

Performance-based Navigation

Enhanced route spacing guidance

CAP 1385



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Chapter 1

Introduction

One of the key supporting enablers for the UK Future Airspace Strategy (FAS) is the re-design of UK terminal airspace¹ 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 and runway transitions. 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).

Generic ICAO and EUROCONTROL studies have indicated minimum spacing of 7 NM between routes and although UK ANSPs are able to design to less than this value, the assurance method (based on developing a Route Design Analysis Report (RDAR)) is 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. There has, however, been a lack of data supporting current airspace design techniques using PBN. The last 'new' CRM analysis used 1980's and 1990's data collected in the en-route sectors of Maastricht (MUAC) and in Zurich terminal airspace. Furthermore, the studies performed to date have been limited to same and opposite direction parallel tracks. Following a review of the previous work, it was

¹ Terminal airspace comprises departure routes (Standard Instrument Departures – SIDs) and arrival routes (Standard Arrivals – STARS, and runway/approach transitions).

concluded that the use of CRM to determine safe PBN route spacing in a complex tactically controlled airspace was inappropriate and that an alternative method was required.

The UK Civil Aviation Authority (CAA) and NATS have worked collaboratively to develop 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. This method has been 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.

The application of LSRM is a foundation piece for airspace change sponsors, and whilst in Chapter 8 and Annex 3 the guidance presents Minimum Acceptable Route Spacing Values for given route interactions, they cannot be applied literally. Chapter 3 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 – see Chapter 3. 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.

Throughout this work, DNV GL was commissioned by the CAA to support the independent review of the LSRM method and the analysis for each of the route interactions. Their report has 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.

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.

The CAA strongly recommends that prior to applying this guidance material the airspace design sponsor contacts the Authority to discuss their proposal.

Chapter 2

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 3NM is applied. The values are based on nominal aircraft navigation performance and do not take account of other factors as outlined in the first three bullets in Chapter 3, below.

The guidance is presented as a number of scenarios applying different straight and turning segments within typical airspace design route interactions. A summary of the respective route spacing values relative to a minimum radar separation standard of 3NM, can be found in Chapter 8. The route interactions covered in this guidance document are as described in Appendix C.

Chapter 3

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:

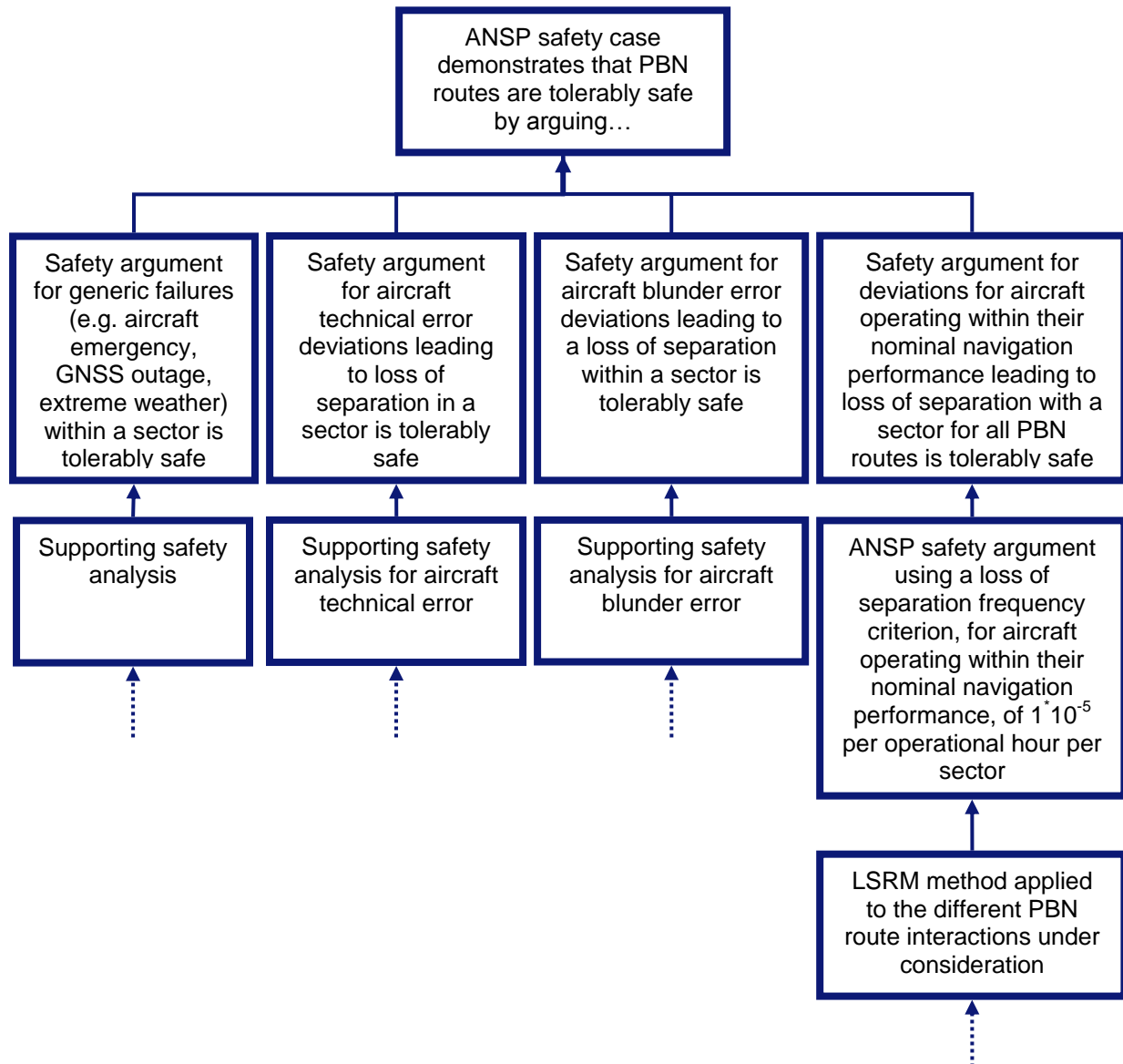
- Operational or ‘blunder’ errors, e.g. flight crew following an instruction intended for a different aircraft or flying of the incorrect procedure;
- Generic failures leading to intentional deviations, e.g. flight crew avoiding weather without informing ATC, aircraft emergencies, loss of GNSS coverage;
- 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



