Performance-based Navigation (PBN):

Enhanced Route Spacing Guidance

CAP 1385

Published by the Civil Aviation Authority, 2022

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First edition published April 2016
Second edition published December 2022

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The latest version of this document is available in electronic format at: www.caa.co.uk/CAP1385

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Executive Summary

One of the key supporting enablers for the UK Airspace Modernisation Strategy (AMS)[1] is the re-design of UK terminal airspace[2] and the wider introduction of ICAO's concept of Performance-based Navigation (PBN). An essential component supporting PBN is the definition of route spacing between proximate departure and/or arrival routes. The application of PBN requires a commitment from aircraft operators to enhance their fleet capability (where necessary) to reflect the navigation performance capability being asked of them within the operational requirements and strategic objectives for the airspace. This depends on the navigation specified being notified and the nature of the operation (RNAV or RNP). What is clear is that PBN can only deliver benefits including safety and capacity, if new routes are introduced which are predicated on a systemisation of the air traffic service through the strategic de-confliction of published routes so as to reduce the need for tactical ATC intervention. This is the commitment being asked of the Air Navigation Service Provider (ANSPs).

With the introduction of PBN and a systemised airspace comes both benefits and disbenefits derived from the accuracy of navigation and predictable and repeatable tracks flown by modern aircraft types. The benefits include the adherence to defined paths enabling a reduction in the required volume of airspace for containment of routes and procedures. These attributes also enable consideration for reduced departure divergence from both single and parallel runway configurations, which in themselves can support increased runway throughput from split departures. PBN also brings concentration of aircraft tracks over the ground and with it, an environmental impact. However, reduced departure divergence can facilitate an increased number of departure options providing environmental mitigation through alternation techniques, see CAP 1378[3].

From an airspace perspective, the adoption of PBN offers techniques to the designer supporting optimum routings including prescribed tracks from the departure end of the runway and linking systemised arrival routes to the final approach segment of an instrument approach procedure.

Edition 1 of CAP 1385 published in April of 2016, provided guidance on the concept of PBN Enhanced route spacing as derived from research work conducted by NATS (NERL). Subsequent trials and research work has yielded further data supporting not only a wider application of PBN route spacing, but also concepts for inclusion in

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[1] Airspace Modernisation Strategy (CAP1711) published in December 2018.

[2] Terminal airspace comprises departure routes (Standard Instrument Departures – SIDs) and arrival routes (Standard Arrivals – STARS, and runway/approach transitions).

[3] Airspace Design Guidance: Noise Mitigation Considerations when Designing PBN Departure and Arrival Procedures (CAP 1378).

future airspace designs. The Second Edition of CAP 1385 captures all of the relevant trials and research work conducted to date, providing a comprehensive compendium of guidance enabling the optimum application of PBN in UK airspace and supporting the strategy for airspace modernisation.

Chapter 1

PBN: Enhanced Route Spacing

Introduction

Early, generic ICAO and EUROCONTROL studies indicated minimum spacing of 7 NM between routes and although UK ANSPs and airspace designers are able to design to less than this value, the assurance method (based on developing a Route Design Analysis Report (RDAR)) was manual and labour intensive.

The traditional method of establishing route spacing has been through Collision Risk Modelling (CRM) supplemented by hazard identification and safety assessments, ideally using representative data sets that have been ‘cleaned’ to remove ATC radar vectoring. Following a review of the previous work, it was concluded that the use of CRM to determine safe PBN route spacing in a complex modern radar environment, or any future equivalent ATC monitored, and controlled environment was both inappropriate and inefficient and that an alternative method was required.

In August 2013 NATS (En Route) plc (NERL) approached the UK Civil Aviation Authority (CAA) with proposals for an alternative approach based on the frequency of potential losses of separation requiring controller intervention.

The proposal centred around developing a Loss of Separation Risk Model (LSRM) which assesses the safe spacing between PBN routes in a tactically controlled airspace environment based on the predicted number of losses of separation.

Operational data trials were conducted by NATS at London Heathrow and Gatwick Airports between December 2013 and January 2015 as Phase 1 of the Departure Enhancement Project (DEP). The method was then applied to data collected from existing RNAV 1 routes and specially designed operational trials and used to establish the predicated frequency of loss of separation associated with specific route spacing for different types of route designs and interactions.

DEP Phase 1 was followed in October 2015 by a more general PBN Research Project (Phase 2) in which further operational data trials were conducted investigating time versus distance holding and expanding the LSRM envelope to include High-Level and High-Speed applications. Phase 2 also encompassed a comprehensive flight simulation programme, involving twelve carriers and eleven aircraft types, with each type simulating up to 192 different procedures. These procedures included weather resilience of SIDs, Tactical Parallel Offset (TPO) capability and Radius to Fix (RF) path containment. The RF scenarios also investigated Instrument Flight Procedure design for closed loop PBN to ILS transitions, in order to better understand the effect of different minimum lengths between ILS establish point and the Final Approach Fix (FAF) with a 90° ILS intercept.

Separate from the NATS PBN Research, in May 2013 London Stansted Airport commenced an operational trial, applying the use of Radius to Fix (RF) paths used in conjunction with the RNP 1 navigation specification. Originally, with the intention of providing greater track adherence and thus avoid overflight of local communities, the operational trial yielded valuable data, separate from the NATS PBN Research, in which to expand the application of LSRM.

Throughout all of the above work, Det Norske Veritas (DNV) was commissioned by the CAA to support the independent review of the LSRM method and the analysis for each of the route interactions and conduct their own analysis on the RF data, which in turn was validated by NATS. Their reports have led the CAA to conclude that subject to the conditions applied, the method is sufficiently robust and is suitable for application in future PBN route developments in UK airspace and that separations between routes of less than 5 NM should be achievable in a region with a radar minimum of 3 NM, even with a number of conservative assumptions regarding traffic levels and route geometries.

Commencing in June 2017, PBN Research Phase 3 built on DEP (Phase 1) and PBN Research Phase 2 by further researching real world aircraft performance in both lateral (LNAV) and vertical (VNAV) navigation. Again, flight simulator based, the project investigated aspects of airspace design including four-waypoint holding, wrap around departures and the sensitivity of fly-ability from placement of the first turn from the Departure End of the Runway (DER) using both fly-over and RF turns. Climb and descent performance and behaviour were also investigated, and Final Reports were published by NATS in November 2019. None of the Phase 3 work is related to LSRM, although clearly, lateral and vertical path fly-ability have a bearing on the proximate spacing of routes and the work has been successful in forging closer working links between NATS, the Lead Operators, navigation data providers, FMS and aircraft Original Equipment Manufacturers (OEMs).

Note: Phase 1 of the Departure Enhancement Programme (DEP) was funded as part of the NATS' Long Term Investment Plan (LTIP) and supplemented by additional SESAR Research and development funding. PBN Research Phase 2 and Phase 3 work was funded by the Future Airspace Strategy (FAS) NERL Fund.

The application of LSRM is a foundation piece for airspace change sponsors, and whilst in the guidance in this chapter presents Minimum Acceptable Route Spacing Values for given route interactions, they cannot be applied literally. As an example, the guidance also details the attendant safety arguments that will have to be demonstrated in order to support a given airspace design concept.

The main difference between the LSRM and the traditional CRM approach is that the lateral track-keeping error distributions are used to estimate (for a particular traffic scenario) the number of losses of separation that would occur when aircraft are operating within their nominal navigation performance, rather than a lateral overlap probability i.e., risk of collision, for a pair of aircraft.

For any given lateral error distribution, the probability of a loss of radar separation is considerably greater than the probability of lateral overlap between a pair of aircraft and less dependent on the probability of very large errors.

The probability of a lateral deviation can be used together with data on the frequency of traffic on the routes and other kinematic factors such as average aircraft speeds and length of route in proximity to estimate the frequency of losses of separation for different route interactions.

The predicated loss of separation frequency forms a part of the overall safety argument which also includes other causes of deviations that could lead to a loss of separation. The loss of separation frequency supports the contributing safety argument generated using the ANSP's Safety Management System (SMS), as to why the proposed route spacing is tolerably safe.

While the route spacing guidance within this document represents an appropriate baseline upon which to build future airspace designs, subject to appropriate safety criteria being met and agreement with the CAA, there is nothing to stop an individual ANSP or other sponsor working to other, bespoke criteria following appropriate analysis.

EUROCONTROL Enhanced Route Spacing - Task Force (ERS-TF)

Separate from the work of the NATS Departure Enhancement Project, in June 2014, EUROCONTROL established an Enhanced Route Spacing Task Force (ERS-TF) under the auspices of EUROCONTROL's Network Operations Team (NETOPS) to look at the spacing of proximate flight procedures, focusing specifically on terminal and extended terminal areas in European Radar surveillance environments. A number of ANSPs (including NATS) supplied EUROCONTROL with radar data from which CRM analysis was performed to establish sample spacing distances. The results can be found in the EUROCONTROL publication titled, European PBN Route Spacing Handbook[4].

Of significant interest from the analysis was the suggestion that navigation performance is not the prevalent factor in route spacing determination today. Indeed, the analysis suggested that there are other limiting factors in drawing routes closer together. These include the radar separation minima of respectively 3 NM and 5 NM in terminal and en route operations as well as human factors such as the controller's screen resolution and ATC sector size. The examples shown in the handbook also

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[4] EUROCONTROL PBN Handbook No. 3: European PBN Route Spacing Handbook. EUROCONTROL PBN Portal ePBN - home (pbnportal.eu) .

indicate that aspects such as route configuration, procedure complexity and fly-ability have an important effect on achievable route spacing minima.

It should be noted that whilst the European PBN Route Spacing Handbook shows *sample* route spacings, the authors emphasise that these *sample* spacings are linked to particular spacing methodologies using particular traffic samples. As such, their inclusion in in the handbook does not mean that these sample distances are ready-made for implementation. An implementation safety case would need to determine the relevance of the handbook's example to the intended terminal area of application. Furthermore, post implementation lateral navigation performance monitoring would need to confirm the achieved navigation performance.

Irrespective of whichever PBN enhanced route spacing method is applied, the CAA strongly recommends that prior to applying either this guidance material or the sample PBN route spacings derived by EUROCONTROL, the airspace design sponsor contacts the Authority to discuss their proposal.

Purpose and Scope

This guidance document presents route spacing values, for which the predicated loss of separation frequency is 1 loss per 100,000 hours (10^{-5}) of operation, in support of the application of RNAV 1 Performance-based Navigation (PBN) routes in terminal airspace designs for which a minimum radar separation standard of 3 NM is applied. The values are based on nominal aircraft navigation performance and do not take account of other factors as outlined below.

In the First Edition of CAP 1385, the guidance was presented as a number of scenarios applying different straight and turning segments within typical airspace design route interactions. With the expansion of operational data from the High-Level, High-Speed (HLHS) trial, a more generic table has been created, providing a more comprehensive summary of the respective route spacing values relative to a Minimum Radar Separation (MRS) standard. The application of the Radius to Fix (RF) curved path transition, based on both the NATS PBN Research and the London Stansted Airport trial, is addressed separately. The descriptions of the route interactions covered in this guidance document have been retained and can be found in Appendix B.

The Safety Argument

In setting the proximate spacing of routes in a radar monitored terminal airspace environment, there are a number of safety arguments that have to be satisfied. At the top level, the ANSP safety case has to demonstrate that PBN routes are tolerably safe – see acceptability criterion. Thereafter, a number of arguments can be made for:

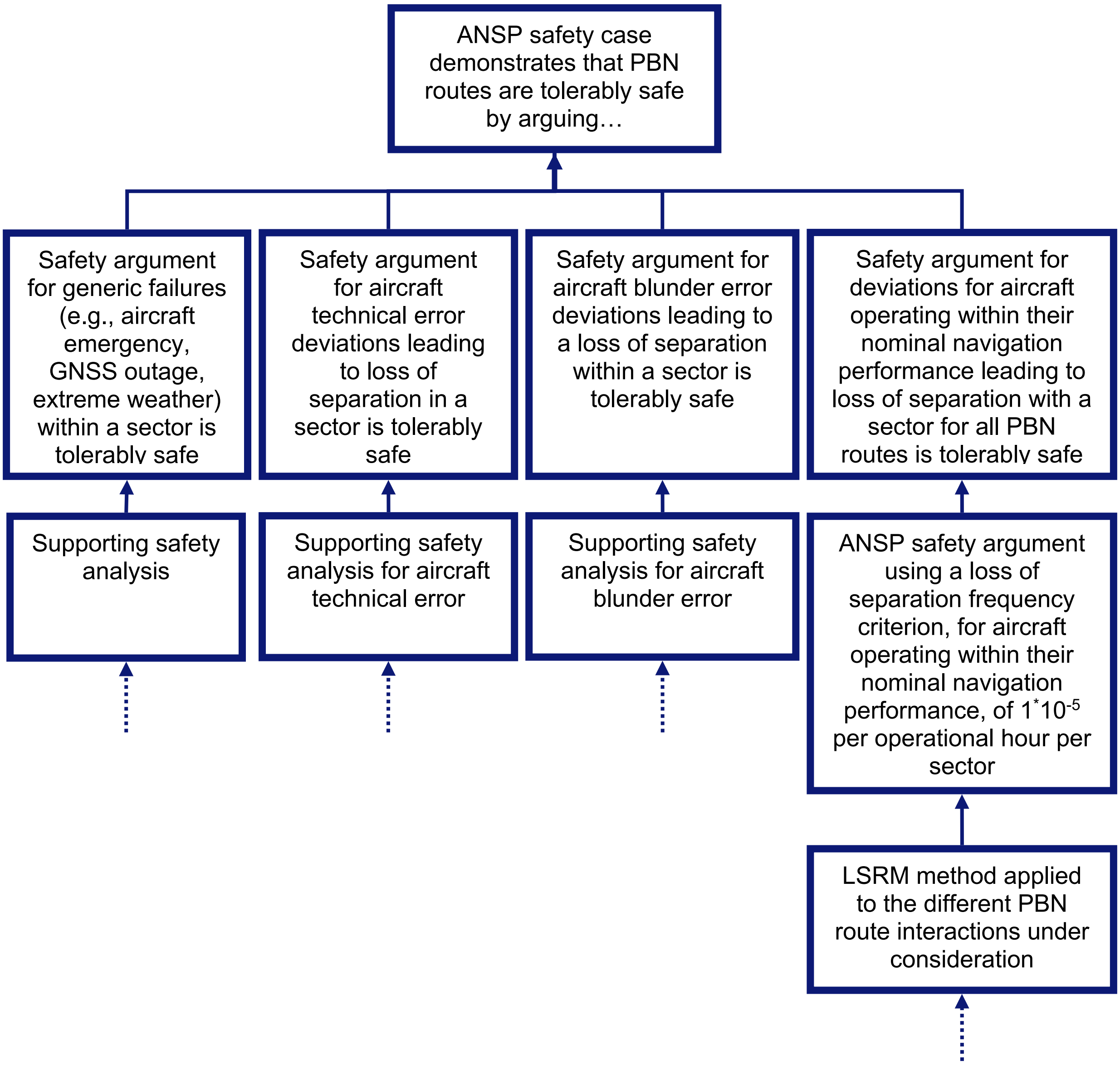
- Operational or ‘blunder’ errors, e.g., flight crew following an instruction intended for a different aircraft or flying of the incorrect procedure.
- Generic failures leading to intentional deviations, e.g., flight crew avoiding weather without informing ATC, aircraft emergencies, loss of GNSS coverage.
- Technical errors, e.g., navigation system failure.
- Deviations for aircraft operating within their nominal navigation performance.

All of these terms can potentially lead to a Loss of Separation requiring ATC intervention in order to maintain safety. It is the nominal aircraft navigation performance for which a frequency of Loss of Separation has been established and for which the Loss of Separation Risk Model (LSRM) method is applied. The remaining safety arguments are satisfied by complementary studies to determine whether the route spacing values are acceptably safe with respect to these causes of lateral deviations.

