Assessment of

Wake Vortex Safety

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S-WAKE
Final Report for Work Package 4
Probabilistic Safety Assessment

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Probabilistic Safety Assessment

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Summary

With the steady increase in air traffic, there is an urgent need to use existing and newly proposed technologies in an efficient way. This is reflected in the design of new high capacity aircraft (such as the Airbus A380) and new advanced ATM concepts and procedures (such as the High Approach Landing System (HALS) and the Wake Vortex Warning System (WVWS). An important capacity constraint factor is the risk imposed by wake vortices.

This document describes work undertaken in WP4 “Probabilistic Safety Assessment” of the project S-WAKE for the European Commission. The study comprises a quantitative safety assessment of wake vortex induced risk related to single runway approaches under current practice flight regulations. In view of the uncertainties and the difficulties in understanding the wake vortex phenomena, a probabilistic approach has been followed to evaluate the safety related to different separation distances between landing aircraft on a single runway. This probabilistic model is based on a stochastic framework that incorporates sub models for wake vortex evolution, wake encounter, and flight path evolution, and relates the severity of encounters to possible risk events (i.e. incidents/accidents).

The Wake Vortex Induced Risk assessment (WAVIR) methodology has been applied to study the safety related to single runway approaches. An extensive risk assessment – with different aircraft landing behind a Heavy aircraft and a Medium aircraft – has been carried out. The impact of weather and wind conditions (e.g. turbulence, stratification, crosswinds and head- and tailwinds) and procedural aspects (e.g. glide slope intercept altitudes, navigation performance, glide path angles, steep descent approaches) on incident/accident risk has been evaluated.
The risk assessment results have been compared with proposed risk requirements – based on historical incident data – to assess safe and appropriate separation distances under different conditions. It has been shown that a reduction of the current separation minima – and consequently an increase of capacity – might be possible under most operational and weather/ wind conditions (in particular crosswind and/or strong headwind conditions). However, it has also been shown that the separation distances might need to be increased under some specific weather conditions (e.g. with low atmospheric turbulence).

With respect to validation, it is recommended to analyse data collected within the Heathrow Data Base (HDB) (as part of S-Wake WP5) in more detail. So far, only partial sets of encounter data have been analysed and compared with the results from the probabilistic safety assessment. Further validation activities shall focus on specific elements of the individual sub-models, thereby taking into account validity, applicability and limitations of these sub-models.

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List of Abbreviations

ALARP	As Low As Reasonably Practicable
ATC	Air Traffic Control
ATM	Air Traffic Management
AVOSS	Aircraft VOrtex Spacing System
DP	Deceleration Point
EDR	Eddy Dissipation Rate
ETWIRL	European Turbulent Wake Incidence Reporting Log
FDR	Flight Data Recorder
HALS	High Approach Landing System
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
ILS	Instrument Landing System
ICAO	International Civil Aviation Organization
JAA	Joint Aviation Authorities
NLR	National Aerospace Laboratory
OM	Outer Marker
S-WAKE	Assessment of Wake Vortex Safety project for EC (2000 - 2003)
TLS	Target Level of Safety
VFR	Visual Flight Rules
WAVENC	WAke Vortex Evolution and WAke Vortex ENCounter (1998 - 1999)
WAVIR	WAke Vortex Induced Risk assessment methodology
WVBC	Wake Vortex Behaviour Classes
WVE	Wake Vortex Encounter
WVWS	Wake Vortex Warning System

1 Introduction

1.1 Scope

With increasing air-traffic congestion problems around major airports, the problem of wake vortex induced risks for aircraft following other aircraft has gained new interest, both in the USA and in Europe, where air traffic service providers such as DFS and NATS are undertaking large efforts. Research in the US by NASA was mainly focused on the development of a wake vortex spacing system (AVOSS) and wake vortex advisory systems (Refs. 33, 34, 35, 42, 48, 54). In Europe, airport operators such as Frankfurt Airport are spending large efforts in introducing new airport approach procedures (e.g. HALS/DTOP, i.e. High Approach Landing System/Dual Threshold Operation) in order to enable separation distances between aircraft to be reduced while retaining safety. The current separation minima based on aircraft maximum take-off weight, basically stem from the early 70s. Since the introduction of wake vortex separation minima the weight classification boundaries have been a matter of debate, and different weight classification boundaries are used in some countries, for example the UK. Although experience obtained over the past 30 years indicates that the wake vortex separation minima are ‘sufficiently safe’, the current safety level is unclear. Also there is a deficiency of tools and methods for bringing into account new developments in operational usage at busy airports and the introduction of new bigger aircraft in the air transport system.