Chapter 4

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 approval

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 approval 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 coupled².

² Less sophisticated aircraft e.g., General Aviation types, operating at slower speeds may be flown manually in LNAV against a Course Deviation Indicator (CDI).

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 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 C. The scenarios may be considered as independent 'building blocks' which when assembled describe a route structure. It is important that the route design elements do not interact so as to assure fly-ability and the demonstrated 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 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 i.e. 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 C 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 DEP project has 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.

Chapter 5

Departure enhancement project methodology

The route spacing values are derived from the data collected and analysis undertaken as part of the NATS Departure Enhancement Project (DEP). 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 $<25^\circ$), moderate turns (a turn of $25 - 55^\circ$), a sharp turn (a turn of $55 - 90^\circ$) and a wrap-around turn (a turn of $90 - 180^\circ$). 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 GL, 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 in Chapter 3, 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 [cumulative risk for sector design](#).

Chapter 6

Origin of the data

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 in DEP involving 66 aircraft types (see Appendix B) 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 250kts³, 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.

³ All reference aircraft speeds are Knots-Indicated Air Speed (KIAS)

Chapter 7

Assumptions and conditions

Airspace designers, when considering application of the recommended route spacing values in our [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 3NM is applied. Where a different radar separation minima is applied, the route spacing values are transferable i.e. $MRS + x \text{ NM}$. 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 in Chapter 4, the NATS 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. For airspace designs outside of these levels, the applicant should make an assessment of the nominal navigation performance and the potential impact on route spacing.

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 reference scenarios NATS has 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

Appendix B lists the aircraft types and the number of flights recorded within the NATS DEP report. Any application of the LSRM method should include an assessment of the aircraft types using the intended routes and either an argument submitted for compatibility with the DEP distribution or else additional justification provided.

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 derived for Scenarios 5 and 6 listed in our [summary of route spacing values](#).

In the course of future data collections and analysis planned as part of the DEP work, it is anticipated that the route spacing for scenarios such as 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 C.

