircraft track of interest was the one between the other two RNP-1 aircraft. The inner RNP-1 aircraft was flying in the opposite direction to the other two on parallel, adjacent, straight en route track segments under radar surveillance with turns of no more than 15º. The hazards and TCVs were the same as Scenario 2. The mathematical model for the calculation of the probability of a TCV was the same. However, the number of exposures to adjacent aircraft was, in general, twice that of Scenario 2.

Scenario 5



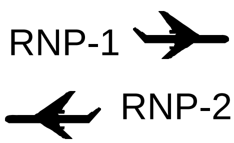
This scenario was the same as Scenario 3 except that there were three RNP-1 aircraft rather than two. The aircraft track of interest was the one between the other two. All aircraft were flying in the same direction on parallel, adjacent, straight en route track segments under radar surveillance with turns of no more than 15º. The hazards and TCVs were the same as Scenario 3. The mathematical model for the calculation of the probability of a TCV was the same. However, the number of exposures to adjacent aircraft was, in general, twice that of Scenario 3.

Scenario 6



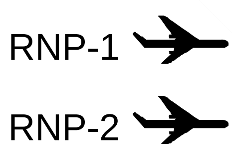
This scenario was the same as Scenario 5 except that the inner RNP-1 aircraft was flying in the opposite direction to one of the other RNP-1 aircraft and in the same direction as the other on parallel, adjacent, straight en route track segments with turns of no more than 15º. The hazards and TCVs were the same as Scenario 5. The mathematical model for the calculation of the probability of a TCV was the same. However, the number of exposures to adjacent aircraft was, in general, the sum of those for Scenario 2 and Scenario 3.

Scenario 7



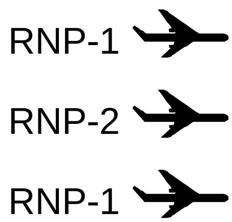
This scenario was the same as Scenario 2 except that one of the aircraft was RNP-2 and the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 2. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 8



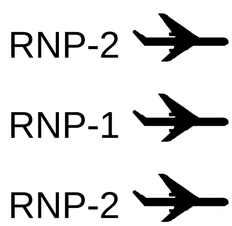
This scenario was the same as Scenario 3 except that one of the aircraft was RNP-2 and the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 3. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 9



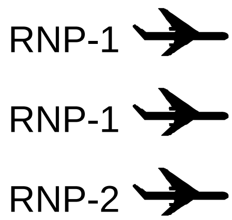
This scenario was the same as Scenario 4 except that the aircraft in the center was RNP-2 and the other two were RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 10



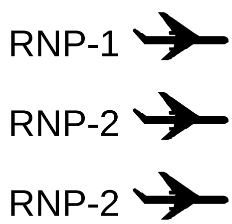
This scenario was the same as Scenario 4 except that the aircraft in the center was RNP-1 and the other two were RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 11



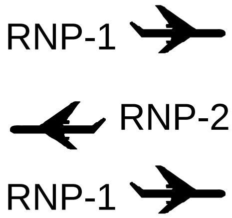
This scenario was the same as Scenario 4 except that the aircraft in the center was RNP-1 and one of the other aircraft was RNP-2 while the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 12



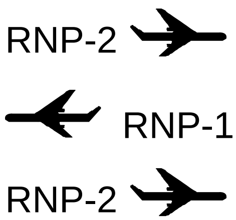
This scenario was the same as Scenario 5 except that the aircraft in the center was RNP-2 and one of the other aircraft was RNP-2 while the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 13



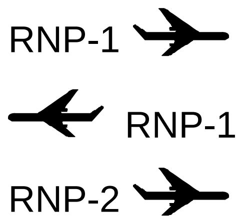
This scenario was the same as Scenario 5 except that the aircraft in the center was RNP-2 and the two other aircraft were RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 14



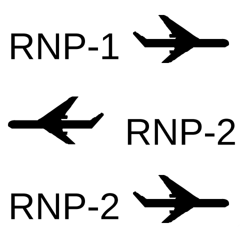
This scenario was the same as Scenario 5 except that the aircraft in the center was RNP-1 and the two other aircraft were RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 15



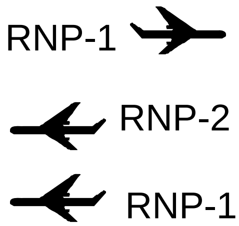
This scenario was the same as Scenario 5 except that the aircraft in the center was RNP-1 and one of the two other aircraft was RNP-1 while the other was RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 16



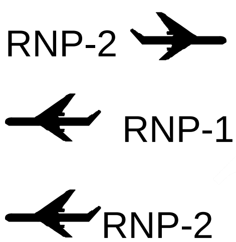
This scenario was the same as Scenario 5 except that the aircraft in the center was RNP-2 and one of the two other aircraft was RNP-1 while the other was RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 17



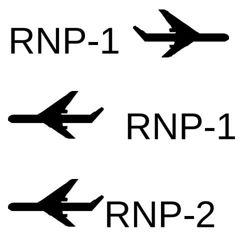
This scenario was the same as Scenario 6 except that the aircraft in the center was RNP-2 and while the other aircraft were RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 18



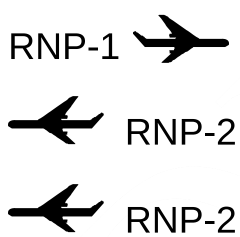
This scenario was the same as Scenario 6 except that the aircraft in the center was RNP-1 and while the other two were RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 19



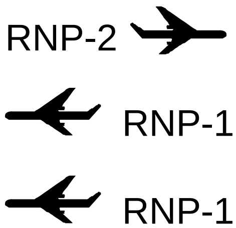
This scenario was the same as Scenario 6 except that the aircraft in the center was RNP-1 and one of the two other aircraft was RNP-1 while the other was RNP-2. One of the RNP-1 aircraft and the RNP-2 aircraft were flying in the same direction while the other RNP-1 aircraft was flying in the opposite direction. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 20



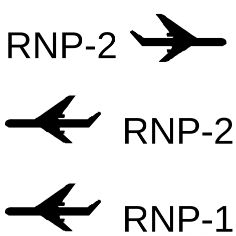
This scenario was the same as Scenario 6 except that the aircraft in the center was RNP-2 and one of the two other aircraft was RNP-1 while the other was RNP-2. The RNP-2 aircraft were flying in the same direction while the RNP-1 aircraft was flying opposite the RNP-2 aircraft. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 21



This scenario was the same as Scenario 6 except that the aircraft in the center was RNP-1 and one of the two other aircraft was RNP-1 while the other aircraft was RNP-2. The RNP-1 aircraft were flying in the same direction while the RNP-2 aircraft was flying opposite the RNP-1 aircraft. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

Scenario 22



This scenario was the same as Scenario 6 except that the aircraft in the center was RNP-2 and one of the two other aircraft was RNP-1 while the other was RNP-2. The RNP-2 aircraft were flying in opposite directions while the RNP-2 aircraft in the center was flying in the same direction as the RNP-1 aircraft. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6. We assumed both independence and mutual exclusivity. The distributions for the lateral deviations of each of the aircraft differed because of the differing RNP values.

2.2 Summary of Data Used

The data used fell into two categories: values specified in AC 90-100 and data from radar tracks reported in previous RNAV studies.