1.2 The S-Wake project

In the European project S-Wake, running from January 2000 until March 2003 and co-ordinated by NLR, 14 partners collaborate to study the different aspects that influence wake vortex safety. Weather influence on wake vortex transport and decay is studied by CERFACS, DLR, NLR, the Met Office and Meteo France. Improved modelling with engineering type models is one of the aims. It is also investigated whether wake vortex behaviour can be classified in Wake Vortex Behaviour Classes (WVBCs) that depend on meteorological parameters. Provided that the WVBCs are sufficiently predictable a dynamic separation matrix might be considered that allows safe mitigation of separation distances under certain (predictable) weather conditions. The upset aerodynamic forces and moments that occur during a wake encounter are studied as well. Engineering-type models based on strip (ONERA) and lifting-surface methods (TU-Berlin) are implemented in flight simulators. Dedicated flight tests with a Do-128 (TU-Braunschweig) and with the NLR Citation II research aircraft behind the DLR ATTAS aircraft have been performed. Flight simulators at TU-Berlin, Airbus-D and NLR are used to study pilot's response during wake encounter and the pilot's perception of safety and hazards during simulated encounters. In parallel, a simplified method for computing the wake induced roll and flight path deviation is developed by ONERA and DLR. It incorporates a pilot wake vortex encounter (WVE) model. Resulting deterministic models for wake evolution and decay and aircraft flight path disturbance are used in a probabilistic tool for assessing the safety level related to single runway approaches. A risk management framework to regulate and control wake vortex induced risk is proposed by NATS and NLR. Finally, the project also includes the collection of data for landing aircraft at London Heathrow during a period of one year (about 30,000 landings). Radar tracking, runway logs and ground based (METAR) meteorological data are stored in the Heathrow data base (HDR). Flight data recorder data are collected by Spirent Systems and analysed by NATS with a wake vortex detection and classification tool developed by NLR. Statistical analysis of the wake encounters detected is meant to give modelling feedback and validation of the probabilistic safety assessments made by NLR.

1.3 Objectives of WP4: Probabilistic Safety Assessment

Tools and methods are needed to perform a quantitative assessment of wake vortex safety. Due to the uncertainties of the wake vortex phenomena, S-Wake WP4 follows a *probabilistic* modelling approach. Simplified deterministic models for wake vortex evolution and decay, and flight mechanics models for wake encounter and pilot response are integrated in a **probabilistic method for assessment of flight safety**. The study concentrates on the safety levels under current ATM separation rules, considering different classes of weather and a matrix of different aircraft weight classes. Results are analysed to explore possibilities for reduced separation rules under certain operational conditions.

The overall objective is to extend a probabilistic safety assessment model for wake vortex induced risk and to apply this model to evaluate the risk of single runway approach operations under current practice flight regulations. The work also includes the development of a risk management framework, which is based on a Target Level of Safety approach and describes how to judge the acceptability of the safety assessment results. This enables assessment of safe and appropriate separation minima under different operational and weather conditions. The outcomes of the probabilistic study are compared with the outcomes of WP5 (FDR data collection and analysis for Heathrow Airport). The work is split in the following Tasks:

- Task 4.1 Probabilistic safety assessment model
- Task 4.2 Safety assessment of current practice

The work is managed by NLR and involves contributions from NATS, DFS, ONERA and DLR.