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 is derived from paragraph 3.2.4 (Hazard identification and severity assessment) of Annex 2 of Commission Implementing Regulation (EU) No. 1035/2011⁴ laying down common requirements for the provision of air navigation services. The Annex defines five severity classes for the outcome from ATM hazards

⁴ CAA Guidance Notes for complying with Commission Implementing Regulation (EU) 1035/2011 can be found at: <http://www.caa.co.uk/Commercial-industry/Airspace/Air-traffic-control/Air-navigation-services/Certification-and-designation/Certification-and-designation/>

with consequential effects on operations. The hazard being evaluated in this scenario requires the intervention of the controller to prevent a loss of radar separation and the best fit is considered to be Severity Class 4 with the effect of the operation described as: a 'Significant Incident' involving circumstances indicating that an accident, a serious or major incident could have occurred, if the risk had not been managed with safety margins, or if another aircraft had been in the vicinity.

In terms of loss of separation frequency, the CAA considers that a Severity Class 4 hazard is considered acceptable for frequencies of less than 10^{-5} events per operational hour per sector. This is therefore the acceptability criterion that has been used in the scenarios in Chapter 8.

Chapter 8

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 nine scenarios considered, as taken from the DEP Final Report and reviewed by DNV GL. Each scenario illustrates the application of the Loss of Separation Model to simple route interactions as described in Appendix C. A minimum radar separation standard of 3NM is assumed, as is applicable for the London Terminal Control airspace.

The minimum acceptable route spacing values have been subject to sensitivity analysis, both in terms of the parameters mentioned in Chapter 7, 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. 200NM instead of the 20NM 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 0.2NM.

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

Table 1: Summary of route spacing

Route spacing scenario	Description of route interaction	Minimum acceptable route spacing (M_x)
1	Same Direction Parallel Straight Routes	MRS + 0.8NM (3.8NM)
2	Opposite Direction Parallel Straight Routes	MRS + 1.2NM (4.2NM*)
3	Moderate Turn** Away when Leaving a Same Direction Parallel Straight	MRS + 0.9NM (3.9NM)
4	Joining a Same Direction Parallel Route with a 90° Turn**	MRS + 0.9NM (3.9NM)
5	180° Wrap-around Turn** Joining a Same Direction Parallel Straight	MRS + 3.4NM (6.4NM)
6	Same Direction Straight against the Apex of a 180° Wrap-around Turn**	MRS + 2.9NM (5.9NM)
7	Same Direction Two Shallow Turns**	MRS + 0.9NM (3.9NM*)
8	Same Direction Two Moderate Turns**	MRS + 1.2NM (4.2NM)
9	Two Opposite Direction Moderate Turns**	MRS + 1.7NM (4.7NM)

* Derived from DNV GL sensitivity analysis investigating tails of the lateral distributions

** All turns are Fly-By turns. Speed constraints apply to 90° and Wrap-around Turns

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 0.1NM to each baseline minima;
2. If 3 or more minimally spaced interactions include a turn greater than 25° then add 0.2NM 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.

Chapter 9

Summary

The NATS DEP project has collected and analysed a comprehensive sample of aircraft navigation performance data from live operations involving departures from Heathrow and Gatwick Airport. This data has been used to develop new methods for the assessment of safe separation between PBN routes in a tactically monitored and controlled environment. The work was undertaken to inform NATS' own position on airspace design and has been verified by the CAA enabling the development of new national guidance on PBN route spacing within the UK.

The operational trials have enabled the collection of a robust and accurate data set comprising aircraft nominal navigation performance reflected in terms of track-keeping accuracy on RNAV 1 Standard Instrument Departures (SIDs) comprising straight segments and 'Fly-by' turns.

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 provides values for the more typical route interactions envisaged in a terminal airspace sector design, although any number of bespoke scenarios can now be derived from the reference data set. The route spacing values are significantly closer than those previously recommended from earlier analysis and are typically 1NM to 2NM greater than the minimum radar separation standard for the airspace depending on the specific geometry of the routes (except for the wrap-around turns).

It should be noted that the recommended route spacing are based specifically on the data collected during the DEP project from departure operations from Heathrow and Gatwick. 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 or en-route phase of flight when compared to the departure phase. As such, this data from departure operations can be seen as directly applicable to all operations within the appropriate speed and altitude parameters.

It is anticipated that, subject to confirmation of the track keeping performance of aircraft operating at higher speeds and flight levels, the route spacing derived within the DEP project will be applicable to the design of RNAV 1 routes within all UK airspace.

As mentioned in Chapters 2 and 3, 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.