AC 90-100 specifies a value for track-keeping accuracy for RNAV aircraft. This criterion was the basis for the analysis.

We examined three studies that have used RNAV track data. We used the data and results from those studies to validate the criterion-based analysis results. That is, these studies were not used as the basis for determining hazard risk, but rather were used to validate the model based on the AC 90-100 criterion. The three studies are described below.

1. “Preliminary Re-evaluation of the Probability of Lateral Overlap, Py(0), based on non-Global Positioning Satellite (GPS) and GPS Equipped Aircraft Performance at Entry into North Atlantic Reduced Vertical Separation Minimum Airspace” [1]

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.

2. “Estimating the Well-Fit Model for the Distribution of Cross Track Deviations of GPS Equipped Aircraft on a North Pacific Route” [2]

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 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.

3. “Analysis of Lateral Track Deviation along Two Q-Routes” [3]

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 in February and March 2003, from 865 flights on Q-Route 100 and Q-Route 102 in the Gulf of Mexico. Each aircraft was using some type of RNAV navigation, typically GPS or Distance Measuring Equipment (DME)/DME Inertial Reference Unit (IRU) on the route.

3.0 Summary of Data Analysis and Risk Evaluation

We determined the probability of the TCVs in each of the scenarios, used those probabilities along with the hazard severities discussed in Section 2.1 (Model Description) to define the risk for each hazard, and then compared those risks with standard acceptable levels of risk.

3.1 Summary of the TCV Probability Analysis

We examined the TCV probability analysis for each scenario beginning with Scenario 1. The results of the analysis for Scenario 1 could be used in the analyses for the other scenarios.

<u>Scenario 1 Probability Analysis</u>

The TCV for this hazard was the deviation of the center of gravity of the aircraft from the nominal track by a lateral distance of 2 NM or more (or 3 NM or more, or 4 NM or more). The purpose of the analysis was to determine the probability of each of these three TCVs associated with the 2, 3, and 4 NM cases. We proceeded by basing the analysis on the track-keeping accuracy specified in AC 90-100 for RNP-1 and RNP-2 aircraft operating on RNAV routes. Then we compared the results from previous empirical en route studies with the results of the AC 90-100 analysis to generate a reasonable set of TCV probabilities.

AC 90-100 Analysis

The track-keeping accuracy specified in AC 90-100 for aircraft operating on RNP-2 RNAV routes is an accuracy "bounded by ±2 NM for 95% of the total flying time." The track-keeping accuracy specified for aircraft operating on RNP-1 RNAV routes is an accuracy "bounded by ±1 NM for 95% of the total flying time." This means that the frequency of an RNP-2 aircraft remaining within the 2 NM boundary is 95% and an RNP-1 aircraft remaining within the 1 NM boundary is 95%. Using the frequency definition of probability, this translated into a 95% probability of containment of RNP-2 within the 2 NM boundary and a 95% probability of containment of RNP-1 within the 1 NM boundary.

This AC 90-100 requirement allowed us to describe one or more statistical distributions for lateral deviation. Such a distribution was symmetric and centered at zero. Also 95% of its area was contained between –2 and +2 NM or –1 and +1 NM. If we specified that the distribution was, say, normal, these requirements allowed us to fix the Probability

Density Function (PDF) exactly. However, since there were multiple distributions that fit the 95% criterion, we used a set of reasonable criteria to find an appropriate distribution.

Criteria for Lateral Deviation Distribution Selection

1. The distribution should be symmetric, centered at zero with 95% of its area contained within –1 and +1 NM (since this distribution is for RNP-1 navigation) as specified in AC 90-100.

2. The distribution should be consistent with current en route separation analysis practice. There are existing en route analyses (for example, oceanic studies such as [1] and [2]) that have made use of certain types of distributions for lateral deviation.

3. The distribution should take radar surveillance into account.

4. The distribution should be conservative compared to existing empirical data for en route separation.

5. The RNP-1 distribution should be consistent with the previously derived [7] RNP-2 distribution.

The en route studies [1] and [2] used a mixed distribution to model lateral deviation. They both used a combination of normal and double exponential distributions. The normal distribution was the primary model for the typical (or core) behavior, and the double exponential distribution accounted (for the most part) for the atypical (or tail) behavior. However, the studies did not attempt to model radar surveillance effects, so there was no attempt to model bounded (or partially bounded) behavior.

The RNAV RNP-2 study [7] used a mixed distribution based upon the first four criteria listed above (with the ± 1 NM replaced by ± 2 NM). That distribution took the first three criteria into account because it was a mixed distribution similar to the normal/double exponential of [1] and [2], but with the normal distribution replaced by a bounded distribution, a symmetric Johnson S_B distribution[7] to model the radar surveillance behavior more accurately. That distribution was of the form:

$$f(y) = \frac{\alpha e^{-|y/\delta|}}{2\delta} + \frac{(1-\alpha)\eta\lambda e^{-0.5\eta^2 Ln\left[\frac{y-\varepsilon}{\varepsilon-y+\lambda}\right]^2}}{\sqrt{2\pi}(y-\varepsilon)(\varepsilon-y+\lambda)}, \tag{3}$$

[7] The Johnson S_B distribution is a transformation of the normal distribution and has been used frequently to model lateral track deviations.

where the first term represents the double exponential and the second the Johnson S_B distribution.

We satisfied the five criteria above by using that distribution with suitable adjustments of the parameters. The parameter, α, is the proportionality factor for the mix of distributions. We set $\alpha = 0.0566$ to match the proportion used in the studies [1] and [2]. We set $\delta = 0.2$ and $\eta = 1.2$ to satisfy the 95% criterion for ± 1 NM. And we set $\lambda = 3$ and $\varepsilon = -1.5$ to provide partial bounding within 1.5 NM of the center (zero) to reflect the surveillance effect. (If the adjacent tracks were separated by, say, 6 NM and aircraft of the adjacent track did not deviate from the nominal, we assumed that controllers typically attempt to prevent the target aircraft from deviating toward the adjacent aircraft by more than 1.0 NM so as to maintain 5 NM separation: 6 minus 1 is 5. We increased the bound from 1.0 to 1.5 NM to allow for the display lag and controller reaction time.) We noted that while the Johnson S_B distribution was bounded, the overall distribution was unbounded due to the double exponential contribution, which was intended to account for atypical lateral deviations. And these atypical lateral deviations were assumed, conservatively, to be no less for RNP-1 than for RNP-2 aircraft.

Next, we compared this distribution with the empirical results of the three studies ([1], [2], and [3]). Since for measuring collision likelihood the critical values were in the tails of the distributions, we compared the tail areas of the distributions used in the three studies with the distribution developed above. Figure 3 depicts the areas we evaluated. And Table 1 gives the areas to the right of the line at *d* NM for each of the four distributions.

