Federal Aviation Administration

Analysis of Area Navigation (RNAV/RNP-1 and RNP-2) En Route Separation Along Adjacent Straight Segments with Radar Surveillance Including Impromptu Routes (Phase IV)

Flight Systems Laboratory
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March 2009

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Flight Systems Laboratory
Flight Technologies and Procedures Division
Flight Standards Service

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Technical Report

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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 without radar surveillance and with either RNP-1 or RNP-2 protection. The results of this analysis show that the hourly rate of collision for suitably equipped RNAV RNP-1 aircraft on parallel adjacent routes without radar surveillance flying the same or opposite directions (with turns of less than 15º), laterally separated by a track-to-track distance of at least 6 NM longitudinally separated by at least 5 NM on average meets an acceptable level of risk of 1.0 E-09 collisions per hour. This is true for a target aircraft adjacent to just one other track (outer track) or for a target aircraft between two other tracks (inner track). For RNAV RNP-2 aircraft, however, the hourly collision rate does not meet the acceptable level of risk using 5 NM longitudinal separation at either 6 or 8 NM lateral separation, but does meet it at 10 NM lateral separation. For combinations of RNAV RNP-1 and RNP-2 aircraft flying adjacent tracks with 5 NM longitudinal separation, the acceptable level of risk is met as long as any RNP-2 aircraft flying adjacent to other RNP-2 aircraft are separated laterally by at least 10 NM.

13. Key Words Lateral separation, Area Navigation (RNAV), en route	**14. Distribution Statement** Controlled by AFS-450
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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 without radar surveillance and with either RNP-1 or RNP-2 protection. As such, this is a follow-on to the studies [7] and [8] which examined en route separation risk under radar surveillance.

This study estimated the risk of RNAV/RNP-1 and RNAV/RNP-2 aircraft flying straight tracks (tracks with turns of less than 15º) deviating from the nominal track laterally by more than 2, 3, or 4 nautical miles (NM). It 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 neither 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. Three studies were examined that 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 aircraft on parallel adjacent routes without radar surveillance flying the same or opposite directions (with turns of less than 15º), laterally separated by a track-to-track distance of at least 6 NM longitudinally separated by at least 5 NM on average met an acceptable level of risk of 1.0 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).

For RNAV RNP-2 aircraft, however, the hourly collision rate did not meet the acceptable level of risk using 5 NM longitudinal separation at either 6 or 8 NM lateral separation, but did meet it at 10 NM lateral separation.

For combinations of RNAV RNP-1 and RNP-2 aircraft flying adjacent tracks with 5 NM longitudinal separation, the acceptable level of risk was met as long as any RNP-2

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

aircraft flying adjacent to other RNP-2 aircraft were separated laterally by at least 10 NM.

In some cases, the acceptable level of risk could be met by changing the assumption of longitudinal separation from 5 NM to larger values. The results for 10 and 20 NM longitudinal separation are shown in the tables of the results section.

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

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1.0 Introduction

This report presents the results of a safety study conducted to evaluate the risk of losing lateral en route separation[2] between parallel Area Navigation (RNAV) routes. 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.

This report is one of a group of studies that address RNAV / RNP enroute lateral separation. 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, December 2008
- "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

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 with separation for both opposite and same direction traffic without radar surveillance and with either Required Navigation Performance Level 1 (RNP-1) or Required Navigation Performance Level 2 (RNP-2) protection. As such,

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

this study was a follow-on to the studies [7] and [8] which examined en route separation risk under radar surveillance.

This study estimated the risk of RNAV/RNP-1 and RNAV/RNP-2 aircraft flying straight tracks (tracks with turns of less than 15º) without radar surveillance 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 neither was under radar surveillance.

1.2 Statement of the Problem

Specifically, this study attempted to quantify the lateral track deviation[3] of typical RNAV/RNP-1 and RNP-2 equipped aircraft[4] on straight en route segments—segments with no turns, or turns of at most 15º—without radar surveillance. This lateral track deviation was used to determine the probability that a typical RNAV/RNP-1 (or RNP-2) 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 without 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 without radar surveillance deviating laterally from that track by more than 2 NM (or 3 NM or 4 NM)?

2. What is the probability of an RNP-2 aircraft flying a straight en route track segment without radar surveillance deviating laterally from that track by more than 2 NM (or 3 NM or 4 NM)?

3. What is the risk of an RNP-1 aircraft flying a straight en route outer track segment without radar surveillance colliding with an aircraft (either RNP-1 or RNP-2)

[3] 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.
[4] As defined in [4], ICAO Document 9689-AN/953, First edition, 1998

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)?

4. What is the risk of an RNP-2 aircraft flying a straight en route outer track segment without 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)?

5. What is the risk of an RNP-1 aircraft flying a straight en route outer track segment without 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)?

6. What is the risk of an RNP-2 aircraft flying a straight en route outer track segment without 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)?

7. What is the risk of an RNP-1 aircraft flying a straight en route inner track segment without 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 the opposite direction to that of the inner aircraft?

8. What is the risk of an RNP-2 aircraft flying a straight en route inner track segment without 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 the opposite direction to that of the inner aircraft?

9. What is the risk of an RNP-1 aircraft flying a straight en route inner track segment without 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?

10. What is the risk of an RNP-2 aircraft flying a straight en route inner track segment without 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?

11. What is the risk of an RNP-1 aircraft flying a straight en route inner track segment without 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?

12. What is the risk of an RNP-2 aircraft flying a straight en route inner track segment without 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?

13. 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.

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2.0 Study Methodology

This study contained 28 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. There were 28 scenarios of interest. The first six scenarios involved RNP-1 aircraft only. The next six scenarios involved RNP-2 aircraft only. The final 16 scenarios involved combinations of RNP-1 and RNP-2 aircraft.

Scenario 1-1

In this scenario, a typical RNP-1 aircraft was flying a straight en route track segment (possibly, an impromptu route) without 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 is 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 a statistical distribution of lateral aircraft deviations. This distribution was used to determine the probability of a TCV.

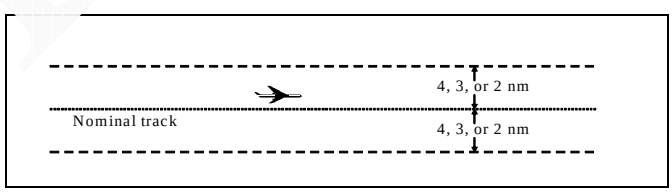


Figure 1: Scenario 1 Hazards

Scenario 2-1

In this scenario, two RNP-1 aircraft were flying in opposite directions (see Figure 2b) on parallel, adjacent, straight en route track segments (possibly impromptu routes) without radar surveillance with turns of no more than 15º. 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 the 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 with the other aircraft were independent. 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 could eliminate 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 mutual exclusivity, the probability of a TCV for this scenario, $P(TCV_2)$, is the sum of the probabilities of collision for each way:

$$P(TCV_2) = P(C_s) + P(C_t) + P(C_n), \quad (1)$$

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

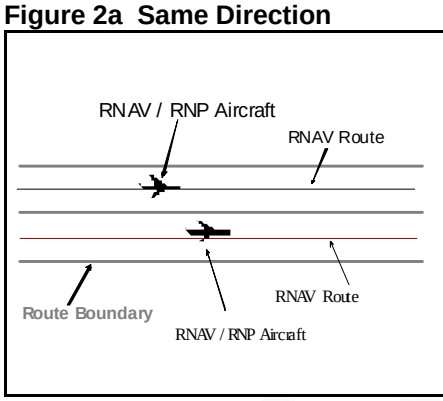
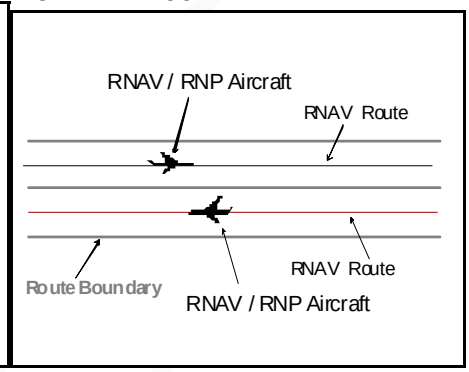
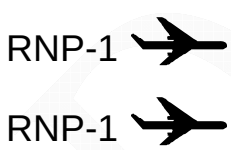


Figure 2b Opposite Direction



Scenario 3-1



This scenario was the same as Scenario 2-1 except the two RNP-1 aircraft were flying in the same direction (see Figure 2a) on parallel, adjacent, straight en route track segments without radar surveillance with turns of no more than 15º. 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, $P(TCV_3)$, is the sum of the probabilities of collision for each way:

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

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.

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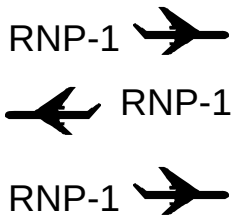
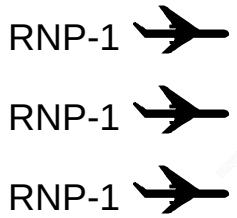
Scenario 4-1



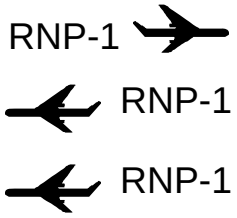
This scenario was the same as Scenario 2-1 except there were three RNP-1 aircraft rather than two. The aircraft track of interest was the one between the other two RNP-1 aircraft. The inner RNP-1 aircraft was flying in the opposite direction to the other two on parallel, adjacent, straight en route track segments without 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 with adjacent aircraft were, in general, twice that of Scenario 2-1.