Chapter 10

Further work

This guidance will be updated and expanded with the addition of route spacing for additional scenarios as further data sets are analysed and route spacing developed. Further trials are being undertaken for aircraft operating at higher speed in the cruise phase, on orbital holding and on terminal procedures utilising RNP with Radius to Fix (RF) leg transitions. Additional scenarios (e.g. higher speeds on sharp turns) are also being assessed through flight simulation. At present the guidance is only applicable for application of RNAV 1 navigation performance. The latter route interaction is seen as vital in facilitating the implementation of PBN in UK Terminal Airspace and UK commitments to the deployment of SESAR through the Commission Implementing Regulation (EU) No. 716/2014 – ‘Pilot Common Project’.

Chapter 11

Acknowledgements

The CAA is indebted to the access to data provided by NATS and in particular for the support of the NATS DEP Team and for the expert advice and opinion provided by DNV GL Limited in helping to develop this guidance document.

Appendix A

List of Acronyms

ANSP	Air Navigation Service Provider
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
FAS	Future Airspace Strategy
FL	Flight Level
FMS	Flight Management System
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
LSRM	Loss of Separation Risk Model
MRS	Minimum Radar Separation
NM	Nautical Miles
PBN	Performance-based Navigation
RDAR	Route Design Analysis Report
RF	Radius to Fix Turns
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
VOR	Very High Frequency Omnidirectional Radio Range

Appendix B

Aircraft types included in the NATS DEP project

Aircraft Type	Number of Flights	Aircraft Type	Number of Flights	Aircraft Type	Number of Flights
A306	49	B753	160	E55P	1
A310	5	B762	1		
A318	9	B763	332	F50	2
A319	13,702	B772	872	F100	15
A320	9,983	B773	16		
A321	2,229	B77L	51	F900	3
A332	315	B77W	155	FA50	1
A333	103	B788	166	FA7X	1
A342	8	B789	3		
A343	169			F2TH	19
A345	1	BE20	1		
A346	336	BE40	3	GLEX	6
A388	88			GLF4	5
		C510	1	GLF5	6
AT72	60	C560	1	GLF6	1
		C56X	7	GL5T	1
B712	1	C680	2		
B722	2			H25B	12
B733	23	CL30	3		
B734	1,986	CL60	3	LJ60	1
B735	19				
B736	3	DA42	1	MD82	5
B737	60			MD83	1
B738	2,300	DH8D	100		
B739	24			P180	1
B744	841	E170	11		
B748	4	E190	175	RJ1H	2
B752	591			RJ85	1
Total					35,059

Appendix C

Route interactions

Introduction

As described in [airspace design considerations](#), route design elements within route interactions or scenarios may be assembled to describe a route structure. The characterisation of route design elements within the scenarios is shown below in Table 2.

Table 2: Characterisation of SID track-keeping performance

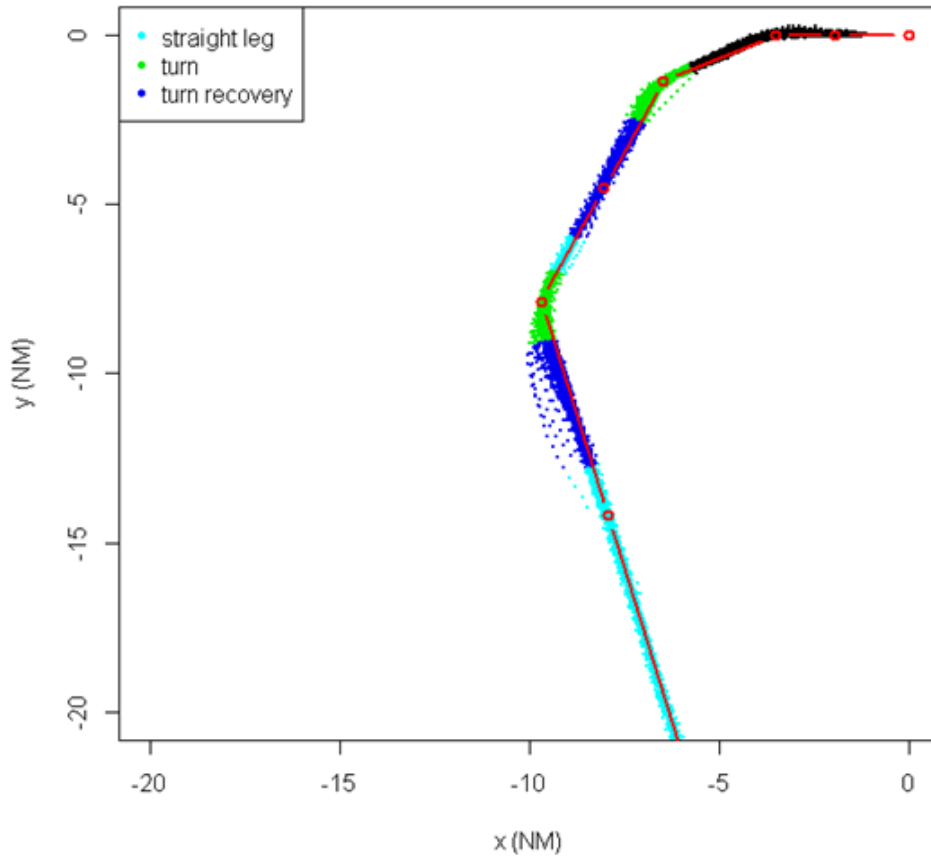
Distribution	Definition	Characteristics
Straight leg	A straight leg section is defined as any part of the SID which is not a turn or turn recovery	A symmetric distribution derived from a single track point from the straight leg for each track
Shallow turn	A turn of <25° starting 1NM before the turn waypoint and ending 1NM 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
Moderate turn	A turn of 25-55° starting 1NM before the turn waypoint and ending 1NM 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 1.5NM before the turn waypoint and ending 1.5NM 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 flyby waypoints, starting 2NM before the first turn waypoint and ending 2NM 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 1NM after the turn waypoint and ending 5NM 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 1NM after the turn waypoint and ending 5NM 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 1.5NM after the turn waypoint and ending 5.5NM 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 flyby waypoints, starting 2NM after the second turn waypoint and ending 6NM 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