Note: These causes already exist in conventional operations and the safety arguments needed are no different to the safety assurance applied for any new airspace design in terms of addressing the risks arising from them.

Figure 1 depicts the role of LSRM in meeting the safety argument for nominal navigation performance and the overall safety case.

Figure 1: High-Level Safety Argument and the Role of LSRM



The Operating Environment

The Loss of Separation Risk Model (LSRM) method has been developed from and is applicable to a specific set of service constraints as defined by the operating environment found in UK terminal airspace. These service constraints include:

- A tactical radar monitored environment.
- The controller retaining capacity to monitor all traffic within their sector and have appropriate means of tactical intervention.

- The speed of aircraft established on a PBN route is determined either by published speed constraints on the instrument flight procedure, the airspace itself e.g., airspace below FL100 or by the controller.

PBN Operational Authorisation

The PBN route can itself be considered as a constraint. Aircraft are deemed to be compliant with the published PBN specification as indicated through the airworthiness approval and it is assumed that an operator filing a flight plan for a particular PBN specification has the requisite operational authorisation as required by the State of the Operator or State of Registry. This implies that the flight crew are trained and operate the aircraft using Standard Operating Procedures (SOPs) in accordance with maintaining the required navigation performance. At this point the ANSP can assume that all aircraft filing for a particular PBN route are interoperable on that route in terms of navigation accuracy, integrity, continuity and the functionality required by the respective PBN specification. In order to achieve the required navigation performance, the aircraft is assumed to be operating in a Flight Guidance System mode with ‘LNAV’ engaged and Flight Technical Error (FTE) managed through either Autopilot and/or Flight Director being coupled[5].

Infrastructure

In accordance with PBN principles, all aspects of the Instrument Flight Procedure (IFP) design shall be deployed within coverage of ground-based or space-based navigation aids e.g., DME/DME/IRU or GNSS so as to provide navigation positioning consistent with the promulgated PBN specification.

Airspace Design Considerations

NATS analysis of the data collected from trials and operational data has enabled the characterisation of route design elements as described within the scenarios contained in Appendix B. The scenarios may be considered as independent ‘building blocks’ which when assembled describe a route structure. It is important that the route design elements are not assembled in such a way so as to adversely impact fly-ability and consequently, the desired navigation performance.

Within these route design elements all turns are predicated on fly-by turns, with speed restrictions applied to sharp turns and wrap-around turns. Where a scenario involves one or more turns, it is defined in terms of the earliest the turn will commence and the latest the turn will be completed (including the turn recovery), before an aircraft can be considered to be established on a straight-line segment. The route spacing values are directly linked to these characterisations allowing each

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[5] Less sophisticated aircraft e.g., General Aviation types, operating at slower speeds may be flown manually following lateral track guidance displayed on either a Course Deviation Indicator (CDI) or on a Moving Map Display.

design element to be used as an independent building block within an airspace design.

Whilst IFP design practices and requirements have an important bearing on this characterisation, so does aircraft behaviour and in particular, fly-ability. The published IFP shall have been validated to demonstrate the inherent fly-ability of the design under a representative range of environmental conditions e.g., adverse wind affecting groundspeed in turns. The airspace design sponsor shall therefore demonstrate to the satisfaction of the CAA that the IFP design is not susceptible to phenomena such as FMS waypoint bypass or insertion by the FMS of flight plan Discontinuities (DISCOs). Such phenomena commonly occur with large track changes and consecutive waypoints placed too close together whereby the turn stabilisation has not been achieved. Poor IFP fly-ability can invalidate the assumptions made within the LSRM method i.e., the controller intervention rate will increase beyond that defined for the loss of separation frequency, potentially invalidating the safety argument.

If independence between the design elements in terms of the characterisation defined in Appendix B and IFP fly-ability cannot be shown, additional assurance will have to be provided.

Note: The CAA notes that there is variance in both aircraft lateral and vertical performance and indeed, in individual FMS behaviour. This is particularly evident on fly-by turns. However, PBN brings a minimum standard previously not available and by taking actual navigation performance data spread across representative aircraft type samples, the NATS Departure Enhancement Project (DEP) and subsequent PBN Research Project trials have accounted for these variances. Furthermore, it is assumed that the instrument flight procedure shall have been designed and approved in accordance with ICAO Document 8168 (PANS OPS) and CAA policies e.g., CAP 778 Policy and Guidance for the Design and Operation of Departure Procedures in UK Airspace and the Policy Statement for Validation of Instrument Flight Procedures.

Departure Enhancement Project (DEP) Methodology

The route spacing values are derived from the data collected and analysis undertaken as part of the NATS Departure Enhancement Project (DEP). For simplicity, this guidance document speaks to DEP as the original work in this field but includes the subsequent Phases of the PBN Research Project. The data was obtained from a number of RNAV 1 Performance-based Navigation departure routes covering straight, turn and turn recovery segments. The turns were grouped according to shallow turns (a turn of < 25°), moderate turns (a turn of 25 - 55°), a sharp turn (a turn of 55 - 90°) and a wrap-around turn (a turn of 90 - 180°). Each turn has an associated turn recovery segment based on the observed data fit from the trials.

Having collected and ensured that the collected track deviation data was representative of aircraft performance and was free from ATC intervention i.e., ‘cleaned’, the lateral deviation distributions were modelled. Sensitivity analysis was applied by NATS and was independently verified by DNV, including their own assessment of optimistic and pessimistic distributions of the tails. The lateral deviation distributions are convolved to determine the probability that aircraft nominally separated laterally by the route spacing will actually be separated by less than the Minimum Radar Separation (MRS) standard.

Within this guidance it should be noted that the published values represent the route spacing values that satisfy the acceptability criterion that the frequency of Loss of Separation should be less than 10^{-5} per operational hour per sector.

As noted above, these values consider only the risk arising from the nominal aircraft performance. In order to assess the overall safety of any given airspace design, other factors such as recovery from operational errors and emergency situations also need to be considered. Therefore, the applicant will have to demonstrate, through their Safety Management System (SMS) with appropriate Hazard Identification and mitigations identified, how it can safely assure separation of aircraft with the relevant acceptability criteria.

Note: Whilst the route spacing values per interaction are derived from a criterion of loss of separation of aircraft on an RNAV 1 route of no more than 10^{-5} events per operational hour per sector, the collective application of route interactions within a sector must be accounted for and the route spacing adjusted subject to meeting the overall sector risk budget – see paragraph on Cumulative Risk for Sector Design.

Note: A further consideration from the application of LSRM is the ownership of the risk associated with meeting the 10^{-5} events per operational hour per sector. The airspace designer may be an independent company and not be the provider of Air Traffic Services (ATS) and therefore it is vital that the latter party (the owner of the risk) has been consulted and has accepted route designs within a given operational sector for which they are responsible – see paragraph on Ownership of LSRM Risk.

Origin of the Data

From DEP (Phase 1), the route spacing values are based on the data collected from four operational trials and three existing RNAV 1 Standard Instrument Departures (SIDs) from London Heathrow and London Gatwick Airports. In total, over 35,000 flights were analysed involving 66 aircraft types and a significant number of different operators to create a representative sample of the five major London based airports and other UK airports with similar characteristics. The data has been shown to contain a broad and representative mix of wind conditions, altitudes and speeds.

For the departure sections NATS observed tracks on shallow turns up to approximately FL80 and 250kts[6], moderate turns up to approximately FL120 and 290kts, and straight legs up to approximately FL170 and 300kts. The sharp turns and wrap-around turns within the data set are from the first turns shortly after take-off. These have a 220kts speed restriction and various altitude restrictions which can be as low as 3,000ft. The recommended minimum route spacing values are only directly applicable in similar environments, for example with a modern large air transport jet aircraft fleet mix, weather conditions and speed and altitude characteristics.

No significant differences were observed in the navigation performance of different aircraft types within the sample. The majority of aircraft monitored were equipped with GNSS navigation systems. An analysis of aircraft using DME/DME navigation showed that these aircraft performed similarly in a region with good DME coverage.

High-Level, High-Speed (HLHS) Trial

The High-Level, High-Speed (HLHS) trial conducted under PBN Research Phase 2 contributed another 5,903 flights to the dataset, expanding the scope of application of LSRM.

For the High-Level, High-Speed (HLHS), the analysis conducted by NATS showed that the HLHS lateral deviation straight leg distribution was contained within the conservative theoretical straight leg distribution fitted to the earlier SID trial data. Therefore, it can be concluded that altitude and speed do not affect conformance to RNAV 1 PBN straight leg routes and that the existing theoretical distribution for straight leg deviations is suitable for use in a high-level, high-speed environment with a typical UK fleet mix. Further, it was demonstrated that there was no observable overshooting or ballooning around the turns, and therefore that the outside of a fly-by turn can be considered as a continuation of the straight leg to the waypoint for route spacing purposes. The inside of turns must be considered separately as there is substantial variation in the turn radius due to differences in speed and bank angle. Appropriate distributions have been fit to this data and the NATS Loss of Separation Risk Model (LSRM) applied to identify minimum safe route spacing.

This extends the prior work to provide a comprehensive set of guidelines for safe route spacing in a high-level, high-speed environment.

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[6] All reference aircraft speeds are Knots-Indicated Air Speed (KIAS).

Radius to Fix (RF) Paths

The NATS PBN Research Phase 2 flight simulation programme included RNP 1 procedures with RF paths for both wrap around departures and proximate (closely spaced) turns. From the analysis of lateral deviations, NATS concluded that:

"This shows that aircraft tend to fly slightly wider on the turn than would be expected on a straight leg (by approximately 0.05 NM), but that the probability of a deviation bigger than 0.1 NM occurring is conservatively estimated by the theoretical (straight leg) distribution. On the turn recovery the simulated data is well fitted by the theoretical (straight leg) distribution."

"Since a small bias is observed on the turns, for route spacing purposes it may not be completely conservative to treat the outside of the turn as equivalent to a straight leg. It is therefore recommended to treat the Radius to Fix (RF) path as a straight leg with an additional 0.1 NM added to minimum route spacing against the outside of the RF path."

The CAA and DNV noted that the flight simulation analyses were necessarily constrained in terms of numbers of flights. The CAA therefore chose to make use of the large dataset collected by London Stansted Airport from their operational trials covering a period of one year's RNP departures for 2015 for Runway 04 (Detling) and one year's departures for 2017 for Runway 22 (Clacton). The main review focussed on Runway 22, primarily as there were over 16,000 RNP departures in 2017 flying this SID providing a significant dataset. Comparative work also analysed the departures from Runway 04 (649 tracks).

The DNV analysis of RNP 1 departures with RF tracks gathered at London Stansted airport indicated that:

- RF tracks generally form a wider lateral distribution than straight legs, but the probability of lateral deviations at larger distances (0.4 NM+) from route centreline converge.
- NATS' proposed approach of treating the RF turn as a straight leg with an additional 0.1 NM added to minimum route spacing against the outside of the RF turn is appropriate in terms of nominal navigation performance (with operational failures screened out).
- Losses of separation are likely to be dominated by operational failures and deviation types other than those covered by nominal navigation performance.
- Safety assessment of such operational failures should form an important part of the overall safety argument concerning proposed route spacings as indicated when applying the LSRM methodology.

Reinforcing the principles of having DNV and NATS validate each other's analysis, NATS then took a sample of the London Stansted Airport data, ensured that it was cleaned and concluded that the data plots show that on RNP 1 with RF departures, the bias towards the outside of the turn is consistent and can accounted for successfully by adding 0.1 NM to the straight leg distribution. Although the sample size was small (only 538 tracks available), it provided supporting evidence for the conclusions drawn from the NATS PBN Research flight simulator data.

Assumptions and Conditions

Airspace designers, when considering application of the recommended route spacing values in the summary of route spacing values should first ensure that the assumptions and conditions applicable to the derivation of the route spacing values in a London Terminal Control airspace context, are representative of their own airspace application. In particular, the following points should be examined:

Minimum Radar Separation (MRS) Standard

The objective of the Loss of Separation Risk Model (LSRM) method is to derive a PBN route spacing relative to an existing Minimum Radar Separation (MRS) standard. In the case of the London Terminal Control airspace a standard of 3 NM is applied. For the High-Level, High-Speed en-route airspace, an MRS of 5 NM is typically applied. Where a different Minimum Radar Separation is applied, the route spacing values are transferable i.e., MRS + x NM. However, the safety assessment conducted for the airspace concept would be expected to consider the applied MRS in finalising the route spacing, especially in respect of mitigating against blunders.

Flight Levels

As mentioned above, the NATS DEP Phase 1 operational trials data covered departure tracks on shallow turns up to approximately FL80 and 250kts, moderate turns up to approximately FL120 and 290kts, and straight legs up to approximately FL170 and 300kts. The HLHS trial demonstrated shallow and moderate turns up to 35°, on Upper Air Routes (UAR) with no speed constraints.

Flow Rates

Within the route spacing analysis, the flow rates on any two routes, represents the number of aircraft entering each route per hour of operation. In a practical application of the Loss of Separation Risk Model these numbers would be based on the expected usage of the routes being designed.

For the DEP Phase 1 reference scenarios NATS based the flow rate on the observed peak usage of the operational trial SIDs. The maximum observed flow within any whole hour period was 13 aircraft, with an average flow rate of 5 aircraft per hour. In the scenarios, a conservative flow rate of 15 aircraft per hour on each route has been assumed.

Aircraft Types

The First Edition of CAP 1385 listed the aircraft types and the number of flights recorded within the NATS DEP report. Since then and indeed since the HLHS trial conducted from November 2015 to December 2016, the fleet has modernised. A number of legacy aircraft types have since been retired from airline fleets and the typical UK aircraft fleet mix has changed. Those changes include an almost exclusive use of GNSS as the primary navigation aid, a more sophisticated and more capable navigation capability in terms of both lateral navigation performance, functionality and improved flight guidance systems. Standard Operating Procedures (SOPs) applied by flight crews possibly now have a greater dependency on use of the aircraft flight automation in order to navigate accurately and more efficiently. In summary, the fleet mix in UK airspace in 2022 likely exhibits an improvement in Total System Error (TSE) performance over that seen from 2013/2014 and even the HLHS trial of 2015/2016.

What does this mean for the analysis conducted by NATS to date? In essence, the analysis and assumptions that supported the First Edition of CAP 1385 are now more conservative and whilst the idea of conducting new operational data trials and a new analysis supporting revised LSRM examples might be technically feasible, cost would probably be a major factor against such action. There is also questionable value, given the absolute limitations noted by the EUROCONTROL PBN Enhanced Route Spacing Task Force findings.

Any application of the LSRM method should include an assessment of the aircraft types using the intended routes to ensure either compatibility with the DEP distribution or else an argument of more modern aircraft types e.g., B787, B737MAX, A350 and A320 neo.

Aircraft Speeds

Within the route spacing analysis, parameters are included representing the average along-track speed of aircraft on the two routes. The majority of SIDs have a 250kts speed restriction below FL100, with a 220kts restriction being applied to turns between 90° and 180° including wrap-around turns. Higher aircraft speed mitigates the loss of separation risk since it implies aircraft spend less time within the sector, therefore, to be conservative the analysis assumes a slower average aircraft speed of 240kts or 210kts as appropriate on each route within the scenarios.

It should be noted that higher speeds will increase the risk of a loss of separation in the scenario of opposite direction traffic since it increases the number of longitudinal passing events. However, this is accounted for in the Loss of Separation Risk Model through the relative along-track speed parameter, so does not need to be considered within the choice of aircraft speed values.

Relative Across-Track Speed

Within the route spacing analysis there is an assumption of the average relative across-track speed between aircraft which have lost lateral separation. This parameter has been estimated from the operational trial data by taking the change in lateral deviation from track centreline between every pair of successive track points on straight legs of one of the trial SIDs, converting to an absolute speed in knots and calculating the mean. This calculation gives a mean across-track speed of 4.01kts. To be conservative, a value of 5kts has been used in the scenarios.