Scenario 5-1



This scenario was the same as Scenario 3-1 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 without radar surveillance with turns of no more than 15º. The hazards and TCVs were the same as Scenario 3-1. The mathematical model for the calculation of the probability of a TCV was the same. However, the number of exposures with adjacent aircraft were, in general, twice that of Scenario 3-1.

Scenario 6-1



This scenario was the same as Scenario 5-1 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 5-1. The mathematical model for the calculation of the probability of a TCV was the same. However, the number of exposures with adjacent aircraft were, in general, the sum of those for Scenario 2-1 and Scenario 3-1.

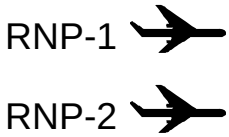
Scenario 1-2 through Scenario 6-2

These scenarios were identical to Scenario 1-1 through Scenario 6-1 except RNP-2 aircraft replaced RNP-1 aircraft.

Scenario 7

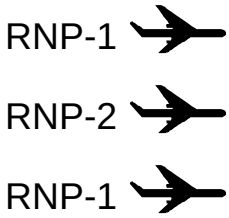
This scenario was the same as Scenario 1-2 except that one of the aircraft was RNP-2 and the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 2-1. We assumed both independence and mutual exclusivity.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

Scenario 8



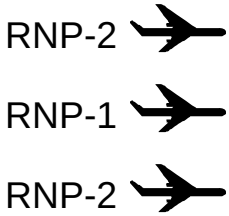
This scenario was the same as Scenario 3-1 except that one of the aircraft was RNP-2 and the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 3-1. We assumed both independence and mutual exclusivity.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

Scenario 9



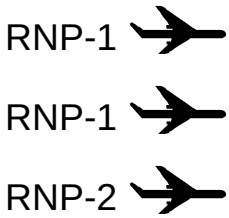
This scenario was the same as Scenario 4-1 except that the aircraft in the center was RNP-2 and the other two were RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4-1. We assumed both independence and mutual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

Scenario 10



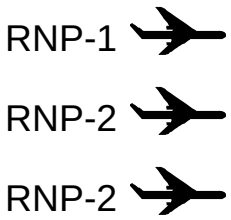
This scenario was the same as Scenario 4-1 except that the aircraft in the center was RNP-1 and the other two were RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4-1. We assumed both independence and mutual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

Scenario 11



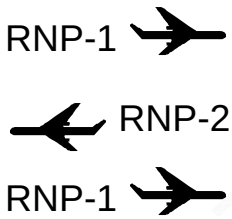
This scenario was the same as Scenario 4-1 except that the aircraft in the center was RNP-1 and one of the other aircraft was RNP-2 while the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4-1. 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



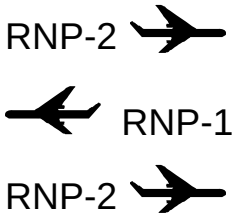
This scenario was the same as Scenario 4-1 except that the aircraft in the center was RNP-2 and one of the other aircraft was RNP-2 while the other was RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 4-1. 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



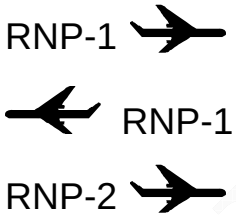
This scenario was the same as Scenario 5-1 except that the aircraft in the center was RNP-2 and the two other aircraft were RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5-1. We assumed both independence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

Scenario 14



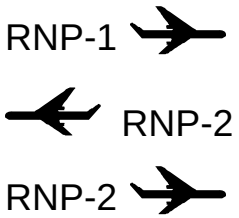
This scenario was the same as Scenario 5-1 except that the aircraft in the center was RNP-1 and the two other aircraft were RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5-1. We assumed both independence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

Scenario 15



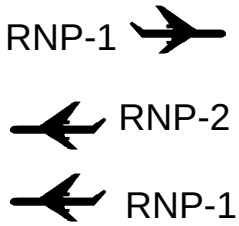
This scenario was the same as Scenario 5-1 except that the aircraft in the center was RNP-1 and one of the two other aircraft was RNP-1 while the other was RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5-1. 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



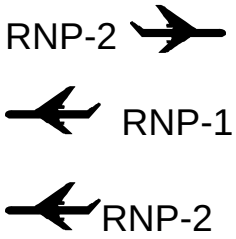
This scenario was the same as Scenario 5-1 except that the aircraft in the center was RNP-2 and one of the two other aircraft was RNP-1 while the other was RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 5-1. 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



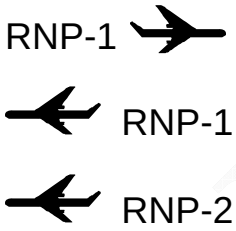
This scenario was the same as Scenario 6-1 except that the aircraft in the center was RNP-2 and while the other two aircraft were RNP-1. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6-1. We assumed both independence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

Scenario 18



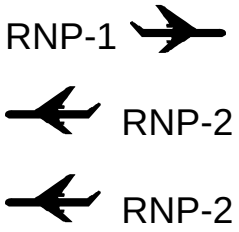
This scenario was the same as Scenario 6-1 except that the aircraft in the center was RNP-1 and while the other two were RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6-1. We assumed both independence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

Scenario 19



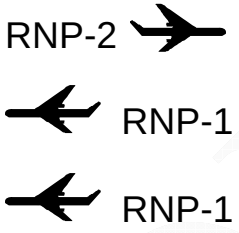
This scenario was the same as Scenario 6-1 except that the aircraft in the center was RNP-1 and one of the two other aircraft was RNP-1 while the other was RNP-2. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6-1. 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



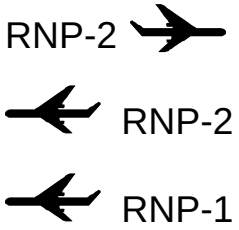
This scenario was the same as Scenario 6-1 except that the aircraft in the center was RNP-2 and one of the two other aircraft was RNP-1 while the other was RNP-2. The RNP-2 aircraft were flying in the same direction while the RNP-1 aircraft was flying opposite the RNP-2 aircraft. The hazards and TCVs were the same. The mathematical model for the calculation of the probability of a TCV was similar to that of Scenario 6-1. 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 6-1 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 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 6-1. 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 6-1 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 6-1. 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.

2.1 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 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 (i.e., without radar surveillance)—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, but without radar surveillance.

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, but without radar surveillance.

3.0 Summary of Data Analysis and Risk Evaluation

We determined the probability of the TCVs in each of the three 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 1-1. The results of the analysis for Scenario 1-1 could be used in the analyses for the other five RNP-1 scenarios. In a similar way, Scenario 1-2 was analyzed first and its results used in the analyses for the other five RNP-2 scenarios.

<u>Scenario 1-1 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 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-1 RNAV routes was an accuracy "bounded by ±1 NM for 95% of the total flying time." The track-keeping accuracy specified for aircraft operating on RNP-2 RNAV routes is an accuracy "bounded by ±2 NM for 95% of the total flying time." This meant that the frequency of an RNP-1 aircraft remaining within the 1 NM boundary is 95% and an RNP-2 aircraft remaining within the 2 NM boundary was 95%. Using the frequency definition of probability, this translated into a 95% probability of containment of RNP-1 within the 1 NM boundary and a 95% probability of containment of RNP-2 within the 2 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 –1 and +1 NM or –2 and +2 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 RNP-1 Lateral Deviation Distribution Selection

1. The distribution should be symmetric, centered at zero with 95% of its area contained within –1 and +1 NM 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 the lack of radar surveillance into account and should take RNP alerting into account.

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

5. The RNP-1 distribution without radar surveillance should be consistent with the previously derived [8] RNP-1 distribution under radar surveillance.

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-1 study [8] used a mixed distribution based upon the first four criteria listed above. 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[5] to model the radar surveillance behavior more accurately. That distribution was of the form:

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

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, was the proportionality factor for the mix of distributions. We set δ = 0.2 and η = 1.2 to satisfy the 95% criterion for ± 1 NM and to be consistent with the RNP-1 under radar distribution. And we set λ = 4 and ε = -2.0 to increase the lateral distribution spread to reflect the lack of surveillance (the RNP-1 under surveillance distribution used the tighter λ = 3 and ε = -1.5). But we kept the distribution bounded to reflect the RNP alerting capabilities[6]. And we set α = 0.738 (a more than ten-fold increase over the 0.0566 value of α in the RNP-1 under radar distribution) to reflect the potential increase in lateral dispersion due to the lack of radar surveillance and to satisfy the 95% criterion for ± 1 NM. 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.

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 five distributions.

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

[6] We assume that while there is no radar surveillance, there will be communication with air traffic and that this communication capability will be used in the event of an RNP alert. Further, we assume that air traffic will take appropriate measures if notified that an aircraft has received an RNP alert.