The specific objectives of WP4, Probabilistic safety assessment, of the S-Wake project, are:

- To assess wake vortex safety in relation to the separation distance between aircraft landing on a single runway, and under different weather and operational conditions;
- To develop a risk management framework, which consists of appropriate risk metrics and associated risk requirements for wake vortex induced risk;
- To extend an existing probabilistic model for wake vortex induced risk, and to integrate simplified deterministic models for wake vortex evolution and decay, and flight mechanics models for wake encounter and pilot response in this probabilistic model;
- To improve an existing flight path evolution model, which describes the nominal flight paths of aircraft and probability distributions for the deviations from these nominal paths;
- To carry out a sensitivity analysis, so as to provide insight into how sensitive the accident risk assessment results are to the model parameters (and procedural aspects);
- To identify the key safety bottlenecks (safety criticalities) that have the largest contribution to the overall wake vortex induced risk;
- To allow for a sufficient level of validation, through evaluation of the safety assessment results and comparison with the outcomes of the S-Wake WP5 Heathrow Data Base (HDB) collection and analysis of "current practice" single runway approaches;
- To define and evaluate promising new concepts for reduced separation under certain operational and weather and wind conditions;
- To feedback operational recommendations to ATM designers of single runway approach procedures, so as to support the design of new and advanced risk reducing ATM procedures

1.4 Outline of the document

This document is organized as follows. Section 2 describes the single runway current practice scenario. Some procedural aspects and operational requirements, roles and responsibilities of humans involved (ATC, pilots), and the impact of weather and wind conditions is given. Section 3 contains the proposed risk criteria framework, to support risk based policy making. In Section 4 the probabilistic wake vortex safety assessment model is described. Section 5 presents the incident/accident risk assessment results for a variety of aircraft landing behind a Heavy aircraft (like e.g. Boeing 747-400) and a Medium aircraft (like e.g. Airbus A320). A sensitivity analysis, including quantification of the impact of weather, wind conditions, aircraft configuration, navigation performance and some procedural aspects on wake vortex induced accident risk, is also included in this section. The evaluation of safe and appropriate separation distances is contained in Section 6. The impact of some new concepts and procedures on runway capacity is evaluated in Section 7. The conclusions and recommendations are given in Section 8.

2 Single runway current practice scenario

2.1 Approach procedure and requirements

Provisions governing wake turbulence separation minima are published by ICAO (Refs. 29, 30, 31), and depend on the weight classes of the involved aircraft and the available equipment (e.g. radar or non-radar operations). The separation minima are based on categories, determined by different aircraft take off weight classes. For aircraft approaching a single runway under radar supported operations, the separation minima as recommended by ICAO are given in table 2.1.

Table 2.1 ICAO radar separation minima (in Nm) (wake induced separation minima in bold)

Leader / Follower	Weight (W)	Heavy	Medium	Light
Heavy	W > 136000 kg	**4**	**5**	**6**
Medium	7000 < W < 136000 kg	3	3	**5**
Light	0 < W < 7000 kg	3	3	3

Note that besides the ICAO categorisation, other weight classifications as a basis for wake turbulence separation are known and applied to operations at various airports. An overview of existing weight classifications is given in reference 44. Wake turbulence separation minima are not prescribed to VFR approaches, nor to IFR on visual approach. Under these circumstances, it is up to the pilot to guarantee separation with other aircraft. According to available facilities (e.g. ground and onboard equipment), a variety of instrument procedures have been developed to guide the aircraft safely to the runways during Instrument Meteorological Conditions (IMC). In general, an instrument procedure may have five segments: arrival, initial, intermediate, final and missed approach, as sketched in Figure 2.1.

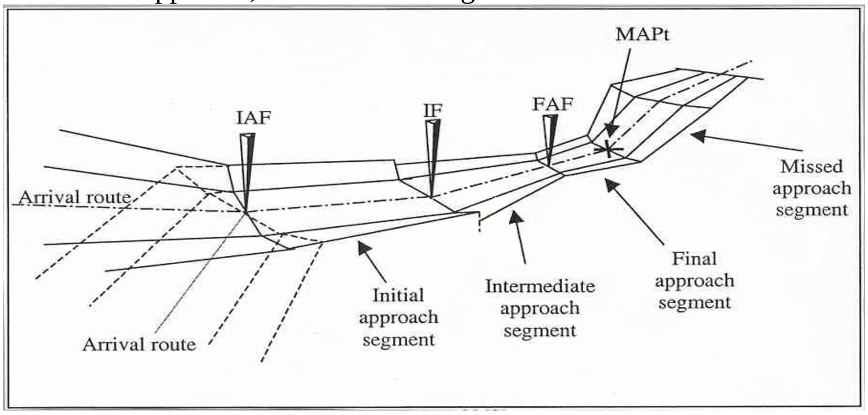

Figure 2.1 Instrument approach segments

This study only considers usage of ILS, the presently most common procedure. A detailed description of ILS procedures can be found in the PANS-OPS (Ref. 29).