Some consideration has been made into the question of whether the across-track speed for non-parallel routes should be amended to reflect the relative speed due to convergence or divergence of routes. The question is of primary importance in the scenario of a track converging towards another track, before turning onto a parallel. It was determined that to incorporate the relative speed due to track convergence would in part be equivalent to modelling the effect of a blunder wherein the aircraft continues on the intersecting track rather than turns onto the parallel route where intended. Since the NATS Loss of Separation Risk Model is not designed or intended to explicitly model turn blunders it was decided that this should not be incorporated.

Relative Along-Track Speed

Within the route spacing analysis there is an assumption of the average relative along-track speed between aircraft on parallel routes having lost longitudinal separation. For same direction routes this parameter has been estimated from the operational trial data by comparing the IAS of successive aircraft on each SID at various points from the second turn onwards along the SID. The calculation is the average absolute difference between leader and follower IAS. This calculation resulted in a value of 11.04kts. In order to be conservative, a value of 12kts has been used in the worked examples.

For opposite direction routes a value of 500kts has been used in the worked examples. This is based on two aircraft travelling in opposing directions at 250kts.

Length of Straight Segments

The fly-ability of the instrument flight procedures comprising the operational trials, used to support this guidance, have been assured through adequate validation using representative aircraft types, operating speeds and environmental conditions. Fly-ability is the degree by which aircraft adhere to the nominal track of the defined instrument flight procedure. This has a significant bearing on the lateral track deviations seen as characterisation of the nominal navigation performance on a given procedure. In particular, the fly-ability seen on the London Gatwick wrap-around departures is reflected in the spacing values listed in the summary of route spacing values.

From the operational data trials conducted at London Stansted using RNP 1 and Radius to Fix (RF), the route spacing for the wrap-round turns can be optimised, reflecting a more repeatable and predictable nominal navigation performance under all operating conditions.

In order to commit to a new airspace design with a given set of proximate spacing of routes, it is important that the airspace designer has an appreciation of instrument flight procedure fly-ability and a data reservoir of proven designs with which to refer to. The airspace designer should also adhere to demonstrated characterisation of design elements as described in Appendix B.

Absence of proven fly-ability and independence of design elements could invalidate a given route spacing and require further validation of nominal navigation performance.

Acceptability Criterion

The acceptability criterion for the frequency of loss of separation events in UK airspace was originally derived from paragraph 3.2.4 (Hazard identification and severity assessment) of Annex 2 of Commission Implementing Regulation (EU) No. 1035/2011 laying down common requirements for the provision of air navigation services. This regulation has since been repealed and superseded (Post EU Exit) by UK Reg (EU) 2017/373 (the UK Air Traffic Management/Air Navigation Services Provision of Services Regulation).

In moving from (EU) No 1035/2011 to (EU) 2017/373, the CAA has agreed that NATS could continue to use the targets in their ATS Functional System risk scheme, albeit within processes that now assign an acceptable rate of occurrence to a *proxy* (so far as (EU) 2017/373 defines them), where a *proxy* is still classified in terms of NATS ability to provide an ATS.

In the First Edition of CAP 1385, NATS used the outcome ‘severities’ classes from their original scheme, whereby the hazard being evaluated in LSRM equated to a Severity Class 4 hazard as being acceptable for frequencies of less than 10^{-5} events per operational hour per sector. Given that there is nothing in the new regulation that necessitates a change to frequency targets used for control of undesirable ATS outcomes, the CAA still considers the frequency of 10^{-5} per operational hour per sector for occurrences of the described *proxy* (the scenario where an intervention by the controller is required to resolve a loss of radar separation) to be acceptable.

This is therefore the acceptability criterion that has been applied in the summary of route spacing values.

Application of Route Spacing in UK Terminal Airspace

Summary of Route Spacing Values

Table 1 below, provides a summary of the minimum acceptable route spacing (M_x) for the scenarios considered, as taken from the DEP Final Report and the HLHS Final Report and audited by DNV. Each scenario illustrates the application of the Loss of Separation Model to simple route interactions as described in Appendix B.

The minimum acceptable route spacing values have been subject to sensitivity analysis, both in terms of the parameters mentioned under assumptions and Conditions section i.e., Flow Rate, Speeds, Across-track Speeds, Along-track Speeds and Length of Straight Segments and investigation of alternative fits to the lateral distributions. The parameters have been chosen to be broadly applicable in a UK airspace context and therefore the minimum route spacing values are directly applicable where the conditions and assumptions of this guidance have been met. If the length of a straight segment is at the upper end of the range (i.e., 200 NM instead of the 20 NM assumed in the base case) or if the flow rate is 30 aircraft per hour per route instead of 15, the minimum acceptable route spacing would increase by typically 0.1 to 0.2 NM.

The summary information provided in Table 1 is intended to illustrate the comparative route spacing for the scenarios considered.

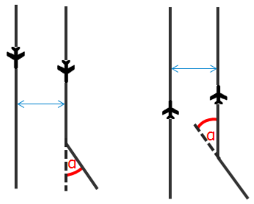
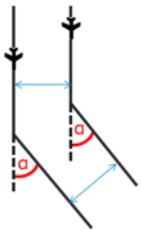
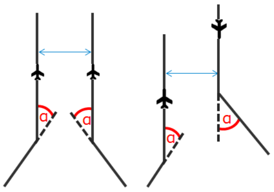
Parallel Straights

Same direction parallel straights: MRS + 0.8 NM

Opposite direction parallel straights: MRS + 1.2 NM

Where straight legs are converging or diverging, take the closest point of approach as the route spacing.

Table 1: Turn Interactions

Turn descriptor	Single turn in the vicinity of straight route 	Two routes turning together 	Two routes turning apart 
<25° fly-by turns in terminal airspace*	Same: MRS + 0.9NM Opp: MRS + 1.2NM	Same: MRS + 0.9NM Opp: MRS + 1.2NM	Same: MRS + 1.0NM Opp: MRS + 1.3NM
25°-55° fly-by turns in terminal	Same: MRS + 1.2NM Opp: MRS + 1.6NM	Same: MRS + 1.2NM Opp: MRS + 1.7NM	Same: MRS + 1.4NM Opp: MRS + 1.7NM
55°-90° fly-by turns in terminal, 220kts speed constraint	Same: MRS + 0.9NM Opp: MRS + 1.2NM	Same: MRS + 1.0NM Opp: MRS + 1.4NM	Same: MRS + 1.0NM Opp: MRS + 1.2NM
55°-90° fly-by turns in terminal	Same: MRS + 1.4NM Opp: MRS + 1.8NM	Same: MRS + 2.2NM Opp: MRS + 2.7NM	Same: MRS + 1.8NM Opp: MRS + 2.1NM
90°-180° fly-by wraparound‡ turns in terminal, 220kts speed constraint	Same: MRS + 3.4NM Opp: MRS + 4.6NM	NA	NA
Radius to Fix (RF) path in terminal	Same: MRS + 0.9NM Opp: MRS + 1.3NM	Same: MRS + 0.9NM Opp: MRS + 1.3NM	Same: MRS + 1.0NM Opp: MRS + 1.4NM
<25° fly-by turns in en-route airspace**	Same: MRS + 0.8NM Opp: MRS + 1.2NM	Same: MRS + 1.3NM Opp: MRS + 1.6NM *(See Note below)*	Same: MRS + 0.8NM Opp: MRS + 1.2NM
25°-35° fly-by turns in en-route	Same: MRS + 0.8NM Opp: MRS + 1.2NM	Same: MRS + 3.5NM Opp: MRS + 4.0NM *(See Note below)*	Same: MRS + 0.8NM Opp: MRS + 1.2NM

*Terminal airspace with maximum 250kts speed constraint unless otherwise stated. MRS is typically 3 NM.

**High-Level, High-Speed en-route airspace. MRS is typically 5 NM.

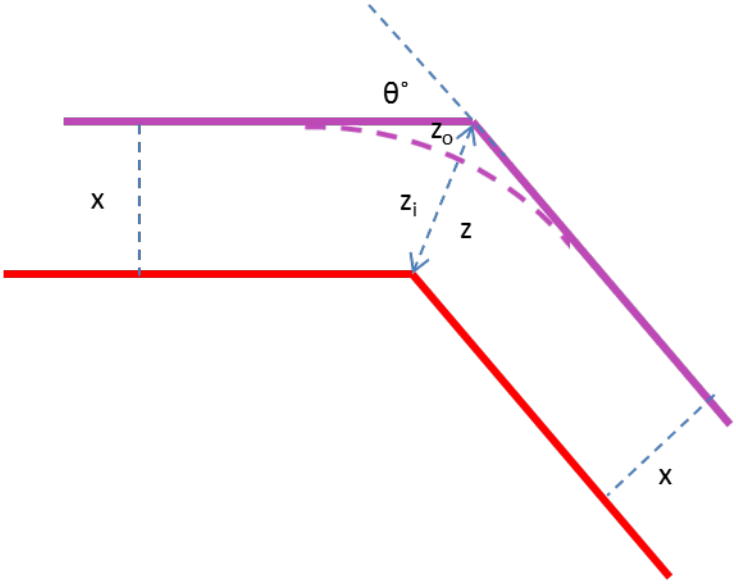
‡Two or more individual fly-by turns longitudinally spaced by less than 7 NM, with a total track change between 90° and 180°.

Two Routes Turning Together in En-Route Airspace

The proposed spacings for two routes turning together in en-route airspace expressed in Table 1 above, are different than that given in the HLHS Trial Report[7]. This is because they are based on the distance between the straight leg portions of routes, instead of the distance between the nominal turn centreline for the outer route and the waypoint for the inner route. The geometry assumptions underpinning the changed proposals, are presented below.

The assumed theoretical geometry is given in Figure 2, where the turn angle is θ, the route shown in purple is uniformly equidistant from the route shown in red by a distance of x NM. The nominal route centreline around the turn is shown in dashed purple. The distance from the inner route waypoint to the outer route waypoint is z NM, which can be split up into the distances from the inner route waypoint to the closest point on the nominal outer route centreline z_i and the distance from that point to the turn waypoint z_o.

Figure 2: Assumed Geometry



In the HLHS report the spacing minima are stated in terms of z_i, however in discussions with NATS it was determined that it would be more useful to airspace designers to state the minima in terms of x, the distance between the straight legs. Working on the standard formula for an aircraft's turn radius and a conservative bank angle of 5° bank and a cruising airspeed of 370kts, this gives a turn radius of 22.8 NM, which is the centreline used for the HLHS report.

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[7] NATS PBN Research: HLHS Trial – Final Report, 4987/RPT/36.

Using the 22.8 NM turn radius and conservatively assuming the largest turn angle available in the turn range, the route spacing minima derived in the HLHS report can be mathematically transformed as shown below and these are the values used in Table 1.

Table 2: Comparison of HLHS report route spacing and Table 1 equivalent values

Assumed turn	HLHS report route spacing (z_i)	Straight leg route spacing (x)
25° same direction	5.9NM	6.3NM
25° opposite	6.2NM	6.6NM
35° same	7.8NM	8.5NM
35° opposite	8.3NM	9.0NM

Route Spacing Checklist

In applying the route spacing values given in Table 1, the following checklist should be used.

1. Are turn waypoints less than 7 NM longitudinally spaced? If yes and the sum of the under-spaced turns is greater than 90° then treat these as a combined wraparound turn.
2. Identify the interactions in the airspace design and find the baseline minimum spacing for each in the turn interaction table.
3. For each pair of routes, choose the largest baseline minimum spacing of all relevant interactions.
4. Are there two or more interactions intended to be spaced at the minimum? If yes, then add 0.1 NM to each baseline minima.
5. Are there three or more minimally spaced interactions including a turn greater than 25˚? If yes, then add 0.1 NM to each baseline minima (in addition to the 0.1 NM in point 2.)

Ownership of LSRM Risk

The Loss of Separation Risk Model (LSRM) is intrinsically linked to the Air Traffic Services (ATS) operation and has split responsibilities with the IFP design, the placement of routes and the safety assurance for the sector.

In an airport environment, whereas the responsibility for the IFP design, safety, fly-ability and introduction of the airspace change (ACP), including environmental consultation, lies with the airport / change sponsor, the ATS controlling authority (or authorities) is the only competent body able to participate to or otherwise conduct the operational safety assessment for the airspace volume concerned. Ultimately, they have to accept to operate the procedure and therefore provide the operational mitigation (intervention) in the case of a Loss of Separation.

In summary:

- Only the ATS controlling authority can assure the overall safety of the sector design.
- Coordination between airports, third-party design organisations and the ATS controlling authority is critical.
- Even if LSRM is not being applied, the ATS operational safety of new SIDs and arrival transitions, must be coordinated with the ATS controlling authority.
- Even though the airport owns the IFP design, the ATS controlling authority owns the ATS operational risk and the mitigations associated with receipt and delivery of the airport traffic.

What LSRM Does Not Cover

It is important to note that the application of LSRM does not assure an airspace design for the ATS operational aspects. The airspace design still needs to consider:

- The technical demonstration of the surveillance coverage (area, level).
- Whether the Minimum Radar Separation (MRS) Standard can be applied and is it suitable for the intended operation.
  - For the intended Flight Level, aircraft speed and allowing for aircraft manoeuvrability in the event of an intervention.
  - Radar displays – resolution, level of clutter.
  - Sector size and density of traffic.
  - Need for support tools e.g., conformance monitoring.
- Demonstration of the changed role of the controller i.e., that of a monitoring role rather than full-time tactical control
- Techniques and phraseology for transition to/from, and operating on, closely spaced routes e.g., ensuring that flights do not deviate from the assigned route

All of the above should be considered and addressed within the airspace change, this in addition to the Assumptions and Conditions listed above.

Application of PBN Specifications, Other Than RNAV 1

In the Assumptions and Conditions section the change in aircraft types to more modern models were discussed and the impact on the LSRM work from DEP (Phase 1). All of the DEP operational trials specified an RNAV 1 navigation specification. The Radius to Fix (RF) operational trials at London Stansted Airport specified an RNP 1 navigation specification, with both sets of data based on a lateral navigation accuracy (Total System Error - TSE) of +/- 1 NM for 95% of the flight time per sector.

As previously noted, the vast majority of aircraft are today GNSS equipped and therefore the Navigation System Error (NSE) is typically in the region of 0.05 NM. Flight Technical Error (FTE) is given over to most of the TSE budget and as data has shown, predominance of use of onboard Flight Guidance Systems (FGS) such as Autopilot and/or Flight Director used in all flight phases has led to an actual navigation performance far better than allowed for in the PBN specification.

RNAV 1 and RNP 1 are not the only ICAO PBN specifications designed for use in terminal airspace. Advanced RNP (A-RNP) has a fixed RNP Value of 0.3NM in terminal airspace supporting arrival procedures (STARs) and approach transitions up to the Final Approach Fix (FAF) and departures (SIDs) with a much-reduced lateral navigation accuracy. In the en-route flight phase, whereas the HLHS data has already validated the application of RNAV 1, the ICAO PBN Manual (Doc 9613) offers RNP 2 as an alternative navigation application.

It is the view of the CAA that even if further operational data trials were to be conducted with other PBN specifications, the data distribution would likely look very similar, if not better than that collected through DEP (Phase 1), HLHS, RNP 1 and RF at London Stansted and the PBN Research flight simulator trials. The navigation performance is largely influenced by the NSE (GNSS) and management of FTE (largely through autopilot/flight director). Modern display technologies, including Moving Maps and Head Up Display Landing Systems (HUDLS) also enhance flight crew monitoring of lateral navigation.

Given the finite limitations found in the EUROCONTROL ERS-TF study with respect to operating a surveillance airspace to the Minimum Radar Separation (MRS), it can be assumed that the sample route spacings and CAS Containment values published in this document may be applied to the applications listed in Table 3:

Table 3: Airspace Applications and Associated PBN Specifications

Airspace Application **(ATS or user-defined routeing)**	**ICAO PBN specification**
En-route continental	RNAV 5, RNAV 1, RNP 2, A-RNP, RNP 0.3*
Terminal (Arrivals, Departures, Approach Transitions)	RNAV 1, RNP 1, A-RNP, RNP 0.3*

* RNP 0.3 is intended for the exclusive use of helicopters and rotorcraft.