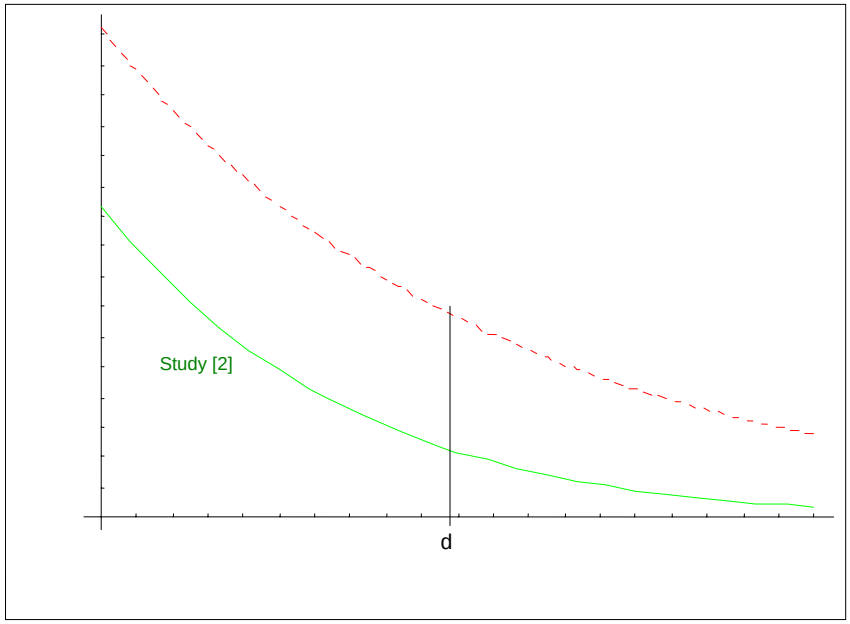


Figure 3: Two Distribution Tail Areas

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

d	Study [1] (N = 11)*	Study [2] (N = 3150)	Study [3] (N = 865)	Previous study: RNP-1 with Radar	This study *f*(*y*): RNP-1 without radar
1	2.0 E-02	1.0 E-13	1.0 E-08	2.5 E-02	2.5 E-02
2	1.0 E-02	4.0 E-25	< 1.0 E-50	1.3 E-06	1.7 E-05
4	7.0 E-03	5.0 E-48	< 1.0 E-50	5.8 E-11	7.6 E-10
6	3.0 E-03	< 1.0 E-50	< 1.0 E-50	2.6 E-15	3.4 E-14

*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 meant 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]. However, it should also be noted that the sample size for study [1] was very small compared to those of the other two studies. Also, the tail values for *f*(*y*) were also larger than those for the RNP-1 with radar distribution (about 10 times larger), which was to be expected due to the potential increase in lateral dispersion due to lack of radar surveillance.

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 the first 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.

Also, given the relationship between the tail areas of the RNP-1 with radar and this distribution (without radar), it was reasonable to conclude that this distribution satisfied the fifth criterion.

Impromptu Routes

Since impromptu routes, even though they are unpublished and controller-initiated, are point-to-point routes using existing 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 applied to both published and impromptu routes.

Scenario 1-1 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 1-1 TCV Probabilities

Lateral Distance from Track	RNP-1 without Radar TCV Probability	RNP-1 with Radar TCV Probability*
±1 NM	5.0 E-02	5.0 E-02
±2 NM	3.4 E-05	2.6 E-06
±3 NM	2.3 E-07	1.7 E-08
±4 NM	1.5 E-09	1.2 E-10

*From the previous study [8]

Scenario 1-2 Probability Analysis

The TCV for this hazard was the deviation of the center of gravity of an RNP-2 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. Again 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.

As with the analysis for Scenario 1-1 above, we used a set of reasonable criteria to find an appropriate distribution for RNP-2 aircraft.

Criteria for RNP-2 Lateral Deviation Distribution Selection

1. The distribution should be symmetric, centered at zero with 95% of its area contained within –2 and +2 NM 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 the lack of radar surveillance into account.

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

5. The RNP-2 distribution without radar surveillance should be consistent with the previously derived [7] RNP-2 distribution under radar surveillance and with the RNP-1 distribution without radar above (Scenario 1-1).

We used the same form of mixed distribution (based upon the first four criteria listed above) as that of the RNP-1 in Scenario 1-1. That distribution was of the form:

$$g(y) = \frac{\alpha e^{-|y/\delta|}}{2\delta} + \frac{(1-\alpha)\eta\lambda e^{-0.5\eta^2 Ln\left[\frac{y-\varepsilon}{\varepsilon-y+\lambda}\right]^2}}{\sqrt{2\pi}(y-\varepsilon)(\varepsilon-y+\lambda)} \qquad (4)$$

In Equation (4) we called the RNP-2 version of the distribution, $g(y)$.

We could satisfy the five criteria above by using that distribution with suitable adjustments of the parameters. The parameter, α, was the proportionality factor for the mix of distributions. We set δ = 0.3 and η = 1.2 to satisfy the 95% criterion for ± 2 NM and to be consistent with the RNP-2 under radar distribution. And we set λ = 8 and ε = -4.0 to increase the lateral distribution spread to reflect the lack of surveillance (the RNP-2 under surveillance distribution used the tighter λ = 6 and ε = -3.0). And we set α = 0.738

(a more than ten-fold increase over the 0.0566 value of α in the RNP-2 under radar distribution) to reflect the potential large increase in lateral dispersion due to lack of radar surveillance, to satisfy the 95% criterion for ± 2 NM, and to remain consistent with the RNP-1 without radar distribution. We again note 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.

Next, we compared this distribution with the empirical results of the three studies ([1], [2], and [3]) and to the other derived distributions (RNP-2 with radar and RNP-1 without radar). Table 3 gives the areas to the right of the line at *d* NM for each of the four distributions.

Table 3: Distribution Areas to the Right of *d* NM with RNP-2

d	Study [1] (N = 11)*	Study [2] (N = 3,150)	Study [3] (N = 865)	Previous study: RNP-2 with Radar	This study g(*y*): RNP-2 without Radar
1	2.0 E-02	1.0 E-13	1.0 E-08	--	--
2	1.0 E-02	4.0 E-25	< 1.0 E-50	2.5 E-02	2.5 E-02
4	7.0 E-03	5.0 E-48	< 1.0 E-50	4.6 E-08	6.0 E-07
6	3.0 E-03	< 1.0 E-50	< 1.0 E-50	5.8 E-11	7.6 E-10

*N represents the sample size for each empirical study.

As with the RNP-1 distribution, the tail values for the distribution developed above, $g(y)$, were larger than those of studies [2] and [3]. This meant 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]. However, it should also be noted that the sample size for study [1] was very small compared to those of the other two studies. Also, the tail values for $g(y)$ were also larger than those for the RNP-2 with radar distribution (again, about 10 times larger), which was to be expected due to the potential increase in lateral dispersion due to lack of radar surveillance.

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, $g(y)$, developed above provided a conservative estimate of en route lateral deviation behavior under radar surveillance compared to the other studies, and therefore satisfied the first four criteria for lateral distribution selection. Given the empirical results available, this distribution appeared to be conservative. Also, given the relationship between the tail areas of the RNP-2 with radar and this distribution (without radar), it was reasonable to conclude that this distribution satisfied the fifth criterion.

Scenario 1-2 Summary

Using the criterion-based distribution, $g(y)$, we could estimate 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, 4 NM, 5 NM, or more). Table 4 lists those probabilities.

Table 4: Scenario 1-2 TCV Probabilities

Lateral Distance from Track	RNP-2 without Radar TCV Probability	RNP-2 with Radar TCV Probability*
±1 NM	--	--
±2 NM	5.0 E-02	5.0 E-02
±3 NM	5.2 E-03	2.6 E-06
±4 NM	1.2 E-06	9.2 E-08
±5 NM	4.3 E-08	--

*From the previous study [7]

Scenario 2-1 Probability Analysis

The TCV for this hazard was the collision with another RNP-1 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.

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[7]:

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.

[7] 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].

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

We assumed that there were 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 1-1 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 be the line $y = S_y$ (see Figure 4), so that the tracks are separated by S_y NM.

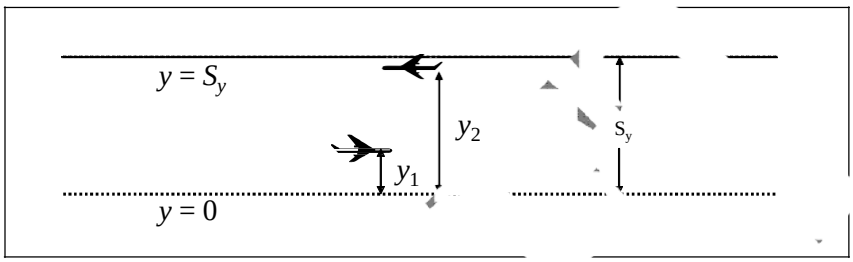


Figure 4: Scenario 2-1 Mathematical Model

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 passed each other, the aircraft were adjacent for a period of $2\lambda/(V_1+V_2)$ hours.