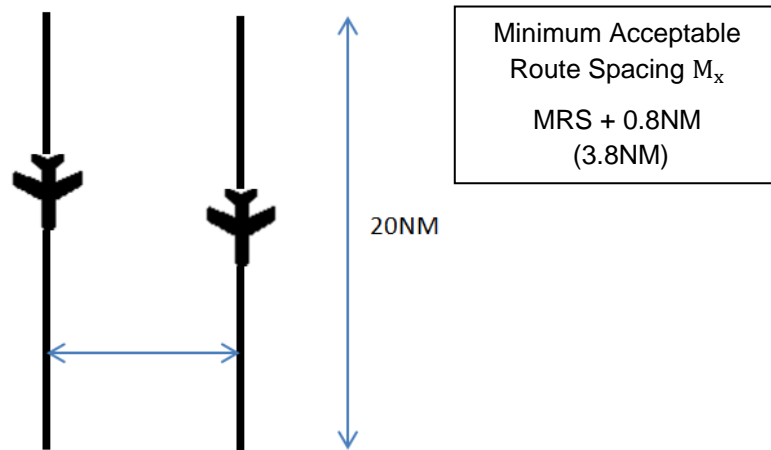
Figure 2 below is taken from the NATS DEP report, and illustrates an example of the segmentation of the DOKEN1A track-keeping data. This data was then used to derive the required lateral distributions.

Figure 2: SID segmentation



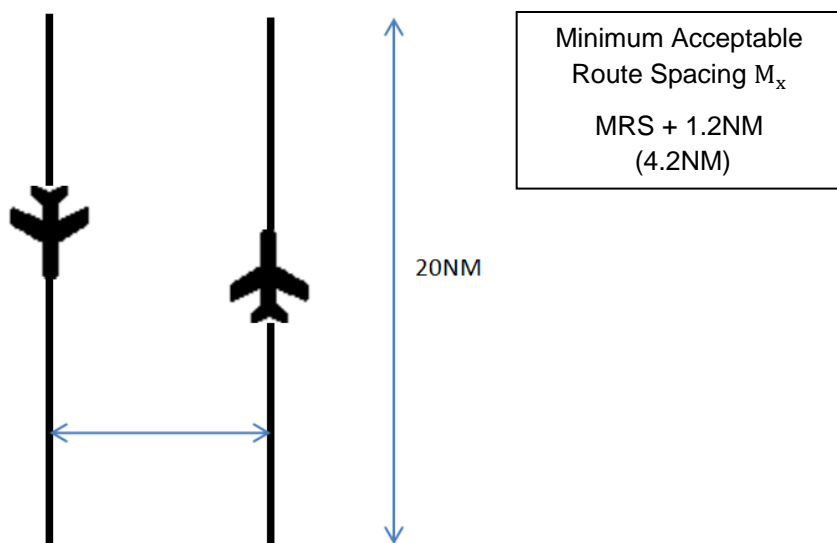
Scenario 1: Same direction parallel straight routes