Fixed Radius Transition (FRT)

The ICAO PBN Manual includes two applications of Fix Radius Paths (FRP), that of the Radius to Fix (RF) leg type and the Fixed Radius Transition (FRT). The latter is defined in ICAO Doc 9613 Volume II Part C, Appendix 3, but has to-date, not been applied in UK airspace and the only data available exists in EUROCONTROL studies. It nevertheless exhibits, in en-route airspace, similar curved path capability to that found in terminal airspace with the use of RF and certainly has greater predictability and repeatability than a fly-by transition. Although no route spacing studies have been made using FRT, it is assumed that the sample route spacings derived from the HLHS, can also be applied to routes using FRT. See also, European Airspace Concept Handbook for PBN Implementation (PBN Handbook No. 1) published April 2021.

Cumulative Risk for Sector Design

Table 1 presents a summary of the minimum acceptable route spacing between proximate PBN routes per operational hour per sector, through application of the Loss of Separation Risk Model to nominal navigation performance. These are defined for typical airspace route interactions employing parallel straights, turn away from a straight parallel, a straight against the apex of a 180° wrap-around, and various others. It is intended that these scenarios can form convenient building blocks for future PBN airspace sector design.

Each of the scenarios is a single interaction and the derived route spacing minima uses the whole Loss of Separation Risk Model budget for the sector. However, if additional minimally spaced interactions were designed into a sector it would be likely that the total risk would be greater than the tolerability criterion of 10^{-5} losses of separation per sector per hour due to the additive nature of the risk.

The following simple rules may be applied to ensure that whole sector risk does not exceed the acceptability criterion:

1. If there are 2 or more interactions that are intended to be spaced at the minimum, then add 0.1 NM to each baseline minima.
2. If 3 or more minimally spaced interactions include a turn greater than 25° then add 0.2 NM to each baseline minima.

It should be noted that these rules and building blocks are designed to be of easy use to sector designers, but that a specific sector design could be optimised by direct calculation of the cumulative Loss of Separation risk.

Study for Route Spacing Against the Boundary of Controlled Airspace (CAS)

Introduction

It is assumed that the risks associated with an aircraft flying within controlled airspace (CAS) on an RNAV 1 route in the vicinity of the CAS boundary can be broken down into three types:

a) Infringement of CAS by aircraft supposed to be outside CAS.

b) Penetration of the CAS boundary by controlled aircraft due to blunder or technical error.

c) Penetration of the CAS boundary by controlled aircraft due to the technical navigation performance of the aircraft on an RNAV 1 route under own navigation.

Risks a) and b) are the same as the risks experienced by an aircraft being vectored in the vicinity of a CAS boundary, therefore the CAS containment required for vectoring can be considered sufficient to manage these risks to a tolerable level. Typically, it is recommended that controllers aim to keep the aircraft under their control at least 2 NM within the boundary while vectoring, although this is sometimes reduced depending on additional risk mitigations and airspace context.

Existing UK containment policy says that that risk c) can be safely managed by designing RNAV 1 routes (SIDs, STARs and ATS Routes) 3 NM from the CAS boundary. This is based on the principle that RNAV 1 route navigation performance standard is based on a Total System Error (TSE) for navigational tolerances being + or – 1 NM either side of the nominal track for 95% of the total flight time, with an acknowledgment of the normal radar vectoring limitation of 2 NM. However, recognising that modern aircraft navigation capability is substantially better than implied by the 95% ±1 NM criterion, which suggests that PBN route design requirements founded on this principle may be excessively conservative.

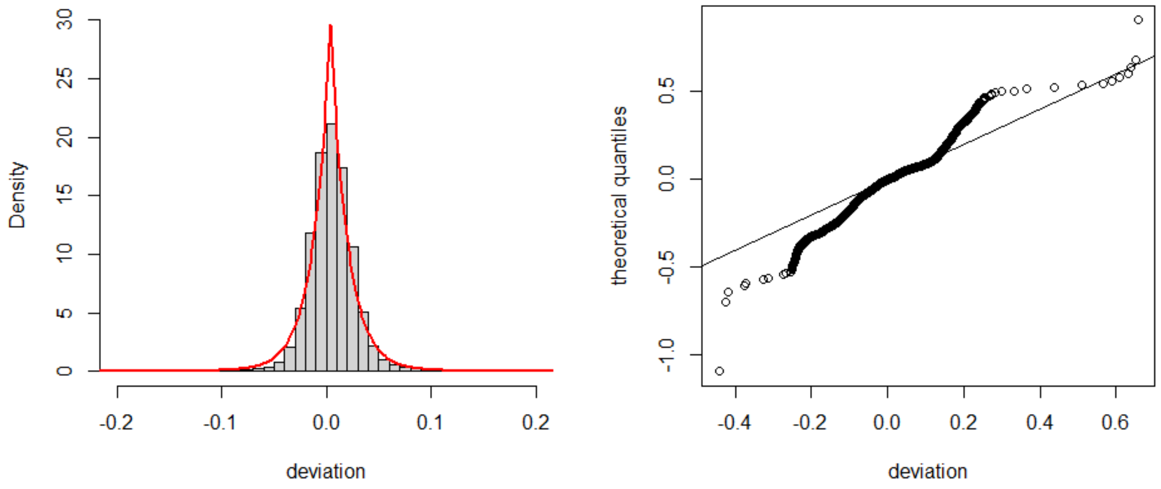
UK PBN Research

In order to better characterise navigation performance and inform UK airspace design guidance, CAA have worked jointly with NATS on both the DEP and PBN research projects, including a programme of RNAV 1 trials and data collection activities. The data from these trials has confirmed that actual navigation performance is better than the 95% ±1 NM criterion by a substantial margin.

The work has resulted in a set of probability distributions describing expected lateral deviations from the nominal track of RNAV 1 turns and straight legs which are much closer to actual navigation performance than the 95% ±1NM criterion, while still being conservative. These distributions have been validated by third-party audit

(DNV) and formed the basis of the First Edition of CAP1385. The goodness-of-fit of the distribution for straight leg navigation performance is shown in Figure 3.

Figure 3: RNAV 1 straight leg deviation data (histogram) with fitted distribution (red line); quantile-quantile plot showing conservatism of fitted distribution in the tails.



RNAV 1 CAS Containment – Straight Legs

New separation or spacing minima are typically found either by performing a quantitative risk assessment of the proposal and comparing to an absolute target level of safety (e.g., 1.55 x 10^{-8} fatal accidents per flight hour), or by doing a relative risk assessment compared to an existing acceptably safe procedure. In the case of CAS containment there is no obvious absolute target level of safety since:

- The recommendation to keep vectored aircraft 2 NM within the CAS is not equivalent to a separation minimum, so the acceptability criterion of 10^{-5} losses of separation per sector hour used in LSRM is not applicable.
- There is no known existing acceptability criterion for penetrations of the CAS boundary.
- The use of the standard target level of safety of 1.55 x 10^{-8} fatal accidents per flight hour could not be applied since a full collision risk assessment would require knowledge of the traffic density and behaviour outside controlled airspace, which is inherently unpredictable.

Instead, a relative risk assessment compared to the existing CAS containment policy can be used. The policy is founded on the assumption of 95% containment within ±1 NM of the nominal route centreline. RNAV navigation inaccuracy is typically assumed to have a zero-mean Gaussian distribution (ICAO Doc 9613 Edition 4 PBN Manual, Volume II, Part A, Chapter 2, paragraph 2.2.1), with a standard deviation of approximately 0.5 NM.

Under this assumption, the probability of CAS boundary penetration for an aircraft which is nominally on an RNAV 1 route 3 NM from a CAS boundary is 2.02 x 10^{-9}.

The actual known distribution for RNAV 1 straight leg navigation performance is a double-exponential mixture distribution as shown in Figure 3. The comparison between this and the assumed Gaussian distribution is shown in Figure 4. Table 4 demonstrates that the true probability of a CAS boundary penetration is many orders of magnitude lower than the current policy is designed to protect against.

Figure 4: Comparison of Assumed Gaussian Distribution Versus Observed Double-Exponential Distribution.

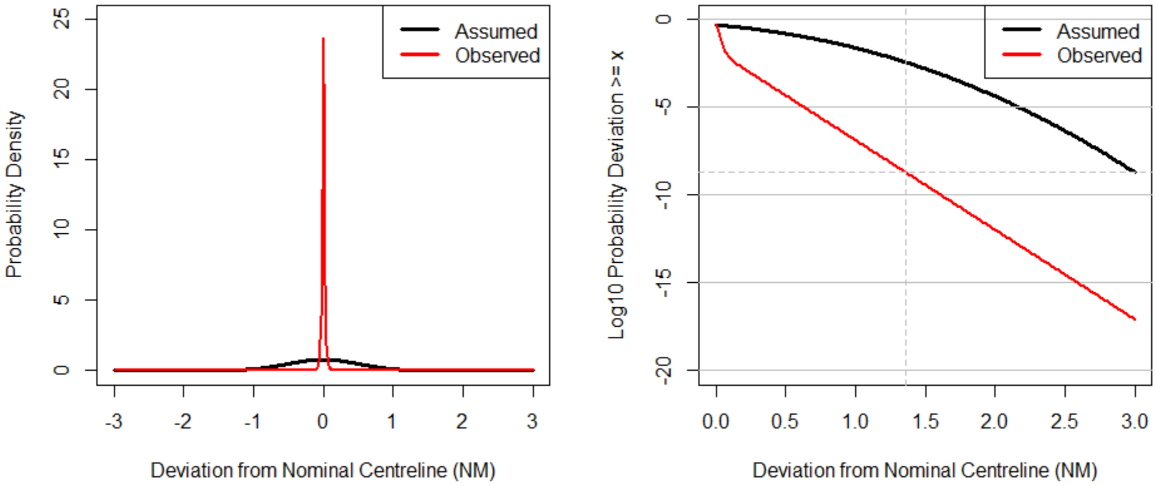


Table 4: Probability of CAS Penetration and Relative Risk Compared to the Policy Requirement

CAS Containment	Probability of CAS Penetration	Relative Risk
3.0 NM	7.96×10^{-18}	3.94×10^{-9}
2.0 NM	1.02×10^{-12}	5.06×10^{-4}
1.4 NM	1.19×10^{-9}	5.89×10^{-1}

Instead, the nearest equivalent CAS containment is 1.4 NM, which gives a probability of boundary penetration of 1.19 x 10^{-9} and would therefore provide a similar or better protection against boundary penetration due to the technical navigation performance of the aircraft than the current policy is designed for. As discussed earlier, additional spacing is likely to be required to cover the risks due to infringement of the CAS, or penetration of the CAS boundary due to blunders or technical error.

The policy for the design of airspace structure will take in consideration the outcome of this study for the determination of new containment values for straight leg portion of RNAV 1 routes.

RNAV 1 CAS Containment – Non-Straight Leg Portions

The nominal track of non-straight leg portions of RNAV 1 routes can be spaced 3 NM from the boundary of controlled airspace. This particular recommendation is unchanged from existing UK policy for the design of controlled airspace structured and has been included for completeness. It is therefore not considered necessary to provide any further justification of the proposal

Relationship with Existing Air Traffic Services Guidance

CAS containment requirements for PBN routes should be read in conjunction with CAA CAP 493, Manual of Air Traffic Services (MATS) Part 1, Section 1: Chapter 6, ATS Surveillance Systems, Paragraph 13A.4, which states:

Although IFR flights within class A-D airspace, and VFR flights within B/C airspace, are deemed to be separated from unknown aircraft flying in adjoining uncontrolled airspace, controllers should aim to keep the aircraft under their control at least two miles within the CAP 493 2 April 2015 Section 1: Chapter 6: ATS Surveillance Systems - Page 16 boundary. Controllers should monitor the operation of aircraft in adjacent uncontrolled airspace, particularly if circumstances have made it necessary to vector an aircraft to be less than two miles from the boundary. In such circumstances, consideration should be given to co-ordinating with the appropriate controlling agency if applicable. However, regardless of airspace divisions and classifications, controllers should take appropriate action with respect to the safety of aircraft if unknown aircraft appear to present a risk of collision.

Additional Guidance for Route Spacing against Holds

Where an RNAV 1 route is proximate to a hold, the route can be spaced 9 NM from the nominal hold centreline if the route direction is the same as the nearest traffic in the hold. The route can be spaced 10.5 NM from the nominal hold centreline if the route direction is opposite the direction of the nearest traffic in the hold.

Straight sections of holds can be spaced 11 NM apart.

Note: Caution should be applied when designing holds with the turns proximate to other holds.

Note: Caution should also be applied when using this route-hold and hold-hold spacing guidance. It is based on established nominal performance of aircraft types used by large commercial operators only. Therefore, this guidance may not be applicable where there is eccentric hold entry behaviour such as with off-axis entries, or where the expected fleet mix includes aircraft types such as the DH8D that fly with constant bank turns, and therefore do not follow the nominal hold centreline in moderate to high wind conditions.

Note: Some configurations of route-hold interaction may permit closer spacing than stated here, especially when supported by historical data demonstrating actual aircraft behaviour.

Note: The above is not a DNV audit finding, but rather a new proposal developed following conversations between CAA and the NATS PBN Research Team.

The NATS Holding Trial Report [*Performance-Based Navigation: Analysis of Aircraft Holding Performance using RNAV1 Based Flight Management Systems, 4987/RP/35*] provided various complex route-hold and hold-hold spacing values depending on the geometry of the interaction. The route-hold and hold-hold spacing values in the proposal were derived by finding the largest of the calculated spacing values for all geometries in the report.

Given the complexities of the geometry options and the strong caveats that apply to this work, it is not felt that a more detailed proposal would be justified. In this respect, further research is required, potentially exploiting the application of the RNP Holding function found on certain aircraft types today.

Chapter 2

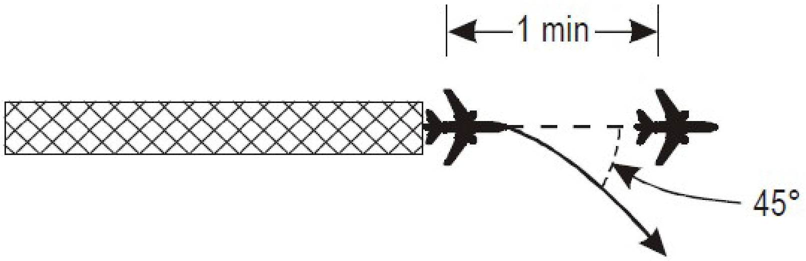
Reduced Departure Divergence (RDD)

International Civil Aviation Organisation (ICAO) Criteria

Although not associated with the LSRM method, another aspect of the NATS DEP (Phase 1) Project was a study into Reduced Departure Divergence (RDD). Current ICAO criteria in PANS ATM Doc 4444, Chapter 5, 5.6 Minimum Separation Between Departing Aircraft, states that:

One-minute separation is required if aircraft are to fly on tracks diverging by at least 45 degrees immediately after take-off so that lateral separation is provided (see Figure 5). This minimum may be reduced when aircraft are using parallel runways or when the procedure in Chapter 6, 6.3.3.1, is adopted for operations on diverging runways which do not cross, provided instructions covering the procedure have been approved by the appropriate ATS authority and lateral separation is effected immediately after take-off.

Figure 5: One-minute separation between departing aircraft following tracks diverging by at least 45 degrees

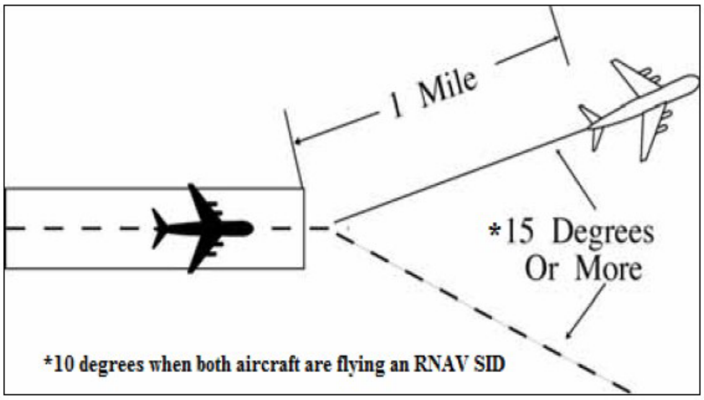


Criterion for divergence of simultaneous departures from parallel runway operations has been developed, based on FAA studies into Equivalent Lateral Spacing Operations (ELSO) and this resulted in publication in May 2020 of ICAO Circular 350, Guidelines for the Implementation of Reduced Divergence Departures.