A side-to-side collision 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, $P(C_s)$, can 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, $P(C_s) = \dfrac{2\lambda}{V_1+V_2} N_y(S_y) P_z(0)$. (5)

A top-to-bottom collision occurred only when the aircraft moved into vertical overlap during that period of adjacency, and also happened to be in lateral overlap when they moved 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 occurred only when the aircraft were in lateral and vertical overlap at the moment they became 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 is $P(TCV_2) = P(C_s) + P(C_t) + P(C_n)$, then

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

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

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

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

So Equation (6) can be written as:

$$P(TCV_2) = \frac{2\lambda}{V_1 + V_2} P_y(S_y) \frac{\left|\dot{y}(S_y)\right|}{2\lambda} P_z(0) + \frac{2\lambda}{V_1 + V_2} N_z(0) P_y(S_y) + P_z(0)\, P_y(S_y). \qquad (7)$$

To evaluate $P(TCV_2)$ we found 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 were 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 -λ 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 1-1. Appendix B gives the details for the convolution of these two PDFs and of the integration that yields the lateral overlap probability. Table 5 gives the lateral overlap probability, $P_y(S_y)$, for each of the three values of S: 4, 6, and 8 NM.

Table 5: Scenario 2-1 Lateral Overlap Probabilities

Track-to-Track Distance (S_y)	$P_y(S_y)$
4 NM	1.2 E-08
6 NM	5.8 E-13
8 NM	2.8 E-17

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, $\overline{\left|\dot{y}(S_y)\right|}$, can be estimated by assuming that the aircraft are converging at a 45º angle, so that

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

Equation (7) then becomes,

$$P(TCV_2) = P_y(S_y)\left[\frac{1}{\sqrt{2}} P_z(0) + \frac{\lambda}{V} N_z(0) + P_z(0)\right]. \qquad (8)$$

We made the conservative assumption[8] 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 (8) becomes,

$$P(TCV_2) = P_y(S_y)\left[\frac{1}{\sqrt{2}} + 1\right]. \tag{9}$$

Scenario 2-1 Summary

The probability of a TCV for this scenario, $P(TCV_{2\text{-}1})$, was, therefore, based on the probability of lateral overlap, $P_y(S_y)$. Table 6 summarizes these probabilities and the corresponding probabilities of the Scenario 2-1 TCVs.

Table 6: Scenario 2-1 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (*S*)	$P_y(S_y)$	$P(TCV_{2\text{-}1})$
4 NM	1.2 E-08	2.0 E-08
6 NM	5.8 E-13	9.9 E-13
8 NM	2.8 E-17	4.8 E-17

Scenario 2-2 Probability Analysis

The TCV for this hazard was the collision with another RNP-2 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, 8, 9, or 10 NM from the first aircraft's track.

The analysis for this scenario was the same as that for Scenario 2-1, except that the RNP-1 distribution $f(y)$ was replaced by the RNP-2 distribution $g(y)$.

The probability of a TCV for this scenario, $P(TCV_{2\text{-}2})$, 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 2-2 TCVs.

[8] 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 was 1.0.

Table 7: Scenario 2-2 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (*S*)	$P_y(S_y)$	$P(TCV_{2\text{-}2})$
4 NM	1.9 E-04	3.2 E-04
6 NM	4.5 E-06	7.7 E-06
8 NM	9.6 E-11	1.6 E-10
10 NM	1.2 E-13	2.0 E-13

Scenario 3-1 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 2-1, 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.

The probability analysis for this scenario was similar to that of Scenario 2-1 except that we substituted the term, ΔV, for the relative velocity, V_1+V_2 of that analysis, where ΔV was the average speed of overtake. Equation (7) becomes,

$$P(TCV_3) = \frac{2\lambda}{\Delta V} P_y(S_y) \frac{\overline{\left|\dot{y}(S_y)\right|}}{2\lambda} P_z(0) + \frac{2\lambda}{\Delta V} N_z(0) P_y(S_y) + P_z(0)\, P_y(S_y). \qquad (10)$$

Also, the lateral passing speed of the two aircraft, $\overline{\left|\dot{y}(S_y)\right|}$, can be estimated by assuming that the aircraft are converging at a (conservative[9]) 45º angle, so that $\overline{\left|\dot{y}(S_y)\right|} \approx \frac{\Delta V}{\sqrt{2}}$.

Equation (10) then becomes,

[9] A 60º angle would result 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 9.2 E-11 rather than 8.4 E-11.

$$P(TCV_3) = P_y(S_y)\left[\frac{1}{\sqrt{2}}P_z(0) + \frac{2\lambda}{\Delta V}N_z(0) + P_z(0)\right]. \qquad (11)$$

If we (again) assume that the probability of vertical overlap, $P_z(0)$, is 1. This implied that the aircraft cannot collide top-to-bottom (i.e., $N_z(0) = 0$). So Equation (11) becomes,

$$P(TCV_3) = P_y(S_y)\left[\frac{1}{\sqrt{2}} + 1\right], \qquad (12)$$

the same probability as for Scenario 2-1. This was reasonable since the approach speeds, the only difference in the two, in each case cancelled out of the final equation.

Scenario 3-1 Summary

The probability of a TCV for this scenario, $P(TCV_{3\text{-}1})$, was, therefore, as with Scenario 2-1, based on the probability of lateral overlap, $P_y(S_y)$. Table 8 summarizes these probabilities and the corresponding probabilities of the Scenario 3-1 TCVs.

Table 8: Scenario 3-1 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (*S*)	$P_y(S_y)$	$P(TCV_{3\text{-}1})$
4 NM	1.2 E-08	2.0 E-08
6 NM	5.8 E-13	9.9 E-13
8 NM	2.8 E-17	4.8 E-17

Scenario 3-2 Probability Analysis

The TCV for this hazard was the collision with another RNP-2 aircraft that was flying in the same direction under radar surveillance on a straight parallel RNAV track at the same altitude and at a lateral track distance of 4, 6, 8, 9, or 10 NM from the first aircraft's track.

The analysis for this scenario is the same as that for Scenario 3-1, except that the RNP-1 distribution $f(y)$ is replaced by the RNP-2 distribution $g(y)$.

The probability of a TCV for this scenario, $P(TCV_{3\text{-}2})$, is, therefore, based on the probability of lateral overlap, $P_y(S_y)$. Table 9 summarizes these probabilities and the corresponding probabilities of the Scenario 3-2 TCVs.

Table 9: Scenario 3-2 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (*S*)	$P_y(S_y)$	$P(TCV_{3\text{-}2})$
4 NM	1.9 E-04	3.2 E-04
6 NM	4.5 E-06	7.7 E-06
8 NM	9.6 E-11	1.6 E-10
10 NM	1.2 E-13	2.0 E-13

Scenarios 4-1, 5-1, 6-1, 4-2, 5-2, and 6-2 Probability Analyses

The TCV probabilities for Scenario 4-1, Scenario 5-1, and Scenario 6-1 were the same as those of Scenario 2-1 and Scenario 3-1. And the TCV probabilities for Scenario 4-2, Scenario 5-2, and Scenario 6-2 were the same as those of Scenario 2-2 and Scenario 3-2. The differences were in the number of exposures per hour, and therefore in the risk of collision per hour of flight. We list those risk 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. (In that scenario, 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 10 contrasts the overlap probabilities for RNP-1 adjacent to RNP-1 and RNP-1 adjacent to RNP-2 aircraft. We have also included the values for RNP-2 adjacent to RNP-2 from [7] for comparison.

Table 10: 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	1.2 E-08	4.7 E-05	1.9 E-04
6 NM	5.8 E-13	1.1 E-09	4.5 E-06
8 NM	2.8 E-17	8.0 E-13	9.6 E-11

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 11 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 11: Scenario 7 and Scenario 8 Lateral Overlap and TCV Probabilities

Track-to-Track Distance (*S*)	$P_y(S_y)$	$P(TCV_7)$
4 NM	4.7 E-05	8.0 E-05
6 NM	1.1 E-09	1.9 E-09
8 NM	8.0 E-13	1.4 E-12

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 2-1 and Scenario 3-1. Therefore, by the same reasoning, the TCV probabilities for Scenario 8 were the same as those of Scenario 7. Table 11 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 Scenarios 2-1, 3-1, 2-2, 3-2, 7, and 8. They were all combinations of RNP-1 and RNP-2 aircraft flying adjacent routes. The differences were in the number of exposures per hour, and therefore in the risk of collision per hour of flight. We list those risk values in the results section.

3.2 Summary of Acceptable Level of Risk

This analysis did not apply to Scenario 1-1 because that scenario dealt only with probability of boundary penetration. The purpose of this section is to recommend an acceptable level of risk for the remaining scenarios upon standards, operational experience, and accepted practices within the 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[10] rate of 5.0 E-09 collisions per hour of flight. However, the FAA Safety Management System Manual, v 1.1 sets the probability of a catastrophic level event at 1.0 E-09 or less.

[10] Based on the ICAO target level of safety for en route separation minima established in [6].