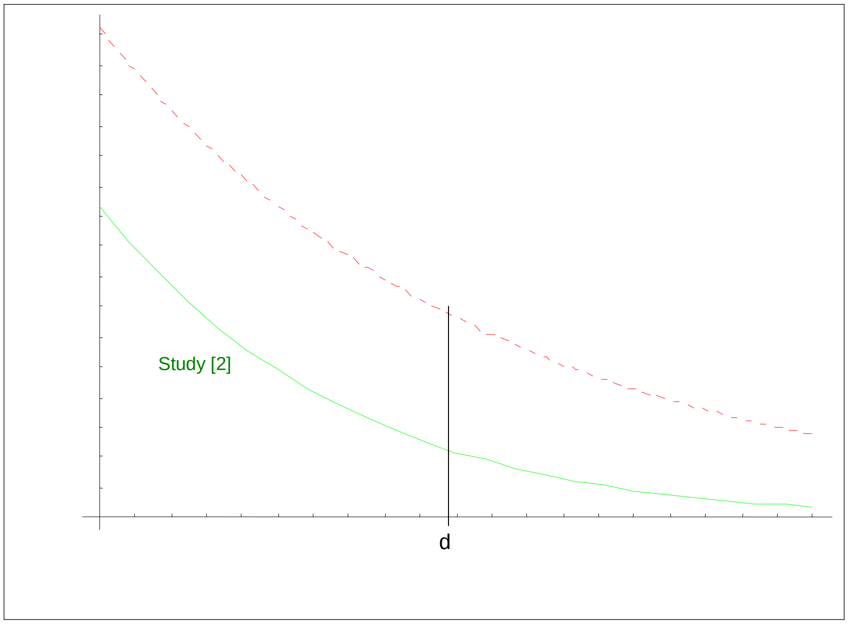


Figure 3: Two Distribution Tail Areas

Table 1: Distribution Areas to the Right of *d* NM

d	Study [1] (*N* = 11)*	Study [2] (N = 3150)	Study [3] (N = 865)	*f*(*y*) (This Study)
1	2.0 E-02	1.0 E-13	1.0 E-08	2.5 E-02
2	1.0 E-02	4.0 E-25	< 1.0 E-50	1.3 E-06
4	7.0 E-03	5.0 E-48	< 1.0 E-50	5.8 E-11
6	3.0 E-03	< 1.0 E-50	< 1.0 E-50	2.6 E-15

*N represents the sample size for each empirical study.

The tail values for the distribution developed above, *f*(*y*), were larger than those of studies [2] and [3]. This means that the distribution developed above gave a larger estimate for collision probability than either study [2] or [3], and was therefore conservative in comparison. It gave a smaller probability estimate than study [1], but this was not unreasonable considering that study [1] did not account for the radar surveillance effect. It should also be noted that the sample size for study [1] was very small compared to those of the other two studies.

Given the relative sample sizes, and the lack of radar surveillance consideration of the three comparison studies, it was reasonable to conclude that the distribution, *f*(*y*), developed above provided a conservative estimate of en route lateral deviation behavior under radar surveillance compared to the other studies, and therefore satisfied all four criteria for lateral distribution selection. Given the empirical results available, this distribution appeared to be conservative. It may be refined, however, as more empirical results from RNAV en route operations become available.

Impromptu Routes

Since impromptu routes, even though they are unpublished and controller-initiated, are point-to-point routes using existing defined[8] waypoints, there was no difference in penetration probability, and thus in risk, between such routes and published routes, given that the other route parameters (such as RNP values, lateral separation, and radar surveillance) were the same.

Therefore, risk assessments for all scenarios in this study could apply to both published and impromptu routes.

Scenario 1 Summary

Using the criterion-based distribution, $f(y)$, we estimated the probabilities for the TCVs for this scenario's hazards (the deviations of the center of gravity of the aircraft from the nominal track by a lateral distance of 1 NM, 2 NM, 3 NM, or 4 NM or more). Table 2 lists those probabilities.

Table 2: Scenario 1 TCV Probabilities

Lateral Distance from Track	RNP-1 TCV Probability	RNP-2 TCV Probability*
±1 NM	5.0 E-02	--
±2 NM	2.6 E-06	5.0 E-02
±3 NM	1.7 E-08	2.6 E-06
±4 NM	1.2 E-10	9.2 E-08

*From the previous study [7]

<u>Scenario 2 Probability Analysis</u>

The TCV for this hazard was the collision with another aircraft that was flying in an opposite direction under radar surveillance on a straight parallel RNAV track at the same altitude and at a lateral track distance of 4, 6, or 8 NM from the first aircraft's track.

8 This means the points are defined as NAVAIDs, airports, or named and published waypoints, intersections, or fixes. So the route must begin and end with charted points.

The probability of a TCV for this scenario was the sum of the probabilities of the three mutually exclusive types of collision of the two aircraft[9]:

1. A side-to-side collision (C_s),
2. A top-to-bottom collision (C_t),
3. Or a nose-to-nose collision (C_n).

That is, $P(TCV_2) = P(C_s) + P(C_t) + P(C_n)$.

We determined each of the three probabilities separately. Then we calculated their sum, the probability of the TCV for this scenario.

The Probability of a Side-To-Side Collision, $P(C_s)$

We assumed that there are two aircraft executing RNAV operations on parallel, adjacent, tracks either 4, 6, or 8 NM apart and that each aircraft displayed a lateral deviation from its track that could be described by the criterion-based distribution developed in the Scenario 1 analysis.

Let the target (first) aircraft's intended track be the $y = 0$ axis and (assuming the tracks are S NM apart), the adjacent (second) aircraft's intended track is the line $y = S_y$ (see Figure 4) so that the tracks are separated by S_y NM.

[9] This probability analysis followed that of Moek [4] for lateral separation, which in turn was based on the Reich Model [5] and was also the methodology recommended in the ICAO "Manual on Airspace Planning Methodology for Determining Separation Minima" [6].

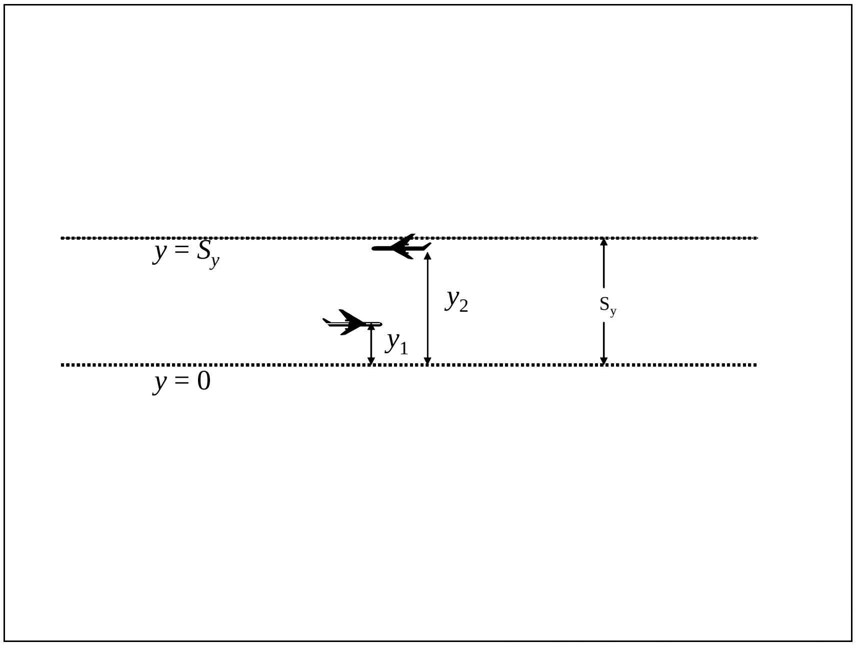


Figure 4: Scenario 2 Mathematical Model

Let V_1 and V_2 denote the target and adjacent aircraft ground speeds, respectively. And assume that the wingspan and length of each aircraft is λ NM. Therefore, when they pass each other the aircraft are adjacent for a period of $2\lambda/(V_1+V_2)$ hours.