Unfortunately, ICAO has no plans to investigate single runway RDD i.e., for successive departures, although FAA Order JO 7110.65Z Chapter 5, Section 8, Radar Departures does support such operations using RNAV or RNP procedures under Radar Surveillance. The FAA Order states that:

Separate aircraft departing from the same airport/heliport or adjacent airports/heliports in accordance with the following minima provided radar identification with the aircraft will be established within 1 mile of the take-off runway end/helipad and courses will diverge by at least 15° degrees or more immediately after departure - see Figure 6. The divergence angle reduces to 10° or more immediately after departure, when both aircraft are flying an RNAV or RNP SID. A note is provided that this procedure does not apply when wake turbulence separation is required.

Figure 6: Successive Departures



UK Experience

Under the DEP (Phase 1) project, NATS conducted an operational trial at London Gatwick Airport from February to August 2014, referred to as the Gatwick ADNID Departure. This trial assessed the conformance of area navigation (RNAV 1) compliant aircraft to a departure route made up of straight segments and turns with angles between 21° and 44°.

Data was collected and analysed for 12,110 flights which used the ADNID trial route. The dataset included 37 aircraft types and 56 operators.

Between June and August 2014, a variation of the operational trial was conducted with departure intervals of one minute between departures on the ADNID SID and the departures on the SAM or KENET SIDs. This was in order to investigate the determination of the safe divergence angle between a pair of PBN Standard Instrument Departures (SIDs) on which 1-minute departure splits are permitted, i.e., aircraft are allowed to alternate departures on the two SIDs with a 1-minute time spacing between take-offs.

As mentioned above, the existing non-PBN ICAO-compliant procedure is that there should be a minimum divergence angle of 45° as soon after take-off as possible. In support of the project goal, a new tool/method for the quantitative safety assessment of sequential departures from the same runway was developed. The method was called the Reduced Angles of Divergence SIMulator (RADSIM).

The RADSIM Model

RADSIM was developed to provide a method to perform a quantitative safety assessment into reduced angles of divergence with departure intervals of less than 2 minutes. The method needed to be able to investigate generic SID splits to find minimum safe angles of divergence, and to assess specific designed splits such as ADNID-SAM/KENET. After consideration of possible assessment methods, it was determined that a Monte Carlo simulator of departures was the only option which would fulfil the requirements.

The tool was used to assess the safety of one minute spacing between consecutive departures on ADNID-SAM/KENET without corrective intervention by ATC or Pilot (i.e., treating the SIDs as procedural airspace). The results of the RADSIM assessment indicated that for the success case (i.e., aircraft correctly spaced on departure and following the correctly assigned SID) the risk of a collision is 6.4×10^{-12} fatal accidents per flight hour.

The probability of a departure pair having a horizontal separation less than 1.5 NM was estimated to be 9.9×10^{-4} across all wind conditions, and the probability of a horizontal separation less than 1.5 NM occurring while there is also a vertical separation of less than 1,000ft was estimated to be 2.3×10^{-6}. The probability of small horizontal separations occurring increases with headwind. Horizontal separations of as little as 0.59NM were simulated in strong headwinds, however these simulated departure pairs typically had a large vertical separation since the catchups were caused by a large speed differential due to the leader climbing more steeply than the follower.

The collision risk due to an aircraft selecting the incorrect SID was calculated (i.e., the collision risk for two aircraft separated by 1 minute at departure and following the same SID). In this scenario the collision risk was estimated to be 9.2×10^{-9} fatal accidents per flight hour.

In response to an outcome of the HAZID workshop, a sensitivity analysis of the collision risk due to under-spacing of departure pairs (departure spacing of 52 seconds instead of 1 minute) was performed. In this scenario the collision risk was estimated to be 9.0×10^{-13} fatal accidents per flight hour.

These results were used as part of the safety case used to support the implementation of the operational trial of the Gatwick ADNID RDD and validation of the RADSIM tool.

The method was subsequently applied for two further assessments, Heathrow Westerly Package (HWP) in 2014, and Edinburgh GOSAM/TALLA, also in 2014. In each case the application of RADSIM was successful, either by demonstrating the acceptable safety of a proposed reduced divergence procedure which supported a successful implementation (ADNID), identifying acceptably safe alternative options to a proposed procedure (GOSAM/TALLA)[8], or identifying that a proposed procedure could not be safely applied (HWP).

Summary of Findings

Features of the research conducted by NATS, and reported to ICAO at the Separation of Airspace Safety Panel (SASP) Twenty Eighth Meeting of the Working Group in May 2016[9], are as follows:

- In practice, the separation between early phase successive departures is procedurally applied until the minimum 3 NM separation is attained. Controller intervention can therefore not be considered as part of the safety assessment.
- An absolute, not relative, collision risk assessment is performed using modern applicable safety standards (TLS) rather than possibly looser historical safety requirements on which the existing guidance is based.
- The safety assessment is performed using Monte-Carlo simulation accounting for observed navigation performance, speed and climb profiles based on real departure tracks from UK airports.

Key points to note are:

- The variation in speed and climb profiles between successive departures has a larger influence on collision risk than navigation performance.
- Reduced divergence departures can be applied safely in some circumstances, but not universally.
- Cases where reduced divergence departures have been shown to be unsafe include:
    - Where the fleet mix is not benign, i.e., there is a significant variation in wake category and aircraft type between successive departures.
    - Where the runway length, runway gradient and/or obstacle clearance requirements allow significant variation in flight deck procedures (i.e., an identical aircraft type can have very different speed/climb profile due to choices of de-rated thrust and flap settings).

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[8] 60 second departure-departure intervals for TALLA-GOSAM sequenced pairings from Runway 06 and 90 seconds for GOSAM-TALLA sequence from Runway 06

[9] ICAO SASP-WG/28-WP/34 of 23.05.2016

- Where some but not all individual pilots or carrier operating procedures will apply an exceptional speed constraint due to a challenging SID construction (e.g., a sharp turn shortly after departure).

These findings were validated by trials in UK airspace, and analysis of minimum separations between successive departures. As an example, during one of the trials a pair of aircraft without wake category restrictions and within the same speed group (i.e., eligible for a 1-minute departure interval otherwise than the divergence) departed Heathrow Airport on tracks that diverged by 25°, with a 2-minute interval between departures (rotation). The lead aircraft flew unusually slowly for several miles. The following aircraft accelerated to the 250kts speed constraint very quickly and was also climbing strongly. It was calculated that if this particular pair had departed with a 1-minute interval, they would have approached < 1 NM horizontally and < 1,000ft vertically. This was one pair observed out of approximately 150 eligible pairs on this procedure, and one would therefore expect to see worse events than this occurring regularly if 1-minute intervals were permitted.

The work to date suggests that the RADSIM tool may be used to assess the safety of a specific case of Reduced Divergence Departures, but that it does not reflect a new generic, universally safe divergence angle.

Without wishing to place substantial constraints on flight deck procedures, further research is recommended, noting the existence of the FAA Successive Departures criteria.

Note: The same argument applied to the application of LSRM in respect of ATS operational shared roles and responsibilities, also applies to Reduced Departure Divergence (RDD) and 1-minute split departures.

Chapter 3

NATS PBN Research Project Simulations

Introduction

Studies into track keeping performance on RNAV holds and on High-Level, High-Speed routes had already been completed through operational trials conducted under the DEP Project and enabling route spacing guidance to be extended into the en-route environment – see Chapter 1.

Following-on from the DEP Project, the retitled PBN Research Project expanded the scope into a Phase 2 and a Phase 3 set of Work Packages investigating both lateral track-keeping performance and vertical flight profiles.

CAA Comment

The findings made from the PBN Research Project represent a data set to inform prospective airspace designs. The methodology applied reflected that which would have been applied if validating a new IFP as part of an Airspace Change Proposal (ACP) conducted under CAA CAP 1616[10]. However, this data is not eligible as part of an ACP submission. Instead, it is intended to inform the airspace designer/sponsor of the validity and fly-ability of a number of route designs and interactions. Any new airspace change should adhere to the CAP 1616 process and validate the respective designs according to CAP 785[11] and ICAO Doc 9906 Volume 5[12].

Phase 2

Scope of Research

The PBN Research Project Phase 2 extended the previous work using flight simulation and involving twelve carriers and eleven aircraft types, with each type simulating up to 192 different procedures.

The following Work Packages (WP) were performed via flight simulation:

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[10] Airspace Change Guidance on the regulatory process for changing the notified airspace design and planned and permanent redistribution of air traffic, and on providing airspace information

[11] CAP 785 Volume I: Oversight of UK Approved Procedure Design Organisation.

[12] ICAO Doc 9906 Quality Assurance Manual for Flight Procedure Design – Volume 5 – Validation of Instrument Flight Procedures – First Edition, 2012.

- WPA - Validate Flight Simulator as fit for purpose by comparison to live data and ensure required output is feasible.
- WPB - Understand effect of speed on aircraft behaviour with sharp turns.
- WPC - RNAV wrap around SID design; RNP RF wrap around SID design.
- WPD - RNP procedures with RF proximate (closely spaced) paths.
- WPE - Inform Procedure Design Criteria for designing closed PBN to ILS procedures. Understand the effect of different minimum lengths between ILS establish point and the FAF with a 90° ILS intercept.
- WPF - Understand aircraft capability to fly Tactical Parallel Offsets (TPO) on SIDs.
- WPG – Understand aircraft capability to fly TPOs on airways.
- WPH – Time and Distance PBN Holding including FMS entries.

Note: Definitions of turn interactions, e.g., moderate, sharp may be found in Appendix B.

Key Findings and Recommendations

This section contains a selection of the key findings of the research taken from the NATS *PBN Research: Flight Simulator Analysis Report (L4987/RPT/37)*.

Simulation Validity

Finding 1: The simulations replicated real navigation performance adequately, including fly-ability issues on the wraparound turn. The detailed track-keeping performance shows more variability than is seen in real data, so conclusions drawn from the simulations should be conservative.

Wraparound Turn Design

Finding 3: No clear evidence has been found to suggest that a specific FMS type or database provider causes the fly-ability issues seen on SIDs with a tight wraparound turn construction such as LAM1X (other than a specific known problem with the B737, now corrected). As such there is no indication that the fly-ability issues could be corrected by any means other than the redesign of the SIDs.

Finding 4: Changing the first turn from a fly-by to a fly-over does not improve tight wraparound fly-ability.

Recommendation 5: Fly-by wraparounds should be designed with a minimum of 5 NM between turn waypoints to minimise fly-ability issues.

Finding 6: An RNP procedure with RF paths with varying different constructions can be substituted for a tight fly-by wraparound turn to minimise fly-ability issues, although in extreme winds lateral track deviations will still be evident but with less likelihood of route discontinuities.

Finding 7: Fly-ability issues are not exhibited on a tight wraparound turn as part of an approach procedure, even in extreme winds.

Sharp Turns

Recommendation 8: Route spacing for sharp turns with 250kts speed constraint can be derived by taking the scenarios involving moderate turns and adding 0.2 NM for each outside sharp turn, and 0.8 NM for each inside sharp turn.

Finding 9: Waypoint positioning is crucial in designing sharp turns in a High-Level, High-Speed environment. A waypoint before the turn waypoint will dictate the earliest point that an aircraft will start the turn. Procedure designs should give sufficient space between waypoints to permit the expected range of turn radii on such a turn, dependent on the expected speed and flight level.

Track Keeping on RNP Procedures with RF Paths

Finding 10: In extreme winds, some overshooting (< 1NM) can be observed on RNP procedures with RF paths. This was evident with certain older business aircraft types, probably due to bank angle limitations.

Recommendation 11: In normal conditions (excluding wind conditions > 80kts at 4000ft), RNP procedures with RF paths can be treated as equivalent to straight legs with an additional 0.1 NM added to the outside of the turn for route spacing purposes. No turn recovery consideration is required - see Chapter 1.

Recommendation 12: In normal conditions (excluding wind conditions > 80kts at 4000ft), RNP procedures with RF paths with a radius down to 2 NM are viable and can be treated as equivalent to other RNP procedures with RF turns for route-spacing purposes.

Finding 13: It is necessary to apply appropriate speed constraints to RNP procedures with RF paths to minimise the risk of overshooting or other fly-ability issues, especially in adverse winds.

Finding 14: When designing high-altitude RNP procedures with RF paths, consideration should be given to bank angle restrictions by some aircraft types (e.g., small-to-medium sized Business Jets such as the H25B).

Recommendation 15: It is feasible to construct chained left and right RNP procedures with RF paths without an intermediate wings-level segment.

ILS Capture

Finding 16: Excluding one regional turbo-prop aircraft type (DH8D), no aircraft experienced difficulty in capturing the ILS with a fly-by turn onto final with only 2 NM intermediate length.

Finding 17: The aircraft type in question did experience difficulties, however these were also present when attempting ILS capture with the currently permitted 5 NM intermediate length. The difficulties were mitigated by monitoring LNAV to decide when to start the final turn, then performing a mode switch immediately afterwards with the flight crew performing the turn onto intercept. In this way the aircraft was able to capture the ILS in all wind conditions with 2 NM intermediate length. However, the operator's Chief Technical Pilot, who was performing the simulation, stated that they would deem it safer to use 3NM intermediate length as this would provide a buffer to correct any pilot error.

Finding 18: No difficulties were experienced by aircraft capturing the ILS with an RNP procedure with RF path onto final with only 2 NM intermediate length.

Tactical Parallel Offset (TPO) Capability

Finding 21: Only one operator reported the ability to apply non-integer value offsets on airways e.g., 1.5 NM.

Finding 24: There were some issues observed on the right offsets (inside of the turns) on both airways tested. These included going wide while taking up the offset and cutting off the turn. It was not clear whether this was due to the offset or a simulator issue.

Finding 25: Disregarding possible errors on the right offset, the distribution of deviations on straight legs and turns is similar to that on a non-offset route. This suggests that existing route spacing guidance can be applied to offset routes on airways.

Note: A number of findings were made from the application of TPO on SIDs but are not included here. Functional capability across the aircraft fleet is varied. TPO on certain leg types are not supported, engagement of TPO is different depending on the equipment and some aircraft types required flight crew intervention. Therefore, it is not recommended for future airspace designs.

Holding

Finding 26: Medium, heavy, and super-heavy jets fly consistent hold racetracks with the size dependent on the magnitude of the wind, but not the direction.

Finding 27: Some aircraft types fly an off-axis entry into a hold within the holding racetrack, and some will fly an extended entry outside of the racetrack.

Finding 28: Some aircraft types (DH8D and H25B) fly highly variable entries and asymmetric hold racetracks, with the axes in various directions depending on the wind direction. This behaviour makes for an unpredictable hold footprint.

Recommendation 29: Further research should be done into different methods for defining RNAV holding in order to allow a predictable footprint from which other routes or holds can be more closely spaced.

General

Finding 30: Some small-to-medium sized Business Jets such as the H25B, have bank angle restrictions (half maximum bank) above certain altitudes which limit their ability to fly predictable tracks on high-level routes, or non-altitude constrained routes. They have better climb performance than heavier jets and so can reach the restrictions earlier than may be expected for the majority of traffic on non-altitude constrained routes.

Phase 3

Scope of Research

Phase 3 of the PBN Research Project built on Phase 2 by researching real world aircraft Vertical Navigation (VNAV), Lateral Navigation (LNAV), Noise and Capacity aspects to inform new national standards regarding airspace efficiency through the application of PBN routes.