The TCV probabilities calculated in the previous sections were probabilities of collision when a target aircraft became adjacent to 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 was 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 2-1), we assumed a longitudinal approach speed, V_1+V_2, of 1,000 knots[11]. For same direction aircraft (Scenario 3-1), we assumed a longitudinal overtake speed, ΔV, of 100 knots[12]. For the spacing density, we assumed a minimum 5 NM longitudinal spacing of aircraft on the adjacent route consistent with FAA Order 7110.65. We also performed the risk analysis with 10 NM and 20 NM longitudinal spacing to allow for the possibility of dense spacing in operations without radar surveillance.

Longitudinal spacing of 5 NM results in (appropriately conservative) values of 200 exposures per hour for Scenario 2-1 and similar scenarios and 20 exposures per hour for Scenario 3-1 and similar scenarios. Longitudinal spacing of 10 NM resulted in values of 100 exposures per hour for Scenario 2-1. And longitudinal spacing of 20 NM resulted in values of 50 exposures per hour for that scenario.

[11] This approach speed (1,000 knots) is reasonably conservative for FL180 and above. It is quite conservative for lower flight levels.
[12] 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 12 through Table 17 summarize the key results for Scenario 1-1 through Scenario 6-1, each dealing with RNP-1 aircraft without radar surveillance. For Scenario 2-1 through Scenario 6-1, 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 can be compared to the acceptable level of risk (5.0 E-09 collisions per hour or 1.0 E-09 collisions per hour).

Table 12: Scenario 1-1 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 15º without radar surveillance.	±2 NM	3.4 E-05
	±3 NM	2.3 E-07
	±4 NM	1.5 E-09

Table 13: Scenario 2-1 Key Results

Two suitably equipped RNP-1 RNAV aircraft are flying in opposite directions on parallel straight en route track segments with turns of no more than 15º without radar surveillance.			RNP-1 RNP-1	
Separation		TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
Along Track	Track-to-Track			
5 NM	4 NM	1.2 E-08	200	2.4 E-06
5 NM	6 NM	5.8 E-13	200	1.2 E-10
5 NM	8 NM	2.8 E-17	200	5.6 E-15
10 NM	4 NM	1.2 E-08	100	1.2 E-06
10 NM	6 NM	5.8 E-13	100	6.0 E-11
10 NM	8 NM	2.8 E-17	100	2.8 E-15
20 NM	4 NM	1.2 E-08	50	6.0 E-07
20 NM	6 NM	5.8 E-13	50	3.0 E-11
20 NM	8 NM	2.8 E-17	50	1.4 E-15

Table 14: Scenario 3-1 Key Results

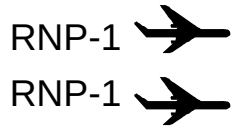
Two suitably equipped RNP-1 RNAV aircraft are flying in the same direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	1.2 E-08	20	2.4 E-07
5 NM	6 NM	5.8 E-13	20	1.2 E-11
5 NM	8 NM	2.8 E-17	20	5.6 E-16
10 NM	4 NM	1.2 E-08	10	1.2 E-07
10 NM	6 NM	5.8 E-13	10	6.0 E-12
10 NM	8 NM	2.8 E-17	10	2.8 E-16
20 NM	4 NM	1.2 E-08	5	6.0 E-08
20 NM	6 NM	5.8 E-13	5	3.0 E-12
20 NM	8 NM	2.8 E-17	5	1.4 E-16

Table 15: Scenario 4-1 Key Results

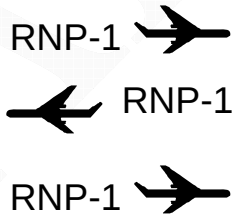
An inner RNP-1 aircraft is flying in the opposite direction between two other RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	1.2 E-08	400	4.8 E-06
5 NM	6 NM	5.8 E-13	400	2.3 E-10
5 NM	8 NM	2.8 E-17	400	1.1 E-14
10 NM	4 NM	1.2 E-08	200	2.4 E-06
10 NM	6 NM	5.8 E-13	200	1.2 E-10
10 NM	8 NM	2.8 E-17	200	5.5 E-15
20 NM	4 NM	1.2 E-08	100	1.2 E-06
20 NM	6 NM	5.8 E-13	100	5.8 E-11
20 NM	8 NM	2.8 E-17	100	2.8 E-15

Table 16: Scenario 5-1 Key Results

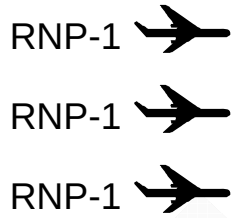
An inner RNP-1 aircraft is flying in the same direction between two other RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	1.2 E-08	40	4.8 E-07
5 NM	6 NM	5.8 E-13	40	2.3 E-11
5 NM	8 NM	2.8 E-17	40	1.1 E-15
10 NM	4 NM	1.2 E-08	20	2.4 E-07
10 NM	6 NM	5.8 E-13	20	1.2 E-11
10 NM	8 NM	2.8 E-17	20	5.5 E-16
20 NM	4 NM	1.2 E-08	10	1.2 E-07
20 NM	6 NM	5.8 E-13	10	5.8 E-12
20 NM	8 NM	2.8 E-17	10	2.8 E-16

Table 17: Scenario 6-1 Key Results

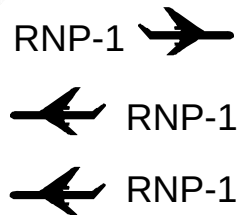
An inner RNP-1 aircraft is flying between two other RNP-1 aircraft, one flying in the same direction and the other flying in the opposite direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	1.2 E-08	220	2.6 E-06
5 NM	6 NM	5.8 E-13	220	1.3 E-10
5 NM	8 NM	2.8 E-17	220	6.2 E-15
10 NM	4 NM	1.2 E-08	110	1.3 E-06
10 NM	6 NM	5.8 E-13	110	6.5 E-11
10 NM	8 NM	2.8 E-17	110	3.1 E-15
20 NM	4 NM	1.2 E-08	55	6.5 E-07
20 NM	6 NM	5.8 E-13	55	3.3 E-11
20 NM	8 NM	2.8 E-17	55	1.6 E-15

Table 18 through Table 23 summarize the key results for Scenario 1-2 through Scenario 6-2, each dealing with RNP-2 aircraft without radar surveillance. For Scenario 2-2 through Scenario 6-2, 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 18: Scenario 1-2 Key Results

Scenario	Track Width	TCV Probability
Scenario 1: A suitably equipped RNP-2 RNAV aircraft is flying a straight en route track segment with turns of no more than 15º without radar surveillance.	±2 NM	5.0 E-02
	±3 NM	5.2 E-03
	±4 NM	1.2 E-06
	±5 NM	4.3 E-08

Table 19: Scenario 2-2 Key Results

Two suitably equipped RNP-2 RNAV aircraft are flying in opposite directions on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
Along Track	**Track-to-Track**			
5 NM	4 NM	1.9 E-04	200	3.8 E-02
5 NM	6 NM	4.5 E-06	200	9.0 E-04
5 NM	8 NM	9.6 E-11	200	1.9 E-08
5 NM	10 NM	2.0 E-13	200	4.0 E-11
10 NM	4 NM	1.9 E-04	100	1.9 E-02
10 NM	6 NM	4.5 E-06	100	4.5 E-04
10 NM	8 NM	9.6 E-11	100	9.5 E-09
10 NM	10 NM	2.0 E-13	100	2.0 E-11
20 NM	4 NM	1.9 E-04	50	9.5 E-03
20 NM	6 NM	4.5 E-06	50	2.3 E-04
20 NM	8 NM	9.6 E-11	50	4.8 E-09
20 NM	10 NM	2.0 E-13	50	1.0 E-11

Table 20: Scenario 3-2 Key Results

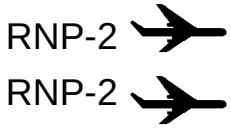
Two suitably equipped RNP-2 RNAV aircraft are flying in the same direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
Along Track	**Track-to-Track**			
5 NM	4 NM	1.9 E-04	20	3.8 E-03
5 NM	6 NM	4.5 E-06	20	9.0 E-05
5 NM	8 NM	9.6 E-11	20	1.9 E-09
5 NM	10 NM	2.0 E-13	20	4.0 E-12
10 NM	4 NM	1.9 E-04	10	1.9 E-03
10 NM	6 NM	4.5 E-06	10	4.5 E-05
10 NM	8 NM	9.6 E-11	10	9.5 E-10
10 NM	10 NM	2.0 E-13	10	2.0 E-12
20 NM	4 NM	1.9 E-04	5	9.5 E-04
20 NM	6 NM	4.5 E-06	5	2.3 E-05
20 NM	8 NM	9.6 E-11	5	4.8 E-10
20 NM	10 NM	2.0 E-13	5	1.0 E-12