A side-to-side collision, $P(C_s)$, occurred only when the aircraft moved into lateral overlap during that period of adjacency, and also happened to be in vertical overlap when they moved into lateral overlap. Since the aircraft motion in the three dimensions was assumed to be independent, the probability of a side-to-side collision, $P(C_s)$, could be taken to be the product of:

- The duration of the period of (longitudinal) adjacency: $2\lambda/(V_1+V_2)$ hours
- The rate of entry into lateral overlap: $N_y(S_y)$ occurrences per hour
- The probability of vertical overlap: $P_z(0)$.

That is, $$P(C_s) = \frac{2\lambda}{V_1+V_2} N_y(S_y) P_z(0). \qquad (4)$$

A top-to-bottom collision, $P(C_t)$, occurred only when the aircraft moved into vertical overlap during that period of adjacency, and also happened to be in lateral overlap when they move into vertical overlap. Since the aircraft motion in the three dimensions was assumed to be independent, the probability of a top-to-bottom collision, $P(C_t)$, could be taken to be the product of:

- The duration of the period of adjacency: $2\lambda/(V_1+V_2)$ hours
- The rate of entry into vertical overlap: $N_z(0)$ occurrences per hour
- The probability of lateral overlap: $P_y(S_y)$.

That is, $P(C_t) = \dfrac{2\lambda}{V_1+V_2} N_z(0) P_y(S_y)$.

A nose-to-nose collision, $P(C_n)$, occurred only when the aircraft were in lateral and vertical overlap at the moment they become adjacent. The probability of a nose-to-nose collision, $P(C_n)$, could be taken to be the product of:

- The probability of vertical overlap: $P_z(0)$
- The probability of lateral overlap: $P_y(S_y)$.

That is, $P(C_n) = P_z(0)\, P_y(S_y)$.

Since, from Equation (1), the probability of a TCV for this scenario was

$P(TCV_2) = P(C_s) + P(C_t) + P(C_n)$, then

$$P(TCV_2) = \frac{2\lambda}{V_1+V_2} N_y(S_y) P_z(0) + \frac{2\lambda}{V_1+V_2} N_z(0) P_y(S_y) + P_z(0)\, P_y(S_y). \qquad (5)$$

Let $\overline{|\dot{y}(S_y)|}$ denote the lateral passing speed of the two aircraft, that is their relative lateral approach speed. Therefore, $\dfrac{2\lambda}{|\dot{y}(S_y)|}$ is the average duration of a lateral overlap in hours.

Since $N_y(S_y)$ is the hourly rate of entry into lateral overlap and $P_y(S_y)$ is the probability that the two aircraft are in lateral overlap, then

$$P_y(S_y) \approx N_y(S_y) \frac{2\lambda}{|\dot{y}(S_y)|}.$$

Therefore, $N_y(S_y) \approx P_y(S_y) \dfrac{|\dot{y}(S_y)|}{2\lambda}$.

So Equation (5) can be written as:

$$P(TCV_2) = \frac{2\lambda}{V_1 + V_2} P_y(S_y) \frac{\overline{|\dot{y}(S_y)|}}{2\lambda} P_z(0) + \frac{2\lambda}{V_1 + V_2} N_z(0) P_y(S_y) + P_z(0)\, P_y(S_y). \qquad (6)$$

To evaluate $P(TCV_2)$ we will find values for the individual factors.

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 $|y_2 - y_1| < \lambda$. And therefore, the probability of lateral overlap,

$$P_y(S_y) = P(|\, y_2 - y_1| < \lambda).$$

But, $P(|\, y_2 - y_1| < \lambda) = P(-\lambda < y_2 - y_1 < \lambda)$. And this probability can be found by integrating the 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 each variable is that of the criterion-based distribution, $f(y)$ developed for Scenario 1. Appendix B gives the details for the convolution of these two PDFs and of the integration that yields the lateral overlap probability. Table 3 gives the lateral overlap probability, $P_y(S_y)$, for each of the three values of S: 4, 6, and 8 NM.

Table 3: Scenario 2 Lateral Overlap Probabilities

Track-to-Track Distance (S_y)	$P_y(S_y)$
4 NM	5.6 E-10
6 NM	2.6 E-14
8 NM	1.2 E-18

To deal with the speeds we let V be the mean of V_1 and V_2. Therefore, $V_1 + V_2 = 2V$. Also, the lateral passing speed of the two aircraft, $\overline{|\dot{y}(S_y)|}$, can be estimated by assuming that the aircraft are converging at a 45º angle, so that

$$\overline{|\dot{y}(S_y)|} \approx \frac{2V}{\sqrt{2}}.$$

Equation (6) then becomes,

$$P(TCV_2) = P_y(S_y)\left[\frac{1}{\sqrt{2}} P_z(0) + \frac{\lambda}{V} N_z(0) + P_z(0)\right]. \qquad (7)$$

We make the conservative assumption[10] that the probability of vertical overlap, $P_z(0)$, is 1. This implies that the aircraft cannot collide top-to-bottom (i.e., $N_z(0) = 0$). So Equation (7) becomes,

$$P(TCV_2) = P_y(S_y)\left[\frac{1}{\sqrt{2}}+1\right]. \qquad (8)$$

Scenario 2 Summary

The probability of a TCV for this scenario, $P(TCV_2)$, is, therefore, based on the probability of lateral overlap, $P_y(S_y)$. Table 4 summarizes these probabilities and the corresponding probabilities of the Scenario 2 TCVs.

Table 4: Scenario 2 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (S)	$P_y(S_y)$	$P(TCV_2)$
4 NM	5.6 E-10	9.6E-10
6 NM	2.6 E-14	4.4E-14
8 NM	1.2 E-18	2.0E-18

Scenario 3 Probability Analysis

The TCV for this hazard was the collision with another aircraft that was flying in the same direction on a straight parallel RNAV track under radar surveillance at the same altitude and at a lateral track distance of 4, 6, or 8 NM from the first aircraft's track.

As with Scenario 2, the probability of a TCV for this scenario was the sum of the probabilities of the three mutually exclusive types of collision of the two aircraft:

1. A side-to-side collision (C_s),
2. A top-to-bottom collision (C_t),
3. Or a nose-to-tail collision (C_n).

That is, $P(TCV_2) = P(C_s) + P(C_t) + P(C_n)$. Note that $P(C_n)$ now represents a nose-to-tail rather than a nose-to-nose collision since the aircraft are flying in the same direction.

[10] As navigation and guidance systems become more accurate, vertical overlap will likely become more probable. Because of this fact, we assumed that the navigation and guidance systems of the aircraft in this study were quite accurate, and, in fact, that the probability of vertical overlap is 1.0.

The probability analysis for this scenario was similar to that of Scenario 2 except that we substituted the term, ΔV, for the relative velocity, V_1+V_2 of that analysis, where ΔV is the average speed of overtake. Equation (6) becomes,

$$P(TCV_3) = \frac{2\lambda}{\Delta V} P_y(S_y) \frac{\overline{|\dot{y}(S_y)|}}{2\lambda} P_z(0) + \frac{2\lambda}{\Delta V} N_z(0) P_y(S_y) + P_z(0)\, P_y(S_y). \qquad (9)$$

Also, the lateral passing speed of the two aircraft, $\overline{|\dot{y}(S_y)|}$, can be estimated by assuming that the aircraft are converging at a (conservative[11]) 45º angle, so that $\overline{|\dot{y}(S_y)|} \approx \frac{\Delta V}{\sqrt{2}}$.