As with Phase 2, this was achieved through close cooperation being achieved with a cross-section of the aviation industry, from operators to aircraft and equipment manufacturers and the navigation data providers.

Phase 3 was split into two groups of work packages. The first group comprised work packages continuing research into lateral navigation performance. The second group investigated vertical profiles in both climb and descent.

Results and analysis from the lateral navigation work packages are documented in NATS Report, *PBN Research Project Phase 3 WP1, WP2 and WP3 (L4987/RPT/40)*. The report includes the analysis of Work Package 1 (Four Waypoint Hold Review), Work Package 2 (Wraparound SIDS) and Work Package 3 (First Turn Assessments).

Results and analysis from the vertical navigation work packages are documented in NATS Report, *PBN Research Project Phase 3 WP4 and WP5 (L4987/RPT/41)*. The report includes the analysis of Work Package 4 (Vertical Assessment (Climb Behaviour and Performance) including Noise Modelling) and Work Package 5 (Vertical Assessment (Descent Behaviour and Performance)).

All simulations were run in varying wind conditions. These work packages are summarised as follows:

WP1 - Four Waypoint Hold Review

Analysis of holding simulations (which tested using four fly-by waypoints as an alternative to standard holding practices using 7 NM leg lengths and 8 NM leg lengths in varying wind conditions) suggested that this concept could be used to provide a limited amount of airborne holding in a PBN environment. However, the results were inconclusive and whilst industry strives to deploy something more optimal in terms of use of airspace, current racetrack holding is the only option. It is recommended that perhaps further research look at the application of RNP Holding or something based on replicating the racetrack hold using RF turns, allowing for seamless entry, multiple hold circuits and exit.

WP2 - Wraparound SIDs

Analysis for the Wraparound SIDs simulations (which built on Phase 2 and aimed to further explore wraparound SIDS using 4 x 45° turns and 3 x 60° turns in varying wind conditions) suggested that the departure procedures with 4 x 45° turns and minimal PANS-OPS compliant spacing between the waypoints can be treated as equivalent to a series of independent moderate turns for route spacing purposes, provided that each turn has a 220kts speed constraint. This is therefore a recommended design for wraparound turns where an RNP procedure with an RF leg is not suitable. A departure procedure with 3 x 60° turns and minimal PANS-OPS compliant spacing between the waypoints had evidence of substantial ballooning in high wind conditions. As such, it is not recommended to design a procedure in this way, despite it being compliant with design requirements.

WP3 - First Turn Assessment

Analysis for the First Turn Assessments Simulations (which investigated the minimum distance required before commencing the first turn for departures using 0.2 NM, 0.4 NM and 0.6 NM) found that procedures with fly-over turns as early as 0.2 NM from the Departure End of the Runway (DER) appear to be attainable. However, pilots reported a preference for the procedure with 0.4 NM to give them time to properly initiate the turn. The RF turn at 0.2 NM was unattainable and required pilots to turn below 400ft in some cases. At 0.4 NM or 0.6 NM the turn appeared attainable (with the turn initiating slightly late but quickly establishing on the intended track). It is recommended that turns be designed with at least 0.4 NM from the DER, and that fly-over turns are preferable to RF turns. Fly-over turns with 0.2 NM from the DER are achievable. These recommendations are based on a limited dataset.

WP4 - Vertical Assessment (Climb Behaviour and Performance) including Noise Modelling

For departures, ‘AT or ABOVE’ and ‘AT or BELOW’ constraints showed the best performance, closely followed by ‘window’ constraints. The use of a series of altitude window constraints to define climb profiles, and thereby provide vertical containment in climb, is recommended. The use of a series of altitude ‘AT’ constraints to define climb profiles is not recommended because FMS predictive capability is often limited, and a series of ‘AT’ constraints provides no margin for predictive error.

The use of Original Equipment Manufacturer (OEM) desktop performance tools to define a series of altitude window constraints for the purposes of providing vertical containment in climb, is recommended.

Whilst the use of vertical departure splits may provide an additional safety margin to support reduced lateral divergence, the use of pure vertical departure splits to allow aircraft to depart with less than 2 minutes spacing is not recommended. However, the use of multiple vertical departure profiles to provide noise benefits to local communities is recommended. Higher profile SIDs, investigated as part of vertical departure splits, demonstrated potential for noise benefits compared to lower profile SIDs. Therefore, if at least some of the aircraft fly higher profile SIDs then this provides some measure of noise respite. Whilst this is basic analysis, the results may be a useful starting point for airspace projects.

The high/medium/low SID profiles were found to appeal to different aircraft types in different scenarios, but in general the Medium SID profile was found to be the most popular, with Business Jets and turboprops preferring the High SID profile and widebody jets preferring the Medium or Low profile. Further research is recommended into tools, procedures and training that could be employed to improve prediction accuracy.

WP5 - Vertical Assessment (Descent Behaviour and Performance).

The use of a series of altitude window constraints to define descent profiles, and thereby provide vertical containment in climb, is recommended. The use of a series of altitude ‘AT’ constraints to define descent profiles is not recommended. Aircraft generally preferred to fly at between 2.5°to 3.0°, finding 3.5° to be more challenging and requiring greater use of speed brakes and flaps.

General

QNH, temperature, and wind component have large effects on aircraft profiles and need to be catered for in the design of vertical profile constraints, as does the effect of acceleration/deceleration in adhering to the 250KIAS below FL100 rule.

Systemisation through multiple SID/STAR profiles which can be assigned to aircraft based on their vertical performance appears to be a realistic prospect.

Within WP5 and WP6, although FMC behaviour was quite consistent in prioritising IAS on climb and altitude on descent, aircraft capability in vertical navigation is varied, in particular for departure with some aircrew needing to manually adjust pitch to make constraints, with others letting the autopilot manage the profile.

CAA Comment on Vertical Navigation (VNAV)

In general, the NATS Phase 3 Project demonstrated that both the climb and descent path can be managed using altitude constraints. In climb, the nature of the “Open Climb” is more challenging to manage, especially given the variation in aircraft performance and to an extent, operator Standard Operating Procedures (SOPs). In descent, path management depends again on the aircraft types and their FMS capability in using the procedure – see Figures 7 and 8. Energy management is key.

Figure 7: Geometric Path Boundaries Between Constraints

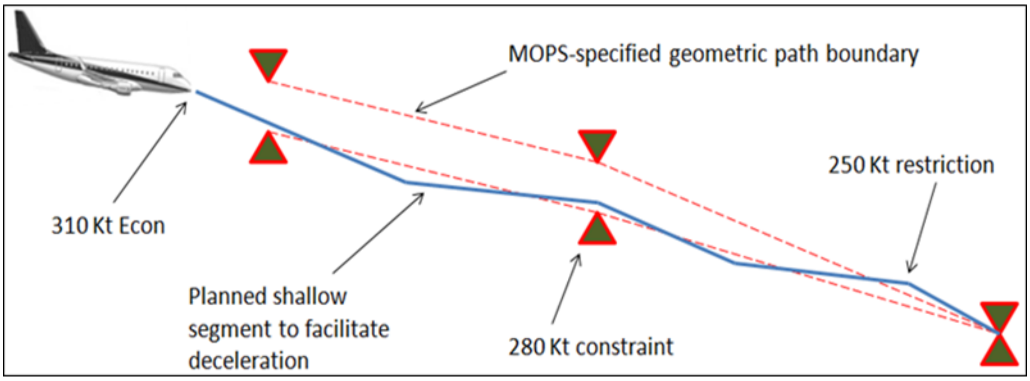
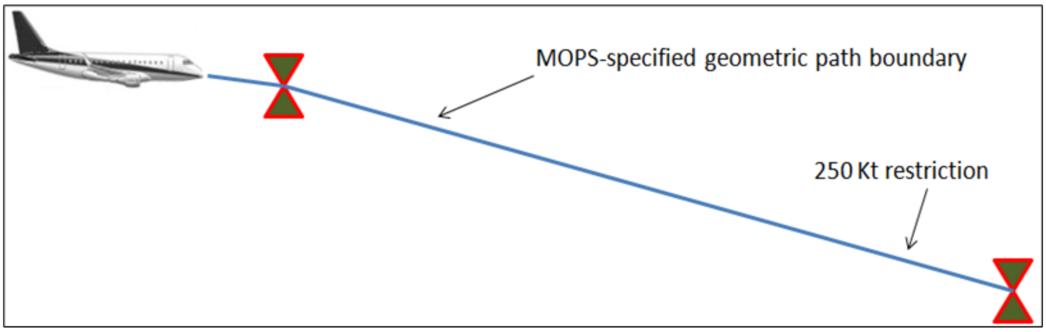


Figure 8: Point-to-Point Altitude Constraints



*MOPS RTCA DO-283B, Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation, 2015.

It is important to note that unlike Lateral Navigation (LNAV), there is no concept of RNP in Vertical Navigation (VNAV). Today’s vertical dimension is dependent on Barometric system performance and the sensitivities that apply, including the effects of pressure changes and pressure altitude corrected for temperature i.e., Density Altitude. There is no vertical equivalent to the lateral Onboard Performance Monitoring and Alerting (OBPMA) concept described in ICAO Doc 9613, PBN Manual. In the forthcoming Edition 5 of the manual, ICAO has gone to lengths to clarify the distinction between ‘vertical guidance for operational credit’ or ‘Approved VNAV’ as opposed to the application on VNAV on procedures where VNAV is not required, often referred to as ‘Advisory VNAV’. The former is required in support of instrument approach procedures for use in the Final Approach Segment, whereas advisory vertical guidance is provided by the aircraft's avionics and its use is left to the discretion of the flight crew.

Further research is required if 'Approved VNAV' is to be used on say departures and arrivals and that might require a technology change to a geometric-based altitude reference system. In the meantime, the airspace designer should factor the vagaries of today's Barometric reference system and how aircraft and the FMS manage the vertical profile in year-round environmental conditions.

CAA Comment on Speed Restrictions

In addition to the above, airspace designers should take account of speed restrictions supported by the FMS (VNAV system) at altitudes and/or waypoints. These restrictions may be required for tactical airspace operations or as part of a procedure supported by the VNAV system. When speed restrictions are assigned at a waypoint, the VNAV System will support "AT", "AT or ABOVE" and "AT or BELOW" types as described in Table 5, Operational Applicability of Speed Restrictions.

Note: Flight phase affects the way the speed restriction is applied before and after the waypoint.

Table 5: Operational Applicability of Speed Restrictions

Speed Restriction Type	Speed Applicability by Operation	
	Departure / Missed Approach (CLIMB)	**Arrival / Approach (DESCENT)**
AT or BELOW	Do not exceed PRIOR to and AT	Do not exceed AT and AFTER
AT	Do not exceed PRIOR, do not go below AFTER, cross AT	Do not go below PRIOR, do not exceed AFTER, cross AT
AT or ABOVE	Do not go below AT and AFTER	Do not go below PRIOR to and AT

1. For an "AT" speed restriction, the aircraft airspeed shall be at the speed restriction when the waypoint is sequenced.
2. For an "AT or ABOVE" speed restriction, the aircraft airspeed shall be at or above the restriction when the waypoint is sequenced.
3. For an "AT or BELOW" speed restrictions, the aircraft airspeed shall be at or below the restriction when the waypoint is sequenced.

4. When the same “AT” speed restriction is used between any two waypoints in the same flight phase, the aircraft shall treat the leg(s) between those waypoints as a constant speed segment at the restriction speed.
5. It is expected that the FMS equipment implementation of speed restrictions will be conveyed to regulatory authorities and airspace/procedure designers so that the operational implementation of speed restrictions will reflect actual avionics operation.

Further information can be found in RTCA / EUROCAE DO-236C Change 1, issued in September 2014 / ED-75E issued in June 2022, Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation.

Chapter 4

EUROCONTROL PBN Research

RNP to xLS

As part of their Single European Sky ATM Research (SESAR) work, EUROCONTROL has conducted extensive RNP to xLS (ILS, MLS or GLS) approach trials, again using flight simulation trials.

Their initial conclusions showed that with an RF leg connected directly to the FAF worked for a 5 NM final segment length.

Other findings included:

According to ARINC 424 (A424) rules a Final Approach Course Fix (FACF) should be coded, besides the Final Approach Fix (FAF). In so doing, EUROCONTROL developed the following practice:

- The point in the procedure, which is officially the FAF, was labelled in the A424 code as the FACF and another point, then labelled as the FAF in the A424 code 2 NM, placed downstream along the Final Approach Segment. This was necessary to have an RF leg that ends at the official FAF (the start of the glide) and not violate any A424 coding rules.

Two papers have been published jointly by EUROCONTROL Brussels, Belgium, and the Technical University Berlin, Germany:

- RNP TO PRECISION APPROACH TRANSITION FLIGHT SIMULATIONS, presented to the 33rd Digital Avionics Systems Conference, October 5-9, 2014.

and:

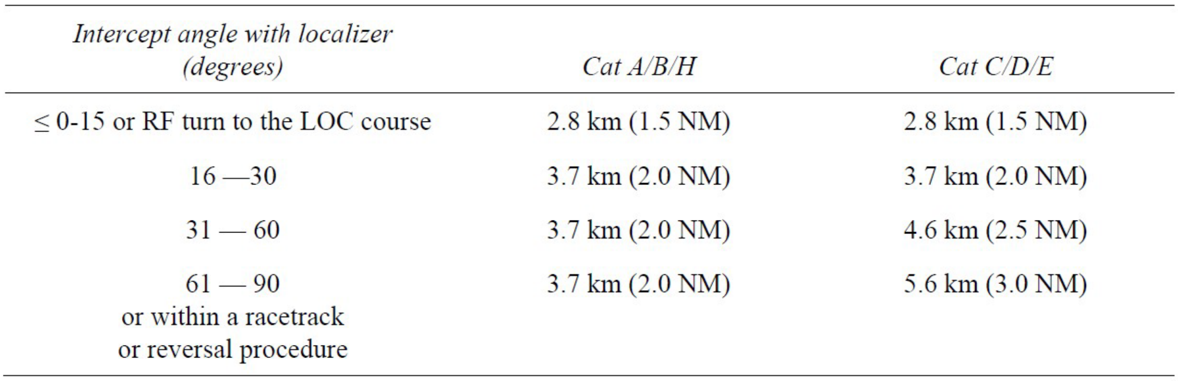
- SIMULATIONS INVESTIGATING COMBINED EFFECT OF LATERAL AND VERTICAL NAVIGATION ERRORS ON PBN TO XLS TRANSITION presented to the 34th Digital Avionics Systems Conference, September 13-17, 2015.

From this work, an industry group submitted proposals to the ICAO Instrument Flight Procedures Panel (IFPP). The proposal was supported by the above experiments but also by detailed analytical computations relating the minimum required distance between glide intercept and localiser intercept to the intercept height, angle at which the glide is intercepted, and temperature. The material was adopted in ICAO PANS-

OPS Doc 8168 Vol II[13] Seventh Edition, 2020 and can be found in Part II, Section 1, Appendix D to Chapter 1 “MINIMUM DISTANCE BETWEEN LOCALIZER AND GLIDE PATH INTERCEPTIONS AFTER AN RF TURN TO THE LOCALIZER/FINAL APPROACH COURSE”.

Based on this guidance a set of general criteria has been developed which apply up to temperatures of ISA +30 degrees and up to glide path interceptions at 3,000 feet above aerodrome elevation. For cases exceeding either of these values, criteria in Appendix D should be applied. The general criteria for an RF path to an ILS localizer can be found in Part II, Section 1, Chapter, 1.3.6 “RF turn to the localizer course (Applicable as of 4 November 2021)”. Reference is made to Doc 8168 Volume II Table II-1-1-1, copied below, which specifies that the minimum distance between localizer and glide path interception shall be 1.5 NM.