Table 21: Scenario 4-2 Key Results

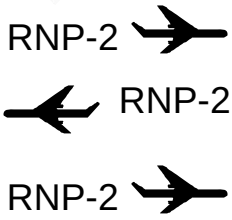
An inner RNP-2 aircraft is flying in the opposite direction between two other RNP-2 aircraft on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV Probability Per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
Along Track	**Track-to-Track**			
5 NM	4 NM	1.9 E-04	400	7.6 E-02
5 NM	6 NM	4.5 E-06	400	1.8 E-03
5 NM	8 NM	9.6 E-11	400	3.8 E-08
5 NM	10 NM	2.0 E-13	400	8.0 E-11
10 NM	4 NM	1.9 E-04	200	3.8 E-02
10 NM	6 NM	4.5 E-06	200	9.0 E-04
10 NM	8 NM	9.6 E-11	200	1.9 E-08
10 NM	10 NM	2.0 E-13	200	4.0 E-11
20 NM	4 NM	1.9 E-04	100	1.9 E-02
20 NM	6 NM	4.5 E-06	100	4.5 E-04
20 NM	8 NM	9.6 E-11	100	9.5 E-09
20 NM	10 NM	2.0 E-13	100	3.8 E-02

Table 22: Scenario 5-2 Key Results

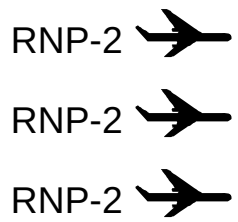
An inner RNP-2 aircraft is flying in the same direction between two other RNP-2 aircraft on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	1.9 E-04	400	7.6 E-02
5 NM	6 NM	4.5 E-06	400	1.8 E-03
5 NM	8 NM	9.6 E-11	400	3.8 E-08
5 NM	10 NM	2.0 E-13	400	8.0 E-11
10 NM	4 NM	1.9 E-04	200	3.8 E-02
10 NM	6 NM	4.5 E-06	200	9.0 E-04
10 NM	8 NM	9.6 E-11	200	1.9 E-08
10 NM	10 NM	2.0 E-13	200	4.0 E-11
20 NM	4 NM	1.9 E-04	100	1.9 E-02
20 NM	6 NM	4.5 E-06	100	4.5 E-04
20 NM	8 NM	9.6 E-11	100	9.5 E-09
20 NM	10 NM	2.0 E-13	100	2.0 E-11

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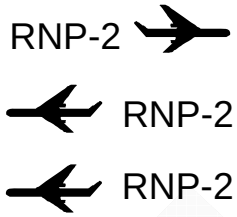
Table 23: Scenario 6-2 Key Results

An inner RNP-2 aircraft is flying between two other RNP-2 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 without radar surveillance.	

Separation		TCV Probability per Exposure	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
Along Track	Track-to-Track			
5 NM	4 NM	1.9 E-04	220	4.2 E-02
5 NM	6 NM	4.5 E-06	220	9.9 E-04
5 NM	8 NM	9.6 E-11	220	2.1 E-08
5 NM	10 NM	2.0 E-13	220	4.4 E-11
10 NM	4 NM	1.9 E-04	110	2.1 E-02
10 NM	6 NM	4.5 E-06	110	5.0 E-04
10 NM	8 NM	9.6 E-11	110	1.1 E-08
10 NM	10 NM	2.0 E-13	110	2.2E-11
20 NM	4 NM	1.9 E-04	55	1.1 E-02
20 NM	6 NM	4.5 E-06	55	2.5 E-04
20 NM	8 NM	9.6 E-11	55	5.3 E-09
20 NM	10 NM	2.0 E-13	55	1.1 E-11

Table 24 through Table 39 summarize the key results for Scenario 7 through Scenario 22, each dealing with both RNP-1 and RNP-2 aircraft without radar surveillance. For these scenarios, 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 24: 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 without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	4.70 E-05	200	9.4 E-03
5 NM	6 NM	1.10 E-09	200	2.2 E-07
5 NM	8 NM	8.00 E-13	200	1.6 E-10
10 NM	4 NM	4.70 E-05	100	4.7 E-03
10 NM	6 NM	1.10 E-09	100	1.1 E-07
10 NM	8 NM	8.00 E-13	100	8.0 E-11
20 NM	4 NM	4.70 E-05	50	2.4 E-03
20 NM	6 NM	1.10 E-09	50	5.5 E-08
20 NM	8 NM	8.00 E-13	50	4.0 E-11

Table 25: Scenario 8 Key Results

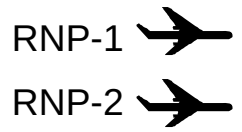
An RNP-1 aircraft is flying adjacent to an RNP-2 aircraft, in the same direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability Per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	4.70E-05	20	9.4E-04
5 NM	6 NM	1.10E-09	20	2.2E-08
5 NM	8 NM	8.00E-13	20	1.6E-11
10 NM	4 NM	4.70E-05	10	4.7E-04
10 NM	6 NM	1.10E-09	10	1.1E-08
10 NM	8 NM	8.00E-13	10	8.0E-12
20 NM	4 NM	4.70E-05	5	2.4E-04
20 NM	6 NM	1.10E-09	5	5.5E-09
20 NM	8 NM	8.00E-13	5	4.0E-12

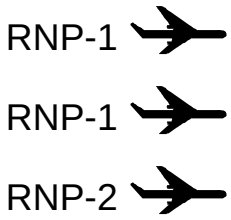
Table 26: Scenario 9 Key Results

An RNP-2 aircraft is flying between two RNP-1 aircraft, in the same direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.			RNP-1 RNP-2 RNP-1	
Separation		**TCV Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
Along Track	**Track-to-Track**			
5 NM	4 NM	4.70 E-05	40	1.9 E-03
5 NM	6 NM	1.10 E-09	40	4.4 E-08
5 NM	8 NM	8.00 E-13	40	3.2 E-11
10 NM	4 NM	4.70 E-05	20	9.5 E-04
10 NM	6 NM	1.10 E-09	20	2.2 E-08
10 NM	8 NM	8.00 E-13	20	1.6 E-11
20 NM	4 NM	4.70 E-05	10	4.8 E-04
20 NM	6 NM	1.10 E-09	10	1.1 E-08
20 NM	8 NM	8.00 E-13	10	8.0 E-12

Table 27: Scenario 10 Key Results

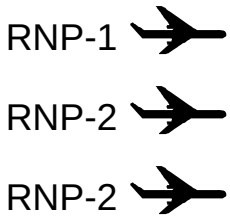
An RNP-1 aircraft is flying between two RNP-2 aircraft, in the same direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.			RNP-2 RNP-1 RNP-2	
Separation		**TCV Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
Along Track	**Track-to-Track**			
5 NM	4 NM	4.70 E-05	40	1.9 E-03
5 NM	6 NM	1.10 E-09	40	4.4 E-08
5 NM	8 NM	8.00 E-13	40	3.2 E-11
10 NM	4 NM	4.70 E-05	20	9.5 E-04
10 NM	6 NM	1.10 E-09	20	2.2 E-08
10 NM	8 NM	8.00 E-13	20	1.6 E-11
20 NM	4 NM	4.70 E-05	10	4.8 E-04
20 NM	6 NM	1.10 E-09	10	1.1 E-08
20 NM	8 NM	8.00 E-13	10	8.0 E-12

Table 28: 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 without radar surveillance.					
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**
Along Track	**Track-to-Track**				
5 NM	4 NM	1.2 E-08	4.70 E-05	20/20	9.4 E-04
5 NM	6 NM	5.8 E-13	1.10 E-09	20/20	2.2 E-08
5 NM	8 NM	2.8 E-17	8.00 E-13	20/20	1.6 E-11
5 NM	6/8 NM*	5.8 E-13	8.00 E-13	20/20	2.8 E-11
10 NM	4 NM	1.2 E-08	4.70 E-05	10/10	4.7 E-04
10 NM	6 NM	5.8 E-13	1.10 E-09	10/10	1.1 E-08
10 NM	8 NM	2.8 E-17	8.00 E-13	10/10	8.0 E-12
10 NM	6/8 NM*	5.8 E-13	8.00 E-13	10/10	1.4 E-11
20 NM	4 NM	1.2 E-08	4.70 E-05	5/5	2.4 E-04
20 NM	6 NM	5.8 E-13	1.10 E-09	5/5	5.5 E-09
20 NM	8 NM	2.8 E-17	8.00 E-13	5/5	4.0 E-12
20 NM	6/8 NM*	5.8 E-13	8.00 E-13	5/5	7.0 E-12

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

Table 29: 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 without radar surveillance.					
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**
Along Track	**Track-to-Track**				
5 NM	4 NM	4.70 E-05	1.90 E-04	20/20	4.7 E-03
5 NM	6 NM	1.10 E-09	4.50 E-06	20/20	9.0 E-05
5 NM	8 NM	8.00 E-13	9.60 E-11	20/20	1.9 E-09
5 NM	8/10 NM*	8.00 E-13	2.00 E-13	20/20	2.0 E-11
10 NM	4 NM	4.70 E-05	1.90 E-04	10/10	2.4 E-03
10 NM	6 NM	1.10 E-09	4.50 E-06	10/10	4.5 E-05
10 NM	8 NM	8.00 E-13	9.60 E-11	10/10	9.5 E-10
10 NM	8/10 NM*	8.00 E-13	2.00 E-13	10/10	1.0 E-11
20 NM	4 NM	4.70 E-05	1.90 E-04	5/5	1.2 E-03
20 NM	6 NM	1.10 E-09	4.50 E-06	5/5	2.3 E-05
20 NM	8 NM	8.00 E-13	9.60 E-11	5/5	4.8 E-10
20 NM	8/10 NM*	8.00 E-13	2.00 E-13	5/5	5.0 E-12