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



Scenario 2: Opposite direction straight parallel routes

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



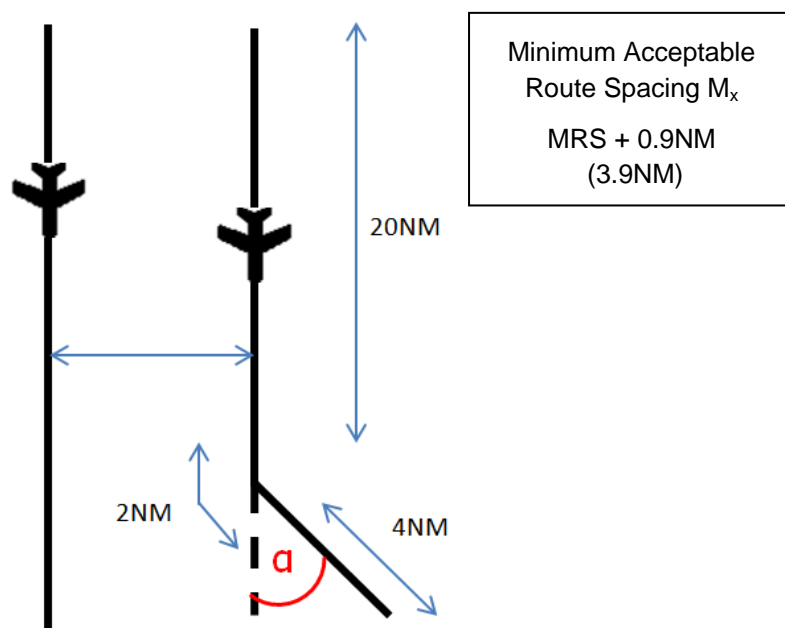
Scenario 3: Moderate turn away when leaving a same direction parallel straight

This scenario considers 20NM 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:

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

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

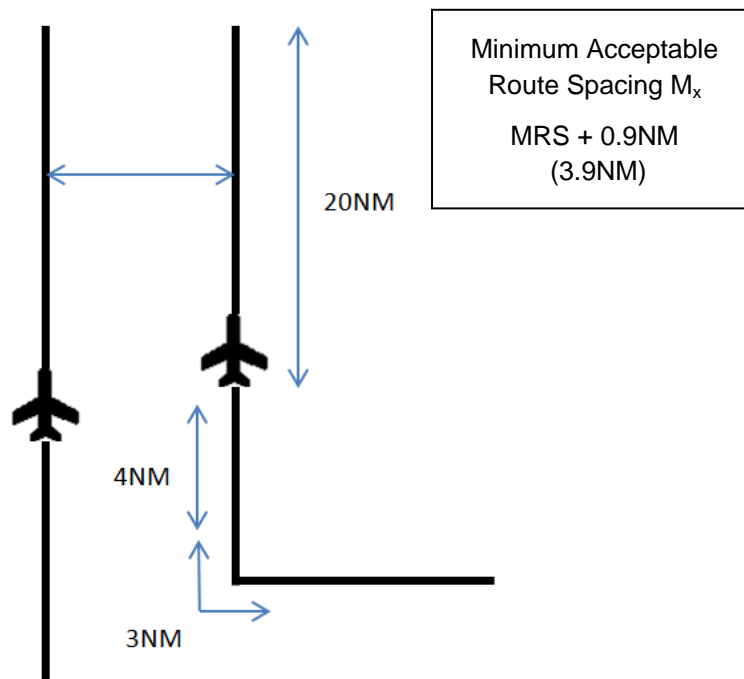


Scenario 4: Joining a same direction parallel route with a 90° turn

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

The scenario comprises:

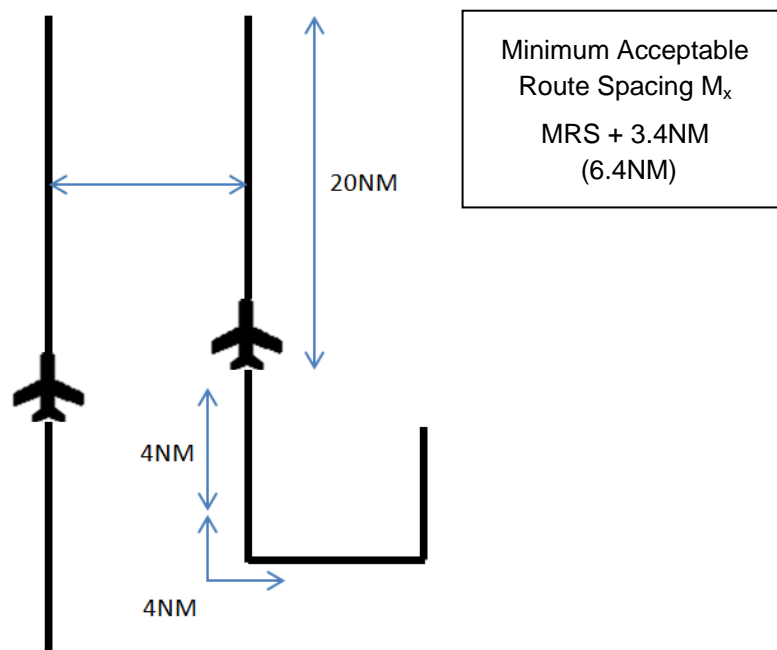
- 3NM of the sharp turn (assumed to be speed constrained at 220kts);
- 4NM of turn recovery (also assumed to be speed constrained for conservatism); and
- 20NM of parallel straight.



Scenario 5: 180° wrap-around joining a same direction parallel straight

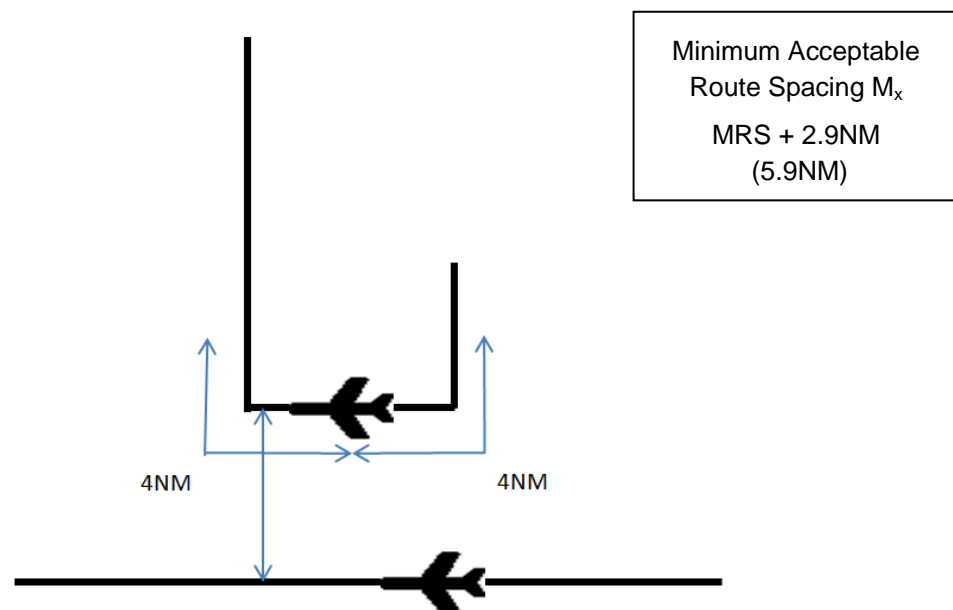
This scenario considers a 180° wrap-around turn joining a same direction parallel straight route.

In this scenario only 4NM of the wrap-around turn has been considered (2NM before and 2NM after the second turn waypoint) since the impact of the first turn waypoint is negligible due to the distance from the parallel straight. 4NM of wrap-around turn-recovery and 20NM 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.



Scenario 6: 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 (2NM before and 2NM after each turn waypoint). A 220kts speed constraint is assumed to be applied on the wrap-around turn.