Table 6: ICAO Doc 8168 Volume II, Table II-1-1-1, Minimum distance between localizer and glide path interceptions



Intercept angle with localizer (degrees)	*Cat A/B/H*	*Cat C/D/E*
≤ 0-15 or RF turn to the LOC course	2.8 km (1.5 NM)	2.8 km (1.5 NM)
16 —30	3.7 km (2.0 NM)	3.7 km (2.0 NM)
31 — 60	3.7 km (2.0 NM)	4.6 km (2.5 NM)
61 — 90 or within a racetrack or reversal procedure	3.7 km (2.0 NM)	5.6 km (3.0 NM)

For MLS, GLS and SBAS approaches there are similar subsections and tables in the applicable sections in ICAO Doc 8168. For GLS and SBAS approaches, minimum distance between final approach and glide path interceptions after an RF path is 1 NM (up to temperatures of ISA +30 degrees and up to glide path interceptions at 3,000 feet above aerodrome elevation, otherwise the criteria in Part II, Section 1, Appendix D to Chapter 1 applies).

In summary, all the available guidance for the design of RNP to xLS procedures, can be found in ICAO PANS-OPS Volume II current edition.

FMS Holding Function Study

More recently, EUROCONTROL has conducted an extensive study with an Analysis of Holding Functions in the ECAC fleet. This work was in support of SESAR Wave 2

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[13] Construction of Visual and Instrument Flight Procedures

PJ14 Solution 76, with a report published in December 2021 followed by a presentation to the Combined 6th ICAO EUR PBN Consolidation Task Force and 33rd EUROCONTROL Navigation Steering Group meeting (PBNC TF/6-ECTL-NSG33), in April 2022.

In their study, EUROCONTROL investigated the functionality, performance and operational use of holding functions available in different aircraft FMS. In total, ten different aircraft / FMS combinations were used with holding performed at 5,000ft, at 230KIAS, with maximum ICAO wind (57kts) coming from four different directions and four different entry positions. The study examined both outbound timing (1 minute) and outbound distance (4 NM) in the scenarios, some 32 scenarios in total.

The study also took in a review of aircraft flight manual, and the applicable procedure design and aircraft equipment standards (ICAO Doc 8168 Vol II, RTCA DO-236C / EUROCAE ED-75D and RTCA DO-283B).

There are currently two sets of criteria for RNAV holding in the Seventh Edition, 2020 of ICAO Doc 8168 (PANS OPS)[14]: RNAV holding requiring a RNAV holding function and RNAV holding not requiring an RNAV holding function. Requirements for the latter are based on the conventional holding criteria. There are currently no developed industry standards for an RNAV holding function although the MASPS and MOPS (RTCA DO-236C / EUROCAE ED-75D and RTCA DO-283B) have criteria for RNP Holding which is further explained in the report.

All simulations were conducted on EASA Level D certified flight crew training simulators. The simulators were equipped with digital data recording and video recording functions.

The plotted tracks were compared with the primary protection areas for both RNAV holding requiring an RNAV holding function and for RNAV holding not requiring an RNAV holding function. It was found that all the tracks were within the protection areas. Based on the visualised tracks the assumptions in PANS-OPS regarding the criteria for RNAV holding requiring an RNAV holding function were evaluated. Whereas in some quadrants, the recorded tracks were close to the protection areas, in other quadrants the protection areas have a relatively large volume of unused airspace. Most of the volume of the protection areas is consumed by the holding entry procedures. Because the aircraft needs to overfly the holding fix before starting the entry procedure, large overshoots of the inbound holding axis happen on the non-holding side, especially for parallel and direct-close-to-parallel entry procedures. This is not the case with RNP Holding including the RTCA DO-236C / EUROCAE

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[14] At IFPP/15, held in April 2021 the panel agreed to a proposal to remove criteria relating to “RNAV Holding with Holding Functionality” and re-introduce criteria related to RNP Holding in line with clarification provided by the ICAO PBN-Study Group and to align with the outcomes of the forthcoming Fifth Edition of Doc 9613, PBN Manual.

ED-75D and RTCA DO-283B recommended entry procedures. The latter function is only available in a subset of the fleet currently but has great potential to significantly reduce the required airspace for holding procedures.

CAA Comment on Holding

The EUROCONTOL Holding Function Study and the NATS PBN Research have provided complimentary research into the perennial issue of how to reduce the volume of airspace required for racetrack holding and how to ensure repeatable and predictable performance from such holding, so as to provide optimal route spacing for routes against holds. The study summary is included here as another reference to the airspace designer.

Until such time as RNP Holding functionality becomes more widespread in the UK and ECAC aircraft fleets and airspace designs can incorporate the benefits, the lessons learned from both the NATS PBN Research and EUROCONTROL studies serve as a design reference for use by industry.

Chapter 5

Summary

The NATS DEP (Phase 1) Project and subsequent PBN Research Phase 2 and 3 Projects have collected and analysed a comprehensive and robust sample of aircraft navigation performance data from live operations, involving departures from Heathrow and Gatwick Airport, a High-Level, High-Speed (HLHS) trial together with flight simulation work packages involving multiple operators and aircraft types.

The NATS data has been supplemented by CAA's own analysis of operational data collected by London Stansted Airport which has enabled route spacing to be derived for routes comprising the Fixed Radius (RF) path. CAA and DNV have validated the NATS operational data and analysis and NATS reciprocated with validation of the London Stansted RF operational data and analysis.

Applying the Loss of Separation Risk Model (LSRM) method to the collected data has enabled the derivation of a set of recommended minimum route spacing values for different route interactions with a given loss of separation frequency. The loss of separation frequency is then used by the ANSP in supporting a safety argument that a particular route spacing is tolerably safe.

This guidance document updates the First Edition of CAP 1385 in providing a matrix for the more typical route interactions envisaged in both terminal airspace sector design and in the en-route flight phase. The route spacing values are significantly closer than those previously recommended from earlier analysis and are typically 1 NM to 2 NM greater than the minimum radar separation standard for the airspace depending on the specific geometry of the routes (except for the wrap-around turns).

The data has been shown to contain a broad mix of aircraft types, operators, wind conditions, altitudes and speeds.

There are no operational reasons why the navigation performance of aircraft would deteriorate in the arrival of flight when compared to the departure phase. As such, the DEP (Phase 1) data from departure operations can be seen as directly applicable to all terminal and extended terminal operations within the appropriate speed and altitude parameters. The en-route flight phase has been independently assessed through the HLHS trial.

Given the inherent conservatism presented by more modern aircraft fleets (improved FMS and Flight Guidance Systems), it is considered that the values may be applied to a broader range of PBN specifications than just RNAV 1.

As mentioned in Chapter 1, these route spacing values consider only the risk arising from the nominal navigation performance. In order to assess the overall safety of any given airspace design, the other factors noted in those chapters would also need to be considered within the scope of the safety argument.

Other constraints should also be noted:

- The minimum safe spacing between PBN routes is dependent on a number of different factors. Given that there is no single acceptable separation standard, the Loss of Separation Risk Model (LSRM) method allows for the calculation of a minimum route spacing value under a specific set of circumstances. The route spacing values in this guidance are therefore based on a number of conservative assumptions deemed to be representative in a UK terminal airspace context.
- It is important that the Air Navigation Service Provider (ANSP) monitors key assumptions including blunder error rates and controller intervention success rates post implementation.
- The LSRM method relies on the current concept of operation with controllers responsible for separating aircraft and cannot be extended to situations in which separation depends solely on navigation performance.
- Assessment of Cumulative Risk should be made as part of any change to a sector where LSRM has been applied, especially noting that the airspace design authority may be an airport.
- Assessment of who owns LSRM risk should also be considered as part of any new airspace design using this guidance. The ATS controlling authority i.e., the owner of the LSRM risk, should be consulted on any application of LSRM in airspace under their control.

In summary, using the methods developed in the First Edition of CAP 1385 for assessing the safe separation between PBN routes in a tactically monitored and controlled environment, the UK now has a comprehensive set of route spacing values that may be applied across all flight phases. The Second Edition of CAP 1385 has also shown how route navigation performance data analysed in support of LSRM, may also be applied to route spacing against the boundary of controlled airspace (CAS). Whilst more problematic, for completeness, guidance is provided in this Edition for the spacing of routes against holds - see Chapter 1.

DEP (Phase 1) was not just concerned with route spacing and in Chapter 2 an assessment of the work conducted by NATS on Reduced Departure Divergence (RDD) is included, together with a commentary on international developments (ICAO and FAA).

The PBN Research Phase 2 and 3 data has helped to inform NATS' own position and that of airports and third-party airspace design companies on the latest PBN techniques available with which to modernise UK airspace. Again, this evidence is strongly supported by EUROCONTROL led studies - see Chapters 3 and 4 respectively.

Chapter 6

Acknowledgements

The CAA is indebted to the access to data provided by NATS and in particular for the support of the respective NATS DEP and PBN Research Teams. Production of this guidance document would not have been possible without the expert advice and opinion provided by DNV in helping to validate the NATS operational data and analysis and in particular, develop the RF route spacing criteria.

Acknowledgement is also made to the Navigation Team within EUROCONTROL with whom the author of this document has worked closely over many years in helping to promote PBN applications and enable implementation across Europe. Their research is another important source of information and their PBN Handbook series a set of invaluable tomes for the designers engaged in modernising UK airspace.

APPENDIX A

List of Acronyms

ACP	Airspace Change Proposal
ANSP	Air Navigation Service Provider
ARINC	Aeronautical Radio Inc
ATC	Air Traffic Control
ATM	Air Traffic Management
CAA	Civil Aviation Authority
CDI	Course Deviation Indicator
CRM	Collision Risk Model
DEP	NATS Departure Enhancement Project
DME	Distance Measuring Equipment
DNV	Det Norske Veritas
ECAC	European Civil Aviation Conference
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FACF	Final Approach Course Fix
FAF	Final Approach Fix
FAS	Future Airspace Strategy
FL	Flight Level
FMS	Flight Management System
FRP	Fixed Radius Paths
FRT	Fixed Radius Transition
FTE	Flight Technical Error
GNSS	Global Navigation Satellite System
ICAO	International Civil Aviation Organisation

IFP	Instrument Flight Procedure
KIAS	Knots-Indicated Air Speed
kts	Knots
LNAV	Lateral Navigation
LSRM	Loss of Separation Risk Model
MRS	Minimum Radar Separation
NM	Nautical Miles
NSE	Navigation System Error
OEM	Original Equipment Manufacturer
PBN	Performance-based Navigation
RDAR	Route Design Analysis Report
RF	Radius to Fix
RNAV	Area Navigation
RNP	Required Navigation Performance
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SMS	Safety Management System
SOPs	Standard Operating Procedures
STAR	Standard Terminal Arrival Route
TLS	Target Level of Safety
TPO	Tactical Parallel Offset
TSE	Total System Error
VNAV	Vertical Navigation
VOR	Very High Frequency Omnidirectional Radio Range
xLS	ILS, MLS or GLS Landing System

APPENDIX B

Route interactions

DEP Phase 1 Trials

As described in Airspace Design Considerations in Chapter 1, route design elements within route interactions or scenarios may be assembled to describe a route structure. The characterisation of route design elements within the DEP (Phase 1) scenarios is shown below in Table 7.

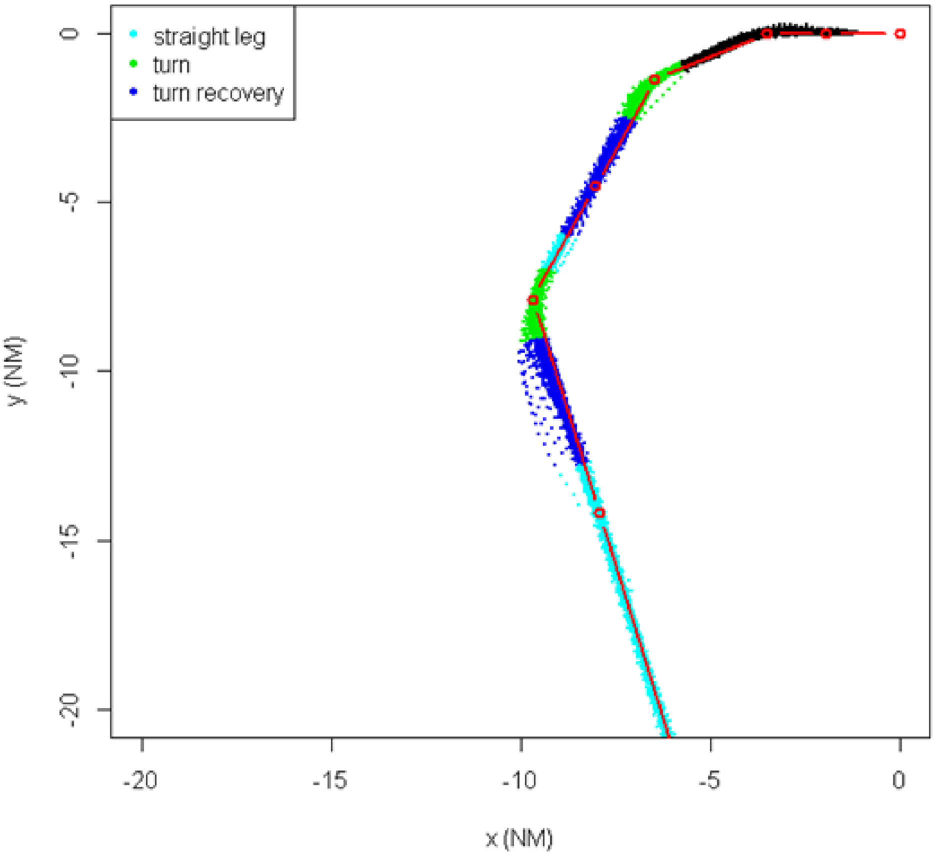
Table 7: Characterisation of SID Track-Keeping Performance

Distribution	Definition	Characteristics
Straight leg	A straight leg section is defined as any part of the SID which is not a turn or turn recovery	A symmetric distribution derived from a single-track point from the straight leg for each track
Shallow turn	A turn of < 25° starting 1 NM before the turn waypoint and ending 1 NM after the turn waypoint	An asymmetric distribution (inside and outside of turn must be treated separately) derived from the single largest observed derivation within the turn definition for each track
Moderate turn	A turn of 25-55° starting 1 NM before the turn waypoint and ending 1 NM after the turn waypoint.	An asymmetric distribution (inside and outside of turn must be treated separately) derived from the single largest observed deviation within the turn definition for each track
Sharp turn	A turn of 55-90° starting 1.5 NM before the turn waypoint and ending 1.5 NM after the turn waypoint	An asymmetric distribution (inside and outside of turn must be treated separately) derived from the single largest observed deviation within the turn definition for each track

Wraparound turn	A turn of 90-180° consisting of two fly-by waypoints, starting 2 NM before the first turn waypoint and ending 2 NM after the second turn waypoint	An asymmetric distribution (inside and outside of turn must be treated separately) derived from the single largest observed deviation within the turn definition for each track
Shallow turn recovery	A turn of < 25° starting 1 NM after the turn waypoint and ending 5 NM after the turn waypoint	An asymmetric distribution (inside and outside of turn recovery must be treated separately) derived from the single largest observed deviation within the turn recovery definition for each track
Moderate turn recovery	A turn of 25-55° starting 1 NM after the turn waypoint and ending 5 NM after the turn waypoint	An asymmetric distribution (inside and outside of turn recovery must be treated separately) derived from the single largest observed deviation within the turn recovery definition for each track
Sharp turn recovery	A turn of 55-90° starting 1.5 NM after the turn waypoint and ending 5.5 NM after the turn waypoint	An asymmetric distribution (inside and outside of turn recovery must be treated separately) derived from the single largest observed deviation within the turn recovery definition for each track
Wraparound turn recovery	A turn of 90-180° consisting of two fly-by waypoints, starting 2 NM after the second turn waypoint and ending 6 NM after the second turn waypoint	An asymmetric distribution (inside and outside of turn must be treated separately) derived from the single largest observed deviation within the turn definition for each track

Figure 9 below is taken from the NATS DEP report and illustrates an example of the segmentation of the DOKEN1A track-keeping data. This data was then used to derive the required lateral distributions.