*****8/10 NM means 8 NM RNP-1/RNP-2 separation and 10 NM RNP-2/RNP-2 separation

Table 30: Scenario 13 Key Results

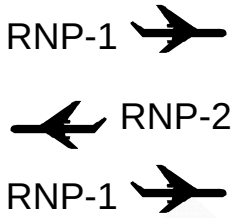
An RNP-2 aircraft is flying between two RNP-1 aircraft and in the opposite direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
Along Track	**Track-to-Track**			
5 NM	4 NM	4.7 E-05	400	1.9 E-02
5 NM	6 NM	1.1 E-09	400	4.4 E-07
5 NM	8 NM	8.0 E-13	400	3.2 E-10
10 NM	4 NM	4.70 E-05	200	9.5 E-03
10 NM	6 NM	1.10 E-09	200	2.2 E-07
10 NM	8 NM	8.00 E-13	200	1.6 E-10
20 NM	4 NM	4.70 E-05	100	4.8 E-03
20 NM	6 NM	1.10 E-09	100	1.1 E-07
20 NM	8 NM	8.00 E-13	100	8.0 E-11

Table 31: Scenario 14 Key Results

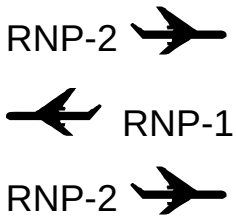
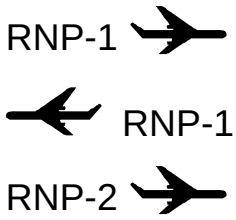
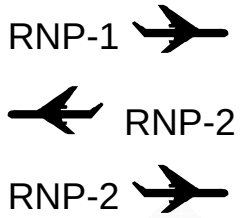
An RNP-1 aircraft is flying between two RNP-2 aircraft and in the opposite direction on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
Along Track	**Track-to-Track**			
5 NM	4 NM	4.7 E-05	400	1.9 E-02
5 NM	6 NM	1.1 E-09	400	4.4 E-07
5 NM	8 NM	8.0 E-13	400	3.2 E-10
10 NM	4 NM	4.70 E-05	200	9.5 E-03
10 NM	6 NM	1.10 E-09	200	2.2 E-07
10 NM	8 NM	8.00 E-13	200	1.6 E-10
20 NM	4 NM	4.70 E-05	100	4.8 E-03
20 NM	6 NM	1.10 E-09	100	1.1 E-07
20 NM	8 NM	8.00 E-13	100	8.0 E-11

Table 32: 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 without radar surveillance.					
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**
Along Track	**Track-to-Track**				
5 NM	4 NM	1.20 E-08	4.70 E-05	200/200	9.4 E-03
5 NM	6 NM	5.80 E-13	1.10 E-09	200/200	2.2 E-07
5 NM	8 NM	2.80 E-17	8.00 E-13	200/200	1.6 E-10
5 NM	6/8 NM*	5.80 E-13	8.00 E-13	200/200	2.8 E-10
10 NM	4 NM	4.70 E-05	1.90 E-04	100/100	4.7 E-03
10 NM	6 NM	1.10 E-09	4.50 E-06	100/100	1.1 E-07
10 NM	8 NM	8.00 E-13	9.60 E-11	100/100	8.0 E-11
10 NM	6/8 NM*	8.00 E-13	2.00 E-13	100/100	1.4 E-10
20 NM	4 NM	4.70 E-05	1.90 E-04	50/50	2.4 E-03
20 NM	6 NM	1.10 E-09	4.50 E-06	50/50	5.5 E-08
20 NM	8 NM	8.00 E-13	9.60 E-11	50/50	4.0 E-11
20 NM	6/8 NM*	8.00 E-13	2.00 E-13	50/50	7.0 E-11

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

Table 33: 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 without radar surveillance.					
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**
Along Track	**Track-to-Track**				
5 NM	4 NM	4.7 E-05	1.9 E-04	200/200	4.7 E-02
5 NM	6 NM	1.1 E-09	4.5 E-06	200/200	9.0 E-04
5 NM	8 NM	8.0 E-13	9.6 E-11	200/200	1.9 E-08
5 NM	8/10 NM*	8.0 E-13	2.0 E-13	200/200	2.0 E-10
10 NM	4 NM	4.70 E-05	1.90 E-04	100/100	2.4 E-02
10 NM	6 NM	1.10 E-09	4.50 E-06	100/100	4.5 E-04
10 NM	8 NM	8.00 E-13	9.60 E-11	100/100	9.5 E-09
10 NM	8/10 NM*	8.00 E-13	2.00 E-13	100/100	1.0 E-10
20 NM	4 NM	4.70 E-05	1.90 E-04	50/50	1.2 E-02
20 NM	6 NM	1.10 E-09	4.50 E-06	50/50	2.3 E-04
20 NM	8 NM	8.00 E-13	9.60 E-11	50/50	4.8 E-09
20 NM	8/10 NM*	8.00 E-13	2.00 E-13	50/50	5.0 E-11

*8/10 NM means 8 NM RNP-1/RNP-2 separation and 10 NM RNP-2/RNP-2 separation

Table 34: Scenario 17 Key Results

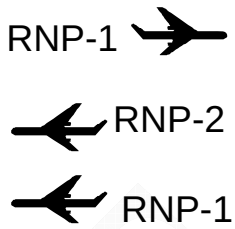
An RNP-2 aircraft is flying between two RNP-1 aircraft, in the same direction as one and in the opposite direction from the other on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	4.7 E-05	220	1.0 E-02
5 NM	6 NM	1.1 E-09	220	2.4 E-07
5 NM	8 NM	8.0 E-13	220	1.8 E-10
10 NM	4 NM	4.70 E-05	110	5.0 E-03
10 NM	6 NM	1.10 E-09	110	1.2 E-07
10 NM	8 NM	8.00 E-13	110	9.0 E-11
20 NM	4 NM	4.70 E-05	55	2.5 E-03
20 NM	6 NM	1.10 E-09	55	6.0 E-08
20 NM	8 NM	8.00 E-13	55	4.5 E-11

Table 35: Scenario 18 Key Results

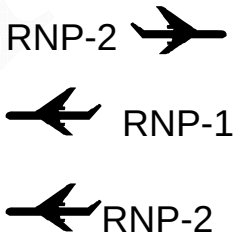
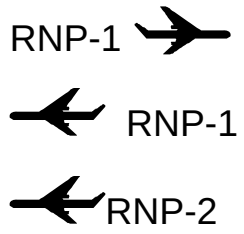
An RNP-1 aircraft is flying between two RNP-2 aircraft, in the same direction as one and in the opposite direction from the other on parallel straight en route track segments with turns of no more than 15º without radar surveillance.				
Separation		**TCV**		
Along Track	**Track-to-Track**	**Probability per Exposure**	**Estimated Number of Exposures per Hour**	**Estimated Hourly Collision Rate**
5 NM	4 NM	4.7 E-05	220	1.0 E-02
5 NM	6 NM	1.1 E-09	220	2.4 E-07
5 NM	8 NM	8.0 E-13	220	1.8 E-10
10 NM	4 NM	4.70 E-05	110	5.0 E-03
10 NM	6 NM	1.10 E-09	110	1.2 E-07
10 NM	8 NM	8.00 E-13	110	9.0 E-11
20 NM	4 NM	4.70 E-05	55	2.5 E-03
20 NM	6 NM	1.10 E-09	55	6.0 E-08
20 NM	8 NM	8.00 E-13	55	4.5 E-11

Table 36: Scenario 19 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-2 aircraft and in the opposite direction from the RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15º without radar surveillance.



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
Along Track	Track-to-Track				
5 NM	4 NM	1.2 E-08	4.70 E-05	200/20	9.4 E-04
5 NM	6 NM	5.8 E-13	1.10 E-09	200/20	2.2 E-08
5 NM	8 NM	2.8 E-17	8.00 E-13	200/20	1.6 E-11
10 NM	4 NM	1.2 E-08	4.70 E-05	100/10	4.7 E-04
10 NM	6 NM	5.8 E-13	1.10 E-09	100/10	1.1 E-08
10 NM	8 NM	2.8 E-17	8.00 E-13	100/10	8.0 E-12
20 NM	4 NM	1.2 E-08	4.70 E-05	50/5	2.4 E-04
20 NM	6 NM	5.8 E-13	1.10 E-09	50/5	5.5 E-09
20 NM	8 NM	2.8 E-17	8.00 E-13	50/5	4.0 E-12

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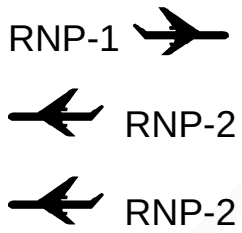
Table 37: Scenario 20 Key Results

An RNP-2 aircraft is flying between another RNP-2 aircraft and an RNP-1 aircraft, in the same direction as the RNP-2 aircraft and in the opposite direction from the RNP-1 aircraft on parallel straight en route track segments with turns of no more than 15º without radar surveillance.