2.2 Human involvement

In the process of securing safety of operations while optimising the airspace and runways, human involvement is of paramount importance. The two most important participants are the air traffic controller (who is responsible for separating aircraft to avoid wake turbulence hazards and for generating information to avoid vortices) and the pilot (who in the worst case experiences the presence of a vortex, and has to take counter actions to minimise the effects).

Air Traffic Control involvement

Beside separation standards, ICAO regulations (Ref. 31) prescribe that for aircraft in the "HEAVY" wake turbulence category, the word "HEAVY" should be included immediately after the aircraft call sign in the initial radiotelephony contact between aircraft and the aerodrome control tower or the approach control office prior to departure or arrival. The controllers also provide to aircraft, with whom they are in communication and which in the tower's opinion may be adversely affected by wake turbulence from a larger aircraft, the position, altitude and direction of flight of larger aircraft followed by the phrase "caution - wake turbulence."

Pilot involvement

Whether or not a warning has been given, the pilot is expected to adjust his/her operations and flight path as necessary to preclude serious wake encounters. Since vortices sink and may level off below the flight path of the generating aircraft, pilots should avoid the area below and behind the generating aircraft, especially at low altitude where even a momentary wake encounter could be hazardous. It is equally important that pilots of larger aircraft plan or adjust their flight paths to minimise vortex exposure to other aircraft. Of course, these actions are far more easy to apply for VFR approaches than for approaches under IMC conditions.

Some operational recommendations to pilots to avoid wake vortices under good visibility conditions are (Refs. 31, 32)

- Landing well beyond the preceding larger aircraft touchdown point;
- Passing over flight path of preceding aircraft, or at least 1000 ft under;
- Staying upwind of preceding aircraft flight paths;
- Extra vigilance on calm days when vortices persist longer.

Besides the above preventive measures, a pilot can take counter control actions or initiate a missed approach when he/she experiences a slight roll upset, and try to minimise the consequences.

2.3 Weather and wind conditions

It is important to realise the major influence of specific weather conditions, in particular wind conditions, turbulence, stable stratification and wind shear (Refs. 11, 12, 27, 44, 45, 51, 53). Generally vortex decay is enhanced in an ambient turbulence environment. Under stable stratification conditions, vortices will decay but may stall or rise. Wind shear, with weak turbulence and weak stable stratification may enhance stalling or rising vortices without significant decay. It was shown that vortices may stall or rebound to the glide path in the convective, stable stratified and sheared boundary layer. Important from a safety point of view is that rising vortices have been observed at higher altitudes that cannot be explained by rebound and ground effect (Ref. 45). Cross wind will of course lead to a drift of wake vortices out of the glide path of aircraft landing on a single runway, thereby reducing the risk to follower aircraft. The impact of headwind and/or tailwind conditions on wake vortex safety, however, is at present not really well understood. Recent research focuses on the development of procedures that may exploit certain weather conditions that enable a reduction of separation minima, so as to increase capacity. Examples are the High Approach Landing System (HALS), the Aircraft Vortex Spacing System (AVOSS), the Wake Vortex Warning System (WVWS), and the Integrated ATC Wake Vortex Safety and Capacity System (ATC-Wake).

2.4 Aircraft types and speed profiles

The (probabilistic) aircraft speed of the involved leader and follower aircraft is of major importance for the assessment of wake vortex induced risk:

1. The initial strength of wake vortices is inversely proportional to the aircraft speed of the leader;
2. The actual separation distance between leader and follower varies along the approach, as a consequence of differences in aircraft speed.