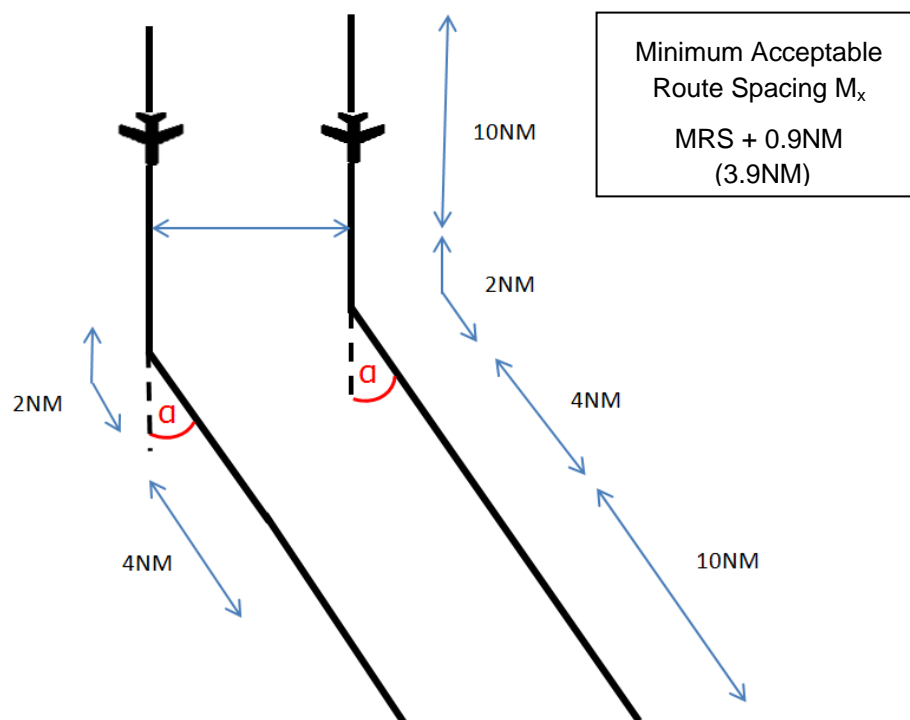


Scenario 7: Same direction two shallow turns

This scenario represents two shallow turns i.e. $<25^\circ$ 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:

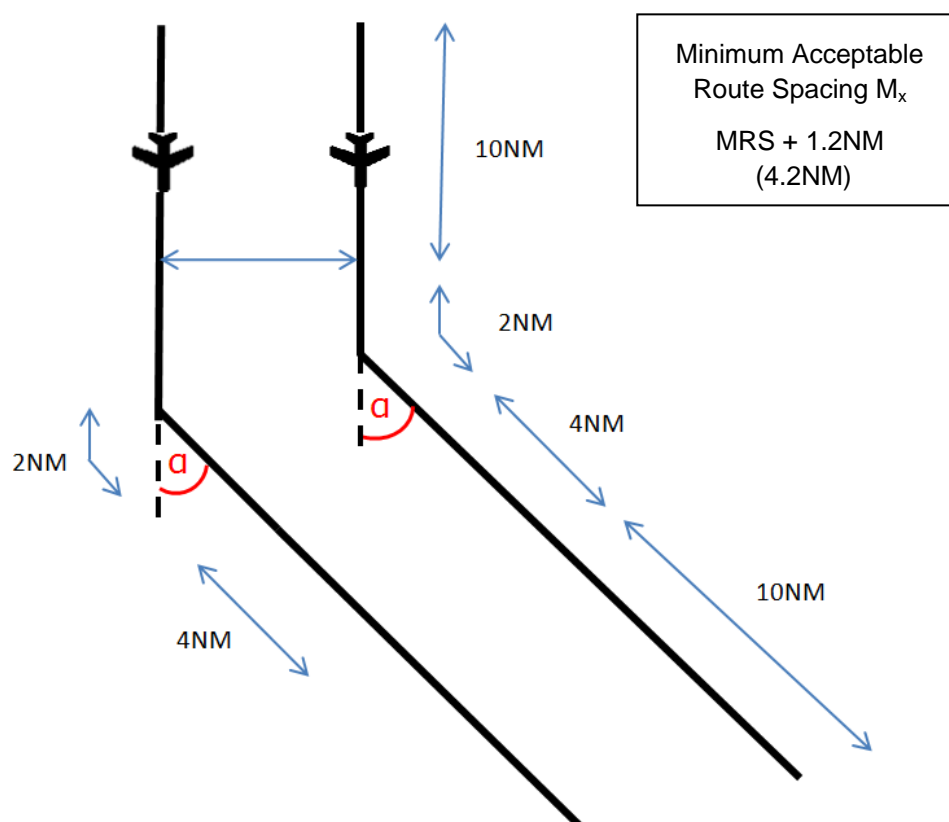
- 2NM of shallow turn;
- 4NM of turn-recovery; and
- 10NM of straight segment before and after the turn.



Scenario 8: 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:

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



Scenario 9: 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.