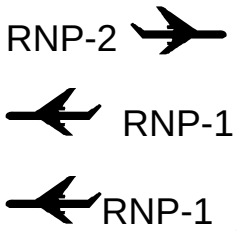


Separation		TCV Probability per Exposure RNP-1 to RNP-1	TCV Probability per Exposure RNP-1 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
Along Track	Track-to-Track				
5 NM	4 NM	4.70 E-05	1.90 E-04	200/20	1.3 E-02
5 NM	6 NM	1.10 E-09	4.50 E-06	200/20	9.0 E-05
5 NM	8 NM	8.00 E-13	9.60 E-11	200/20	2.1 E-09
5 NM	8/10 NM*	8.00 E-13	2.00 E-13	200/20	1.6 E-10
10 NM	4 NM	4.70 E-05	1.90 E-04	100/10	6.5 E-03
10 NM	6 NM	1.10 E-09	4.50 E-06	100/10	4.5 E-05
10 NM	8 NM	8.00 E-13	9.60 E-11	100/10	1.1 E-09
10 NM	8/10 NM*	8.00 E-13	2.00 E-13	100/10	8.0 E-11
20 NM	4 NM	4.70 E-05	1.90 E-04	50/5	3.3 E-03
20 NM	6 NM	1.10 E-09	4.50 E-06	50/5	2.3 E-05
20 NM	8 NM	8.00 E-13	9.60 E-11	50/5	5.3 E-10
20 NM	8/10 NM*	8.00 E-13	2.00 E-13	50/5	4.0 E-11

*8/10 NM means 8 NM RNP-1/RNP-2 separation and 10 NM RNP-2/RNP-2 separation

Table 38: 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 without radar surveillance.

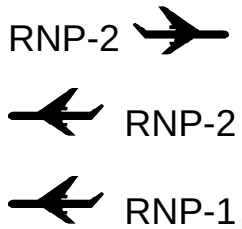


Separation		TCV Probability per Exposure RNP-1 to RNP-1	TCV Probability per Exposure RNP-1 to RNP-2	Estimated Number of Exposures per Hour	Estimated Hourly Collision Rate
Along Track	Track-to-Track				
5 NM	4 NM	4.7 E-05	1.20 E-08	200/20	9.4 E-03
5 NM	6 NM	1.1 E-09	5.80 E-13	200/20	2.2 E-07
5 NM	8 NM	8.0 E-13	2.80 E-17	200/20	1.6 E-10
5 NM	8/6 NM*	8.0 E-13	5.80 E-13	200/20	1.7 E-10
10 NM	4 NM	4.70 E-05	1.90 E-04	100/10	4.7 E-03
10 NM	6 NM	1.10 E-09	4.50 E-06	100/10	1.1 E-07
10 NM	8 NM	8.00 E-13	9.60 E-11	100/10	8.0 E-11
10 NM	8/6 NM*	8.00 E-13	2.00 E-13	100/10	8.5 E-11
20 NM	4 NM	4.70 E-05	1.90 E-04	50/5	2.4 E-03
20 NM	6 NM	1.10 E-09	4.50 E-06	50/5	5.5 E-08
20 NM	8 NM	8.00 E-13	9.60 E-11	50/5	4.0 E-11
20 NM	8/6 NM*	8.00 E-13	2.00 E-13	50/5	4.3 E-11

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

Table 39: 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 without radar surveillance.



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
Along Track	**Track-to-Track**				
5 NM	4 NM	1.90 E-04	4.70 E-05	200/20	3.9 E-02
5 NM	6 NM	4.50 E-06	1.10 E-09	200/20	9.0 E-04
5 NM	8 NM	9.60 E-11	8.00 E-13	200/20	1.9 E-08
5 NM	10/8 NM*	2.00 E-13	8.00 E-13	200/20	5.6 E-11
10 NM	4 NM	4.70 E-05	1.90 E-04	100/10	2.0 E-02
10 NM	6 NM	1.10 E-09	4.50 E-06	100/10	4.5 E-04
10 NM	8 NM	8.00 E-13	9.60 E-11	100/10	9.5 E-09
10 NM	10/8 NM*	8.00 E-13	2.00 E-13	100/10	2.8 E-11
20 NM	4 NM	4.70 E-05	1.90 E-04	50/5	9.8 E-03
20 NM	6 NM	1.10 E-09	4.50 E-06	50/5	2.3 E-04
20 NM	8 NM	8.00 E-13	9.60 E-11	50/5	4.8 E-09
20 NM	10/8 NM*	8.00 E-13	2.00 E-13	50/5	1.4 E-11

*10/8 NM means 10 NM RNP-2/RNP-2 separation and 8 NM RNP-2/RNP-1 separation

4.1 Scenario Risk Evaluation and Conclusions

For Scenario 2-1 through Scenario 6-1, Scenario 2-2 through Scenario 6-2, and Scenario 7 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 for 5 NM longitudinal separation were:

1. For RNP-1 aircraft (Scenario 2-1 through Scenario 6-1)

    - For all scenarios at 4 NM separation* the acceptable level of risk was exceeded.
    - For all scenarios at 6 NM separation the acceptable level of risk was met.
    - For all scenarios at 8 NM separation the acceptable level of risk was met.

    *Track-to-track

2. For RNP-2 aircraft (Scenario 2-2 through Scenario 6-2)

    - For all scenarios at 4 NM separation the acceptable level of risk was exceeded.
    - For all scenarios at 6 NM separation the acceptable level of risk was exceeded.
    - For all scenarios at 8 NM separation the acceptable level of risk (the more stringent level of 1.0 E-09) was exceeded.
    - For all scenarios at 10 NM separation the target level of safety was met.

3. For combinations of RNP-1 and RNP-2 aircraft (Scenario 7 through Scenario 22)

    - For all scenarios at 4 NM separation the acceptable level of risk was exceeded.
    - For all scenarios at 6 NM separation the acceptable level of risk was exceeded.
    - For all scenarios at 8 NM separation the acceptable level of risk was met except for scenarios in which two RNP-2 aircraft are flying adjacent to one another.
    - For scenarios in which two RNP-2 aircraft were adjacent, increasing the 8 NM separation to 10 for the RNP-2 pair only decreased the level risk to a point where the acceptable level of risk was met.

4. For scenarios in which the acceptable level of risk was not met (e.g., two RNP-2 aircraft with 5 NM longitudinal separation and 8 NM track-to-track separation) it would have been possible to reduce the level of risk to an acceptable level by increasing the longitudinal separation. Since the longitudinal spacing was assumed to be the worst case of an aircraft every 5 NM, increasing the spacing to one every 10 NM would have decreased the level of risk to one-half the previous risk level. In general increasing the spacing by a factor of *n* would have decreased the risk by a factor to 1/*n* times the previous level.

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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

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Appendix B: Statistical Distributions Used in the Study

The Johnson S_B Distribution PDF

$$f_B(x) = \frac{\eta\lambda}{\sqrt{2\pi}} \frac{1}{(x-\varepsilon)(-x+\varepsilon+\lambda)} \exp\left[-\frac{1}{2}\left(\eta^2 \ln\left\{\left(\frac{x-\varepsilon}{-x+\varepsilon+\lambda}\right)^2\right\}\right)\right] \qquad \text{(A1)}$$

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

$$f_D(x) = \frac{1}{2\delta} \exp\left[-\frac{|x|}{\delta}\right] \qquad \text{(A2)}$$

The Mixed Johnson S_B and Double Exponential Distribution PDF

$$f(x) = \left\{ \begin{array}{l} \dfrac{\alpha e^{-Abs[x/\delta]}}{2\delta} + \dfrac{(1-\alpha)\eta\lambda e^{-0.5\eta^2 Log^2[\frac{x-\varepsilon}{\varepsilon+\lambda-x}]}}{\sqrt{2\pi}(x-\varepsilon)(\varepsilon+\lambda-x)}, x < \varepsilon+\lambda, x > \varepsilon \\ \dfrac{\alpha e^{-Abs[x/\delta]}}{2\delta}, x \le \varepsilon ... or ... x \ge \varepsilon+\lambda \end{array} \right\} \qquad \text{(A3)}$$

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

$$f(u) = \int_{-\infty}^{\infty} f_1(y_1) f_2(u - y_1) dy_1 \qquad \text{(A4)}$$

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,

$$P(\,|\,y_2 - y_1| < W\,) = \int_{-W}^{W} f(x)dx\,. \tag{A5}$$

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

$$P(|y_2 - y_1| < W\,) = \int_{-W}^{W}\int_{-\infty}^{\infty} f_1(y_1) f_2(x - y_1)dy_1 dx \tag{A6}$$

where f_1 and f_2 are defined in (1).

Substituting the definitions of f_1 and f_2, and letting[13] ε = 0 in f_1 and ε = S in f_2, Equation (4) becomes

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

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

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

References

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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"

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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.

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7 May 2001, Geert Moek, National Aerospace Laboratory NLR, Edward Lutz, ARINC Incorporated, William Mosberg, ARINC Incorporated.

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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.

[8] "Analysis of Area Navigation (RNAV/RNP-1) En Route Separation along Adjacent Straight Segments with Radar Surveillance including Impromptu Routes (Phase III)"

AFS-400 Safety Study
DOT-FAA-AFS-450-50

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