Equation (9) then becomes,

$$P(TCV_3) = P_y(S_y)\left[\frac{1}{\sqrt{2}} P_z(0) + \frac{2\lambda}{\Delta V} N_z(0) + P_z(0)\right]. \qquad (10)$$

If we (again) assume that the probability of vertical overlap, $P_z(0)$, is 1. This implies that the aircraft cannot collide top-to-bottom (i.e., $N_z(0) = 0$). So Equation (10) becomes,

$$P(TCV_3) = P_y(S_y)\left[\frac{1}{\sqrt{2}} + 1\right], \qquad (11)$$

the same probability as for Scenario 2. This is reasonable since the approach speeds, the only difference in the two, in each case cancelled out of the final equation.

Scenario 3 Summary

The probability of a TCV for this scenario, $P(TCV_3)$, was, therefore, as with Scenario 2, based on the probability of lateral overlap, $P_y(S_y)$. Table 5 summarizes these probabilities and the corresponding probabilities of the Scenario 3 TCVs.

---

[11] A 60º angle would results in a TCV probability about 9% greater than that for a 45º angle. The 60º angle value for the 6 NM case in Table 5 would be 4.8 E-14 rather than 4.4 E-14.

Table 5: Scenario 3 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (*S*)	P_y (S_y)	$P(TCV_3)$
4 NM	5.6 E-10	9.6E-10
6 NM	2.6 E-14	4.4E-14
8 NM	1.2 E-18	2.0E-18

Scenario 4, Scenario 5, and Scenario 6 Probability Analysis

The TCV probabilities for Scenario 4, Scenario 5, and Scenario 6 were the same as those of Scenario 2 and Scenario 3. The differences were in the number of exposures per hour. We list these values in the results section.

Scenario 7 Probability Analysis

Scenario 7 in which an RNP-1 aircraft and an RNP-2 aircraft were flying adjacent, parallel paths in opposite directions, was similar to Scenario 2. (However, in Scenario 2, both aircraft were RNP-1.) The difference was that the probability of lateral overlap, $P_y(S_y)$, must take into account the two different lateral deviation distributions, one for an RNP-1 aircraft and one for an RNP-2 aircraft. Since the RNP-2 aircraft's lateral distribution allowed for a higher probability of the aircraft's lateral position being far from its track, we expected the probability of overlap for RNP-1 and RNP-2 to be greater than that of RNP-1 and RNP-1.

Table 6 contrasts the overlap probabilities for RNP-1 adjacent to RNP-1 and RNP-1 adjacent to RNP-2 aircraft. We also included the values for RNP-2 adjacent to RNP-2 from [7] for comparison.

Table 6: Scenario 7 Lateral Overlap Probabilities

Track-to-Track Distance (*S*)	RNP-1 RNP-1 P_y (S_y)	RNP-1 RNP-2 P_y (S_y)	RNP-2 RNP-2 P_y (S_y)
4 NM	5.6 E-10	6.8 E-07	3.7 E-04
6 NM	2.6 E-14	4.9 E-11	1.9 E-09
8 NM	1.2 E-18	5.9 E-14	2.4 E-12

The probability of a TCV for this scenario, $P(TCV_7)$, was, therefore, based on the probability of lateral overlap, $P_y(S_y)$. Table 7 summarizes these probabilities and the corresponding probabilities of the Scenario 7 TCVs. A TCV in this scenario was the collision between an RNP-1 aircraft and an RNP-2 aircraft flying the opposite direction.

Table 7: Scenario 7 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (S)	P_y (S_y)	$P(TCV_7)$
4 NM	6.8 E-07	1.2 E-06
6 NM	4.9 E-11	8.4 E-11
8 NM	5.9 E-14	1.0 E-13

Scenario 8 Probability Analysis

Scenario 8 was similar to Scenario 7 except the aircraft were flying in the same direction. These scenarios (Scenario 7 and Scenario 8) were in the same relationship as Scenario 2 and Scenario 3. Therefore, by the same reasoning, the TCV probabilities for Scenario 8 were the same as those of Scenario 7. Table 7 therefore applies to both Scenario 7 and Scenario 8.

Scenarios 9 through 22 Probability Analysis

The TCV probabilities for Scenario 9 through Scenario 22 were the same as those of Scenario 2, Scenario 3, Scenario 7, and Scenario 8. They are all combinations of RNP-1 and RNP-2 aircraft flying adjacent routes. The differences are in the number of exposures per hour. We list these values in the results section.

3.2 Summary of Acceptable Level of Risk

This analysis applied to scenarios other than Scenario 1, because those scenarios dealt with risk of collision while Scenario 1 dealt only with probability of boundary penetration. The purpose of this section is to recommend an acceptable level of risk for scenarios other than Scenario 1 based upon standards, operational experience, and accepted practices within the National Airspace System (NAS) and to develop a basis for comparing the estimated TCV risk with this acceptable level of risk.

The guidelines for this study established an acceptable level of risk[12] rate of 5.0 E-09 collisions per hour of flight. However, the FAA Safety Management System Manual, v 1.1 set the probability of a catastrophic level event at 1.0 E-09 or less.

The TCV probabilities calculated in the previous sections were probabilities of collision when a target aircraft became adjacent or exposed to an aircraft on an adjacent track. To compare those risks to the acceptable level of risk (an hourly rate), we transformed the TCV probabilities per exposure into hourly rates. Since each TCV exposure probability was very small, this was accomplished by multiplying the TCV probability by the estimated number of exposures in an hour.

The number of exposures per hour is a function of the relative longitudinal approach speed of the target and adjacent aircraft and the spacing density of the aircraft on the adjacent track. The assumptions of higher approach speeds and denser spacing were conservative, that is they resulted in higher hourly collision rates.

For opposite direction aircraft (Scenario 2) we assumed a longitudinal approach speed, V_1+V_2, of 1,000 knots[13]. For same direction aircraft (Scenario 3), we assumed a longitudinal overtake speed, ΔV, of 100 knots[14]. For the spacing density, we assumed a minimum 5 NM longitudinal spacing of aircraft on the adjacent route consistent with FAA Order 7110.65.

These assumptions resulted in (appropriately conservative) values of 200 exposures per hour for Scenario 2 and related scenarios and 20 exposures per hour for Scenario 3 and related scenarios.

[12] Based on the ICAO target level of safety for en route separation minima established in [6].
[13] This approach speed (1,000 knots) is reasonably conservative for FL180 and above. It is quite conservative for lower flight levels.
[14] This overtake speed of 100 knots is conservative.

4.0 Results and Conclusions

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

4.1 Summary of Results

Table 8 through Table 13 summarize the key results for Scenario 1 through Scenario 6. For Scenario 2 through Scenario 6, the TCV probability (the probability of collision per exposure) was multiplied by the estimated number of exposures per hour to arrive at an estimated hourly collision rate that could be compared to the acceptable level of risk (5.0 E-09 collisions per hour or 1.0 E-09 collisions per hour).