Figure 9: SID Segmentation

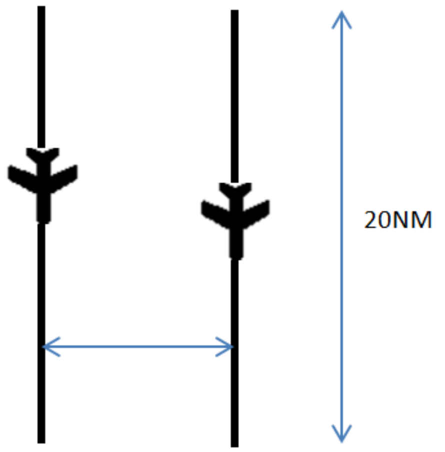


Having characterised various turn interactions, the First Edition of CAP 1385 created 9 scenarios using the above as building blocks. In this Second Edition, Table 1 has represented these turn interactions and the respective route spacing values in a matrix, extending from departures up to High-Level, High-Speed interactions.

DEP Phase 1 ATS Route Interaction Descriptions

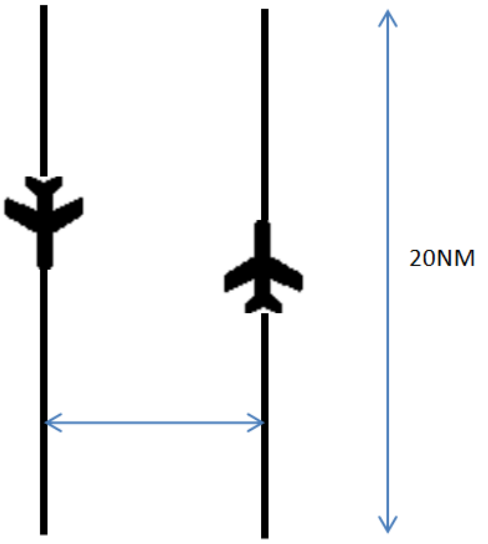
Same direction parallel straight routes

This scenario is of a sector with 20 NM of straight parallel routes with all aircraft travelling in the same direction.



Opposite direction straight parallel routes

This scenario is of a sector with 20 NM of straight parallel routes with aircraft travelling in opposite directions on the two routes.



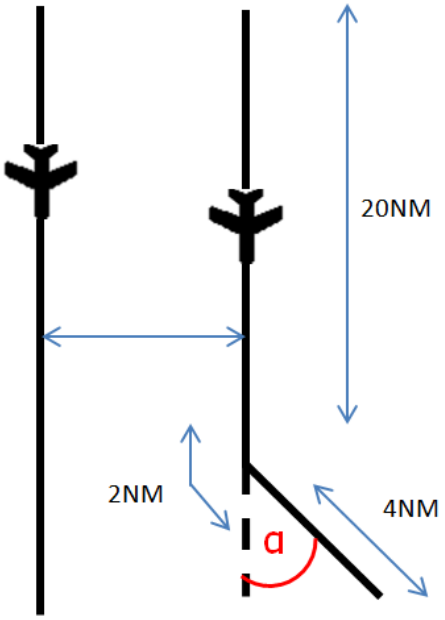
Moderate turn away when leaving a same direction parallel straight

This scenario considers 20 NM of same direction straight parallel routes with one route turning away at a 25° angle. This turn angle is the most conservative option since it falls within the worst case turn type (moderate turn) but with the slowest divergence from the neighbouring route.

This scenario comprises three separate sections, as follows:

- 20 NM of straight against straight.
- straight against a moderate outer turn of 2 NM; and
- straight against a moderate outer turn-recovery of 4 NM.

The divergence of the tracks after the turn has also been taken into account.

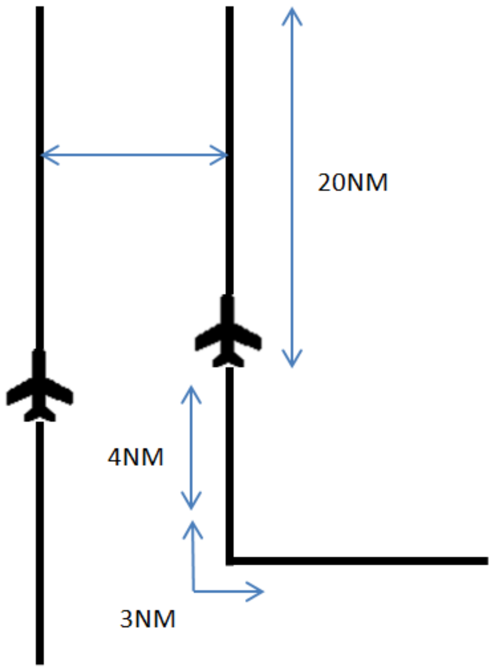


Joining a same direction parallel route with a 90° turn

This scenario considers a 90° turn joining a same direction parallel straight route.

The scenario comprises:

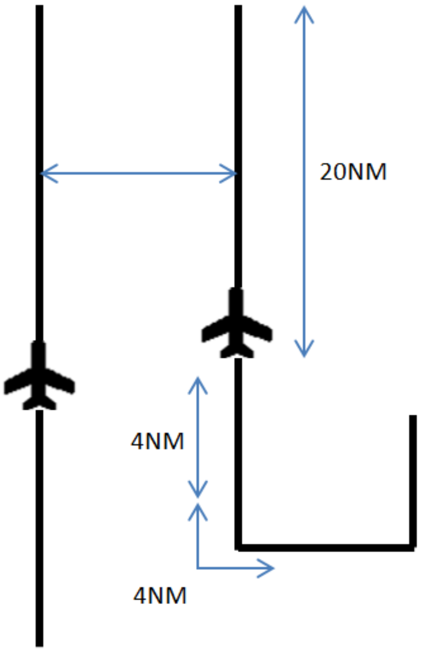
- 3 NM of the sharp turn (assumed to be speed constrained at 220kts).
- 4 NM of turn recovery (also assumed to be speed constrained for conservatism); and
- 20 NM of parallel straight.



180° wrap-around joining a same direction parallel straight

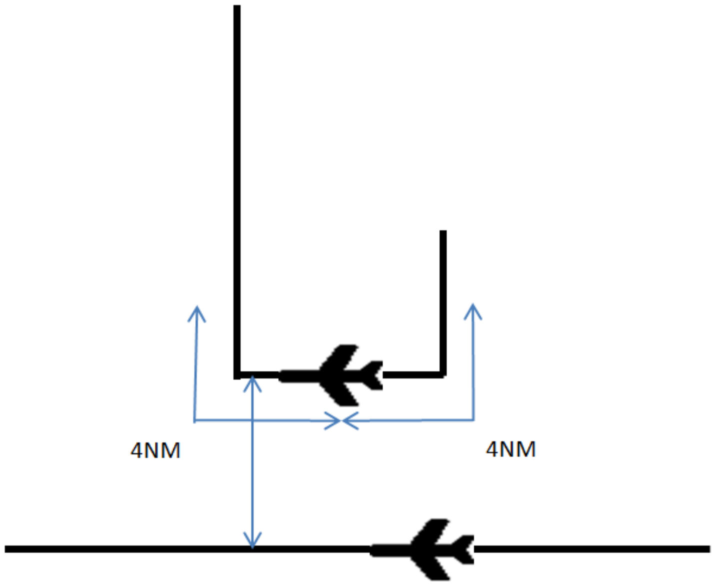
This scenario considers a 180° wrap-around turn joining a same direction parallel straight route.

In this scenario only 4 NM of the wrap-around turn has been considered (2 NM before and 2 NM after the second turn waypoint) since the impact of the first turn waypoint is negligible due to the distance from the parallel straight. 4 NM of wrap-around turn-recovery and 20 NM of parallel same direction straight is also considered. A 220kts speed constraint is assumed to be applied on the wrap around turn and the turn-recovery, with the aircraft accelerating to 250kts for the straight leg.



Same direction straight against the apex of a 180° wrap-around turn

This scenario considers a same direction straight leg in the vicinity of the apex of a 180° wrap around turn. The wrap-around consists of parallel straight is in the vicinity of two 4NM sections of wrap-around turn (2 NM before and 2 NM after each turn waypoint). A 220kts speed constraint is assumed to be applied on the wrap-around turn.

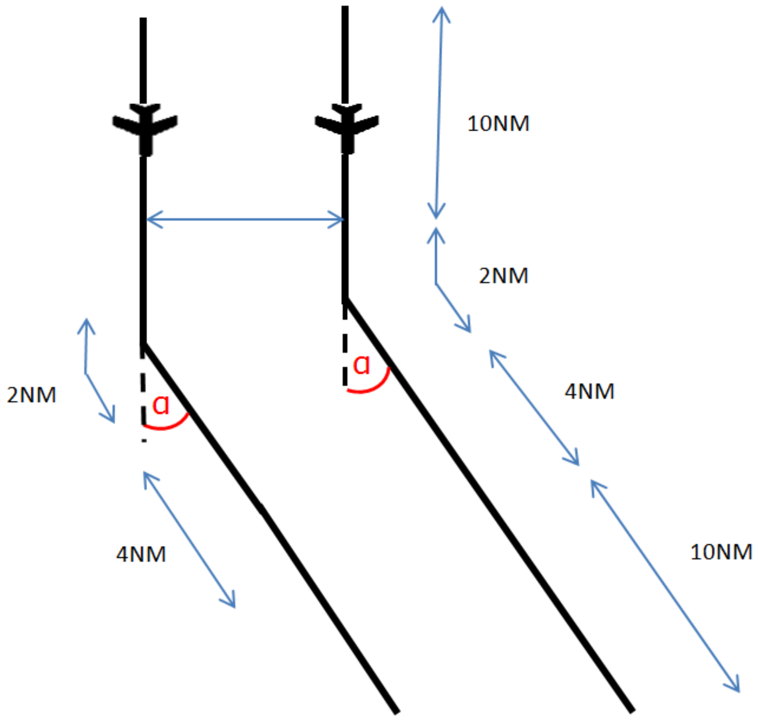


Same direction two shallow turns

This scenario represents two shallow turns i.e., < 25° where one turn is inside the other. In this scenario, the outside of one turn is in the vicinity of the inside of the other turn.

The scenario comprises:

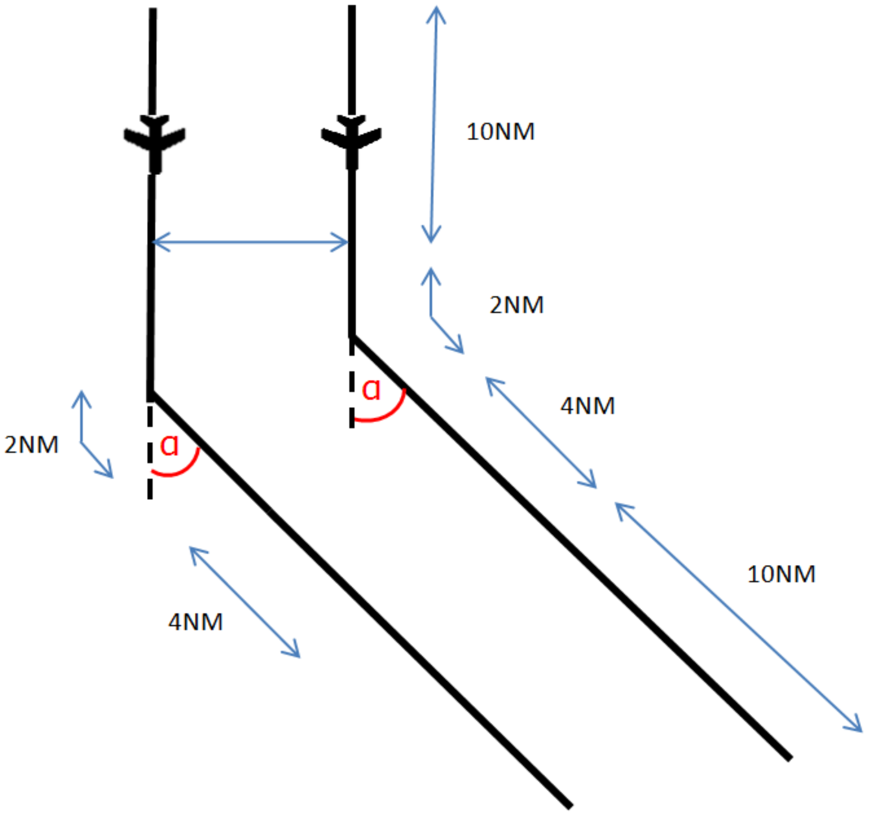
- 2 NM of shallow turn.
- 4 NM of turn-recovery; and
- 10 NM of straight segment before and after the turn.



Same direction two moderate turns

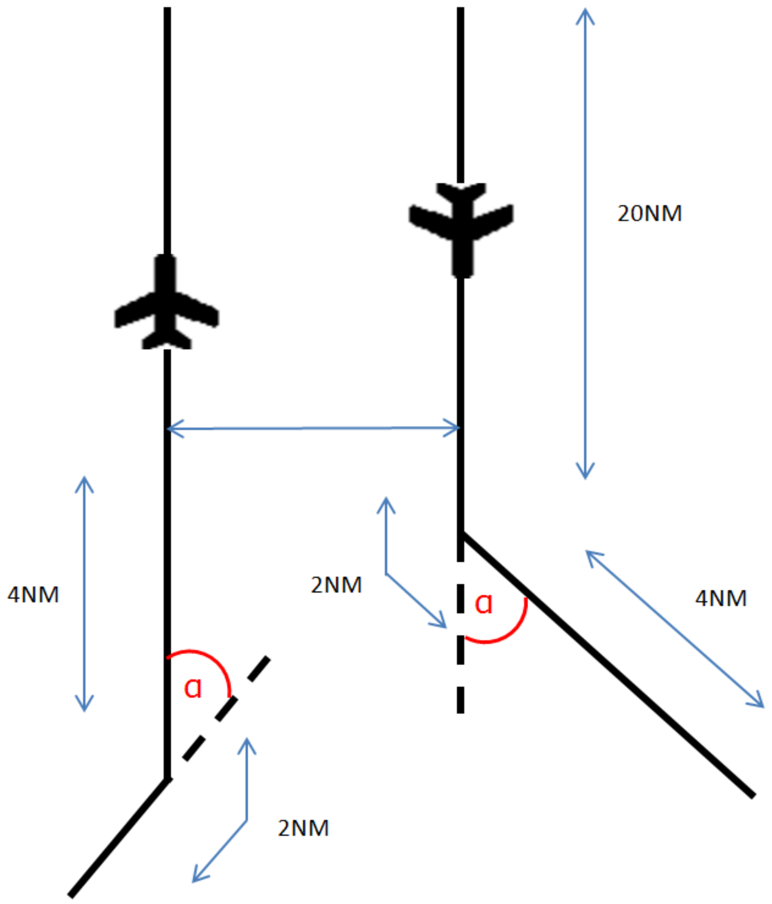
This scenario represents two moderate turns i.e., between 25° and 55° where one turn is inside the other. In this scenario, the outside of one turn is in the vicinity of the inside of the other turn. The scenario comprises:

- 2 NM of moderate turn.
- 4 NM of turn-recovery; and
- 10 NM of straight segment before and after the turn.



Two opposite direction moderate turns

This scenario represents the worst-case route interaction that can be envisaged, excluding wrap-around turns. It has two opposite direction routes, both with 25° turns in which the outer turn and outer turn recovery are in conflict.



High-Level, High-Speed (HLHS) Trial

Route segmentation for High-level High-Speed (HLHS) are summarised below.

Table 8: High-Level, High-Speed Route Segmentation

Distribution	Definition
Straight leg	A straight leg section is defined as any part of the route which is not a turn
Shallow turn	A turn of < 25° starting 4 NM before the turn waypoint and ending 4NM after the turn waypoint
Moderate turn	A turn of 25-55° starting 10 NM before the turn waypoint and ending 10 NM after the turn waypoint.

These definitions are based on the equivalent turn types identified in the prior research on terminal operations. However, since the moderate turn has only been assessed at 35°, it is not certain whether the results are applicable for 36-55° turns.