Table 8: Scenario 1 Key Results

Scenario	Track Width	TCV Probability
Scenario 1: A suitably equipped RNP-1 RNAV aircraft is flying a straight en route track segment with turns of no more than 15° under radar surveillance.	±2 NM	2.6 E-06
	±3 NM	1.7 E-08
	±4 NM	1.2 E-10

Table 9: Scenario 2 Key Results

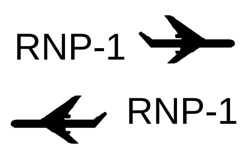
<table>
<tr><td colspan="2">Two suitably equipped RNP-1 RNAV aircraft are flying in <u>opposite</u> directions on parallel straight en route track segments with turns of no more than 15° under radar surveillance.</td><td colspan="2">
</td></tr>
<tr><th>Track-to-Track Separation</th><th>TCV Probability per Exposure</th><th>Estimated Number of Exposures per Hour</th><th>Estimated Hourly Collision Rate</th></tr>
<tr><td>4 NM</td><td>5.6 E-10</td><td>200</td><td>1.1 E-07</td></tr>
<tr><td>6 NM</td><td>2.6 E-14</td><td>200</td><td>5.2 E-12</td></tr>
<tr><td>8 NM</td><td>1.2 E-18</td><td>200</td><td>2.4 E-16</td></tr>
</table>

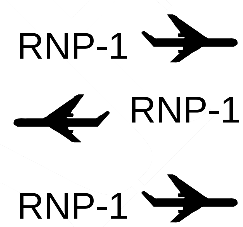
Table 10: Scenario 3 Key Results

Two suitably equipped RNP-1 RNAV aircraft are flying in the same direction on parallel straight en route track segments with turns of no more than 15° under radar surveillance.

Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	5.60 E-10	20	1.1 E-08
6 NM	2.60 E-14	20	5.2 E-13
8 NM	1.20 E-18	20	2.4 E-17

Table 11: Scenario 4 Key Results

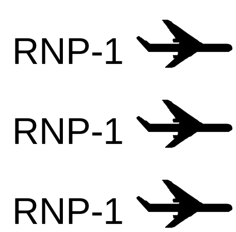
An inner RNP-1 aircraft is flying in the opposite direction between two other RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15° under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	5.6 E-10	400	2.2 E-07
6 NM	2.6 E-14	400	1.0 E-11
8 NM	1.2 E-18	400	4.8 E-16

Table 12: Scenario 5 Key Results

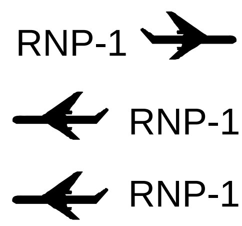
An inner RNP-1 aircraft is flying in the same direction between two other RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15°under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	5.6 E-10	40	2.2 E-08
6 NM	2.6 E-14	40	1.0 E-12
8 NM	1.2 E-18	40	4.8 E-17

Table 13: Scenario 6 Key Results

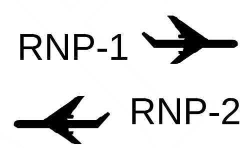
An inner RNP-1 aircraft is flying between two other RNP-1 aircraft, one flying in the same direction and the other flying in the opposite direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	5.6 E-10	220	1.2 E-07
6 NM	2.6 E-14	220	5.7 E-12
8 NM	1.2 E-18	220	2.6 E-16

Table 14: Scenario 7 Key Results

An RNP-1 aircraft is flying adjacent to an RNP-2 aircraft, in the opposite direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	200	1.4 E-04
6 NM	4.9 E-11	200	9.8 E-09
8 NM	5.9 E-14	200	1.2 E-11

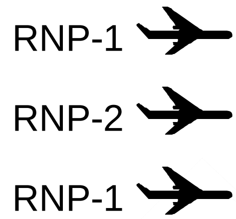
Table 15: Scenario 8 Key Results

An RNP-1 aircraft is flying adjacent to an RNP-2 aircraft, in the same direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.

Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	20	1.4 E-05
6 NM	4.9 E-11	20	9.8 E-10
8 NM	5.9 E-14	20	1.2 E-12

Table 16: Scenario 9 Key Results

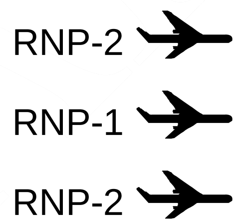
An RNP-2 aircraft is flying between two RNP-1 aircraft, in the <u>same</u> direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	40	2.7 E-05
6 NM	4.9 E-11	40	2.0 E-09
8 NM	5.9 E-14	40	2.4 E-12

Table 17: Scenario 10 Key Results

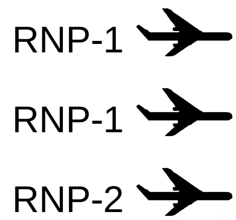
An RNP-1 aircraft is flying between two RNP-2 aircraft, in the <u>same</u> direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	40	2.7 E-05
6 NM	4.9 E-11	40	2.0 E-09
8 NM	5.9 E-14	40	2.4 E-12

Table 18: Scenario 11 Key Results

An RNP-1 aircraft is flying between another RNP-1 aircraft and an RNP-2 aircraft, in the same direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure RNP-1 to RNP-1	TCV Probability per Exposure RNP-1 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	5.6 E-10	6.8 E-07	20/20	1.4 E-05
6 NM	2.6 E-14	4.9 E-11	20/20	9.8 E-10
8 NM	1.2 E-18	5.9 E-14	20/20	1.2 E-12
6/8 NM*	2.6 E-14	5.9 E-14	20/20	1.7 E-12

*6/8 NM means 6 NM RNP-1/RNP-1 separation and 8 NM RNP-1/RNP-2 separation

Table 19: Scenario 12 Key Results

An RNP-2 aircraft is flying between another RNP-2 aircraft and an RNP-1 aircraft, in the same direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.

Track-to-Track Separation	TCV Probability per Exposure RNP-1 to RNP-2	TCV Probability per Exposure RNP-2 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	3.7 E-04	20/20	7.4 E-03
6 NM	4.9 E-11	1.9 E-09	20/20	3.9 E-08
8 NM	5.9 E-14	2.4 E-12	20/20	4.9 E-11

Table 20: Scenario 13 Key Results

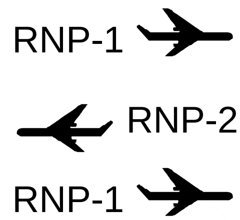
An RNP-2 aircraft is flying between two RNP-1 aircraft and in the <u>opposite</u> direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.			
Track-to-Track Separation	**TCV Probability per Exposure RNP-1 to RNP-2**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
4 NM	6.8 E-07	400	2.7 E-04
6 NM	4.9 E-11	400	2.0 E-08
8 NM	5.9 E-14	400	2.4 E-11

Table 21: Scenario 14 Key Results

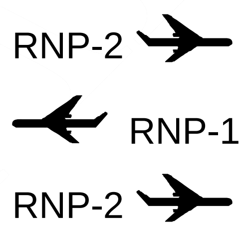
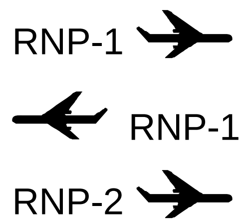
An RNP-1 aircraft is flying between two RNP-2 aircraft and in the <u>opposite</u> direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.			
Track-to-Track Separation	**TCV Probability per Exposure RNP-1 to RNP-2**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
4 NM	6.8 E-07	400	2.7 E-04
6 NM	4.9 E-11	400	2.0 E-08
8 NM	5.9 E-14	400	2.4 E-11

Table 22: Scenario 15 Key Results

An RNP-1 aircraft is flying between another RNP-1 aircraft and an RNP-2 aircraft and in the opposite direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.

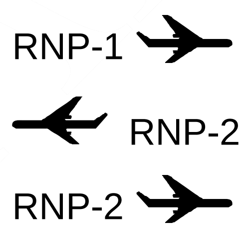


Track-to-Track Separation	TCV Probability Per Exposure RNP-1 to RNP-1	TCV Probability Per Exposure RNP-1 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	5.6 E-10	6.8 E-07	200/200	1.4 E-04
6 NM	2.6 E-14	4.9 E-11	200/200	9.8 E-09
8 NM	1.2 E-18	5.9 E-14	200/200	1.2 E-11
6 / 8 NM	2.6 E-14	5.9 E-14	200/200	1.7 E-11

*****6/8 NM means 6 NM RNP-1/RNP-1 separation and 8 NM RNP-1/RNP-2 separation.

Table 23: Scenario 16 Key Results

An RNP-2 aircraft is flying between another RNP-2 aircraft and an RNP-1 aircraft and in the opposite direction on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure RNP-1 to RNP-2	TCV Probability per Exposure RNP-2 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	3.7 E-04	400	7.4 E-02
6 NM	4.9 E-11	1.9 E-09	400	3.9 E-07
8 NM	5.9 E-14	2.4 E-12	400	4.9 E-10

Table 24: Scenario 17 Key Results

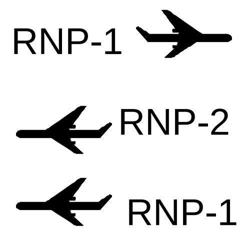
An RNP-2 aircraft is flying between two RNP-1 aircraft, in the <u>same</u> direction as one and in the <u>opposite</u> direction from the other on parallel straight en route track segments with turns of no more than 15º under radar surveillance.			
Track-to-Track Separation	**TCV Probability per Exposure RNP-1 to RNP-2**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
4 NM	6.8 E-07	220	1.5 E-04
6 NM	4.9 E-11	220	1.1 E-08
8 NM	5.9 E-14	220	1.3 E-11

Table 25: Scenario 18 Key Results

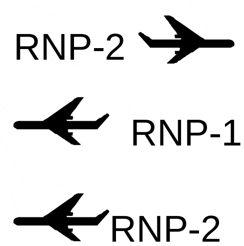
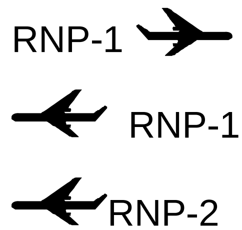
An RNP-1 aircraft is flying between two RNP-2 aircraft, in the <u>same</u> direction as one and in the <u>opposite</u> direction from the other on parallel straight en route track segments with turns of no more than 15º under radar surveillance.			
Track-to-Track Separation	**TCV Probability per Exposure RNP-1 to RNP-2**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
4 NM	6.8 E-07	220	1.5 E-04
6 NM	4.9 E-11	220	1.1 E-08
8 NM	5.9 E-14	220	1.3 E-11

Table 26: Scenario 19 Key Results

An RNP-1 aircraft is flying between another RNP-1 aircraft and an RNP-2 aircraft, in the <u>same</u> direction as the RNP-2 aircraft and in the <u>opposite</u> direction from the RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15º under radar surveillance.

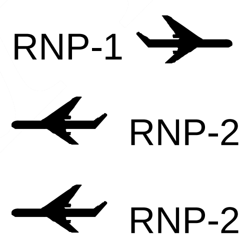


Track-to-Track Separation	TCV Probability per Exposure RNP-1 to RNP-1	TCV Probability per Exposure RNP-1 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	5.6 E-10	6.8 E-07	200/20	1.4 E-05
6 NM	2.6 E-14	4.9 E-11	200/20	9.9 E-10
8 NM	1.2 E-18	5.9 E-14	200/20	1.2 E-12
6/8 NM	2.6 E-14	5.9 E-14	200/20	6.4 E-12

***6/8 NM means 6 NM RNP-1/RNP-1 separation and 8 NM RNP-1/RNP-2 separation**

Table 27: Scenario 20 Key Results

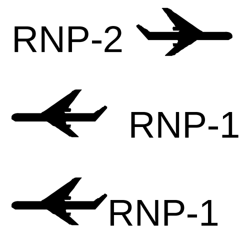
An RNP-2 aircraft is flying between another RNP-2 aircraft and an RNP-1 aircraft, in the <u>same</u> direction as the RNP-2 aircraft and in the <u>opposite</u> direction from the RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure RNP-1 to RNP-2	TCV Probability per Exposure RNP-2 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	3.7 E-04	200/20	7.5 E-03
6 NM	4.9 E-11	1.9 E-09	200/20	4.8 E-08
8 NM	5.9 E-14	2.4 E-12	200/20	6.0 E-11

Table 28: Scenario 21 Key Results

An RNP-1 aircraft is flying between another RNP-1 aircraft and an RNP-2 aircraft, in the same direction as the RNP-1 aircraft and in the opposite direction from the RNP-2 aircraft on parallel straight en route track segments with turns of no more than 15º under radar surveillance.

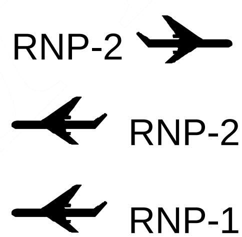


Track-to-Track Separation	TCV Probability per Exposure RNP-1 to RNP-2	TCV Probability per Exposure RNP-1 to RNP-1	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	6.8 E-07	5.6 E-10	200/20	1.4 E-04
6 NM	4.9 E-11	2.6 E-14	200/20	9.8 E-09
8 NM	5.9 E-14	1.2 E-18	200/20	1.2 E-11
8 / 6 NM	5.9 E-14	2.6 E-14	200/20	1.3 E-11

*8/6 NM means 8 NM RNP-2/RNP-1 separation and 6 NM RNP-1/RNP-1 separation.

Table 29: Scenario 22 Key Results

An RNP-2 aircraft is flying between another RNP-2 aircraft and an RNP-1 aircraft, in the same direction as the RNP-1 aircraft and in the opposite direction from the RNP-2 aircraft on parallel straight en route track segments with turns of no more than 15º under radar surveillance.



Track-to-Track Separation	TCV Probability per Exposure RNP-2 to RNP-2	TCV Probability per Exposure RNP-1 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
4 NM	3.7 E-04	6.8 E-07	200/20	7.4 E-02
6 NM	1.9 E-09	4.9 E-11	200/20	3.8 E-07
8 NM	2.4 E-12	5.9 E-14	200/20	4.8 E-10

4.2 Scenario Risk Evaluation and Conclusions

For Scenario 2 through Scenario 22, we evaluated the risk of collision with an adjacent aircraft. This evaluation required us to compare the estimated hourly collision rate with the corresponding acceptable level of risk.

For the acceptable level of risk established for this study (5.0 E-09 collisions per hour of flight and even for the more stringent level of 1.0 E-09 collisions per hour of flight), the risk evaluation results were:

- For all scenarios at 4 NM separation: the acceptable level of risk was exceeded.
- For all RNP-1 only scenarios at 6 NM separation: the acceptable level of risk was met.
- For most RNP-1 adjacent to RNP-2 scenarios at 6 NM separation: the acceptable level of risk was exceeded.
- For all scenarios at 8 NM separation: the target level of safety was met.

Appendix A: Severity Definitions Based on the Perspective of the Flying Public

(FAA Safety Management System Manual, Version 1.0, July 24, 2003)

No Safety Effect	Minor	Major	Hazardous	Catastrophic
No effect on flight crew. Has no effect on safety. Inconvenience.	Slight increase in workload such as flight plan changes. Slight reduction in safety margin or functional capabilities. Minor illness, environmental damage, or system damage. Some physical discomfort to occupants of aircraft (except operators).	Significant increase in flight crew workload. Significant reduction in safety margin or functional capability. Major illness, injury, environmental damage, or system damage. Physical distress to occupants of aircraft (except flight crew) including injuries.	Large reduction in safety margin or functional capability. Serious or fatal injury to small number of persons (other than flight crew). Physical distress/ Excessive workload such that flight crew cannot be relied upon to perform required tasks accurately or completely.	Outcome would result in: - Hull loss - Multiple fatalities - Fatal injury or incapacitation

Appendix B: Statistical Distributions Used in the Study

The Johnson S_B Distribution PDF

$$f_B(x) = \frac{\eta\lambda}{\sqrt{2\pi}} \frac{1}{(x-\varepsilon)(-x+\varepsilon+\lambda)} \exp\left[-\frac{1}{2}\left(\eta^2 \ln\left\{\left(\frac{x-\varepsilon}{-x+\varepsilon+\lambda}\right)^2\right\}\right)\right] \qquad \text{(B1)}$$

where $\varepsilon < x < \varepsilon + \lambda$, $-\infty < \gamma < \infty$, $-\infty < \varepsilon < \infty$, $\eta > 0$, $\lambda > 0$. The location parameter is ε. The scale parameter is λ. And the shape (including skewness) parameters are γ and η.

The Double Exponential Distribution PDF

$$f_D(x) = \frac{1}{2\delta} \exp\left[-\frac{|x|}{\delta}\right] \qquad \text{(B2)}$$

The Mixed Johnson S_B and Double Exponential Distribution PDF

$$f(x) = \left\{ \begin{array}{l} \dfrac{\alpha e^{-Abs[x/\delta]}}{2\delta} + \dfrac{(1-\alpha)\eta\lambda e^{-0.5\eta^2 Log^2[\frac{x-\varepsilon}{\varepsilon+\lambda-x}]}}{\sqrt{2\pi}(x-\varepsilon)(\varepsilon+\lambda-x)}, x < \varepsilon+\lambda, x > \varepsilon \\ \dfrac{\alpha e^{-Abs[x/\delta]}}{2\delta}, x \le \varepsilon ...or... x \ge \varepsilon + \lambda \end{array} \right\} \qquad \textbf{(B3)}$$

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

$$f(u) = \int_{-\infty}^{\infty} f_1(y_1) f_2(u - y_1) dy_1, \qquad \text{(B4)}$$

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,

$$P(|y_2 - y_1| < W) = \int_{-W}^{W} f(x)dx. \qquad \text{(B5)}$$

But $f(x)$ is defined in Equation (2) where f_1 and f_2 are both Johnson S_U PDFs defined in Equation (1). Therefore,

$$P(|y_2 - y_1| < W) = \int_{-W}^{W} \int_{-\infty}^{\infty} f_1(y_1) f_2(x - y_1) dy_1 dx \qquad \text{(B6)}$$

where f_1 and f_2 are defined in Equation (1).

Substituting the definitions of f_1 and f_2, and letting[15] $\varepsilon = 0$ in f_1 and $\varepsilon = S$ in f_2, Equation (B4) becomes $P(|y_2 - y_1| < W) = \int_{-W}^{W} \int_{-\infty}^{\infty} f_1(y_1) f_2(x - y_1) dy_1 dx =$

$$\int_{-W}^{W}\int_{-\infty}^{\infty}\left\{\begin{array}{l}\dfrac{\alpha e^{-Abs[y/\delta]}}{2\delta}+\dfrac{(1-\alpha)\eta\lambda e^{-0.5\eta^2 Log^2[\frac{y-\varepsilon}{\varepsilon+\lambda-y}]}}{\sqrt{2\pi}(y-\varepsilon)(\varepsilon+\lambda-y)}, y<\varepsilon+\lambda, y>\varepsilon \\ \dfrac{\alpha e^{-Abs[y/\delta]}}{2\delta}, y\le\varepsilon...or...y\ge\varepsilon+\lambda\end{array}\right\}\left\{\begin{array}{l}\dfrac{\alpha e^{-Abs[x-y-8/\delta]}}{2\delta}+\dfrac{(1-\alpha)\eta\lambda e^{-0.5\eta^2 Log^2[\frac{x-y-8-\varepsilon}{\varepsilon+\lambda-x+y+8}]}}{\sqrt{2\pi}(x-y-8-\varepsilon)(\varepsilon+\lambda-x+y+8)}, x-y-8<\varepsilon+\lambda, x>\varepsilon \\ \dfrac{\alpha e^{-Abs[x-y-8/\delta]}}{2\delta}, x-y-8\le\varepsilon...or...x-y-8\ge\varepsilon+\lambda\end{array}\right\}dy_1 dx$$

[15] Since ε is the location parameter, the PDF for y_1 uses $\varepsilon = 0$ and the PDF for y_2 uses $\varepsilon = S$, where the two tracks are S NM apart.

References

[1] "Preliminary Re-evaluation of the Probability of Lateral Overlap, Py(0), based on non-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 5 operators with 3 aircraft types (B747-200, B747-400, A340). Each aircraft was using GPS navigation on an oceanic route -- 5 flights were North Atlantic routes, 5 were Pacific Oceanic Airspace, and one was a South Atlantic route.

[2] "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.

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

AFS-400 Safety Study

This paper was published by the FAA's Flight Technologies and Procedure s 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 DME/DME on the route.

[4] "Risk Assessment of RNP10 and RVSM in the South Atlantic Flight Identification Regions", Prepared for SAT Group In cooperation with Aena, IATA, and Indra
7 May 2001, Geert Moek, National Aerospace Laboratory NLR, Edward Lutz, ARINC Incorporated, William Mosberg, ARINC Incorporated.

[5] "Analysis of Long Range Air Traffic Systems: Separation Standards – I, II, and III."

Reich, P.G., *Journal of the Institute of Navigation* **19**, No. 1, pp. 88-96; No. 2, pp. 169-176; No. 3, pp. 331-338.

[6] "Manual on Airspace Planning Methodology for the Determination of Separation Minima"

First Edition, 1998, ICAO (International Civil Aviation Organization)

[7] "Analysis of Area Navigation (RNAV) En Route Separation along Adjacent Straight Segments with Radar Surveillance (Phase I)"

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

This paper was published by the FAA's Flight Technologies and Procedure s Division (AFS-400) in January 2007. It treats only RNAV RNP-2 aircraft. It's models serve as a basis for those of the current paper.