Relevant from wake turbulence perspective is that adequate separation has to be guaranteed anywhere along the glide path, and the speed control is often applied by ATC to ease fluent traffic (e.g. at London Heathrow airport and at Frankfurt airport). Thus, relevant are the *reference positions along the flight track at which appropriate separation distances are to be monitored by Air Traffic Control (ATC)*. Different European airports use different reference points: some airports use the runway threshold, whereas other airports use the Outer Marker. This also implies that – at such airports – the actual aircraft speed should not be dependent on the actual performance of aircraft types. The situation is even further complicated: first, different methods are used to indicate the speed of an aircraft and second, the actual wind situation (headwind or tailwind) influences the ground speed and actual separation distance and time (through the vertical wind *profile*) along the aircraft flight track.

3 Risk based policy making

3.1 Wake vortex risk requirements

WAVIR is developed as a safety management tool for regulating and controlling wake vortex induced risk on the basis of incident/accident risk *probability assessment* followed by a comparison with risk criteria. This requires the development of a probabilistic relation between the occurrence of wake vortex encounters and the severity of accidents and incidents. For incident and accident investigation purposes, ICAO consequence definitions are: accident, serious incident, non-serious incident, and non-determined incidents (Refs. 37, 38). For safety assessment purposes, the JAA has defined severity classes for adverse conditions: catastrophic, hazardous, major, and minor (Ref. 39). These two classification schemes have been combined into a classification of wake vortex induced consequences as follows (Refs. 1, 2, 23):

1. *Catastrophic accident:* aircraft encountering a wake hits the ground, resulting in loss of life;
2. *Hazardous accident*: the wake vortex encounter results in one or more on-board fatalities or serious injuries (but no crash into the ground);
3. *Major incident*: the wake vortex encounter results in one or more non-serious injuries, but no fatality, on-board the encountering aircraft;
4. *Minor incident*: encounter results in inconvenience to occupants or increase in crew workload.

A method to derive safe and appropriate separation minima for different operational and weather/wind conditions has been introduced (Refs. 1, 2). This method is based on:

- Risk metrics in terms of incident / accident probabilities per movement;
- Risk requirements derived on the basis of historical incident data from Heathrow airport.

Risk requirements based on the Target Level of Safety (TLS) approach are proposed. It should be noted that the use of the As Low As Reasonably Practicable (ALARP) approach was also considered. However, the usage of ALARP is not recommended for considering the issue of wake vortices because it is a small proportion of the overall landing risk. The approach followed in reference 4 is largely based on historical data, resulting in the proposed TLS values for the risk event probabilities per *queued* movement given in Table 3.1. Note that the TLS value for catastrophic accidents is based on the assumption that 2% of the landing risk is due to wake vortices and that about 50% of landing movements are queued.

The usage of the concept of *queued landings* is proposed. This concept is defined as a pair of aircraft with the following aircraft separated from the leading aircraft by a distance less than the appropriate wake vortex minima for the pairing plus 3Nm. This definition can be used for airports with single runway operations (e.g. London Gatwick), independent parallel operations (e.g. London Heathrow), and closely spaced dependent parallel runways (e.g. Frankfurt airport).

Table 3.1 Risk requirements (per queued *aircraft movement) (Ref. 2))*

Risk event	Proposed Target Levels of Safety
Catastrophic Accident	0.9×10^{-8}
Hazardous Accident	3.0×10^{-7}
Major Incident	1.0×10^{-5}
Minor Incident	5.0×10^{-4}

The method proposes that all four risk requirements are to be satisfied, i.e. the most stringent requirement will determine the required separation minima. This approach supports two commonly accepted rationales for acceptance of a newly proposed wake alleviation system (or procedure) by involved interest groups (i.e. pilots, controllers, regulators): by showing that the number of wake vortex induced risk events:

- does not exceed some pre-defined, and agreed upon, safety requirement;
- does not increase with the introduction of a new ATM procedure.

3.2 Illustration of method to derive safe separation minima

Figure 3.1 illustrates the proposed risk based policy making procedure to derive safe and appropriate separation distances for different operational and weather conditions. It is proposed that the most stringent of the four requirements determines the required separation minima (Refs. 2, 6, 8). Note that the derived separation minima (as determined with WAVIR) currently refer to the minimum separation distance *along the entire arrival path.* Airports might relate the required separation minima to specific points (e.g. the threshold or the Outer Marker).

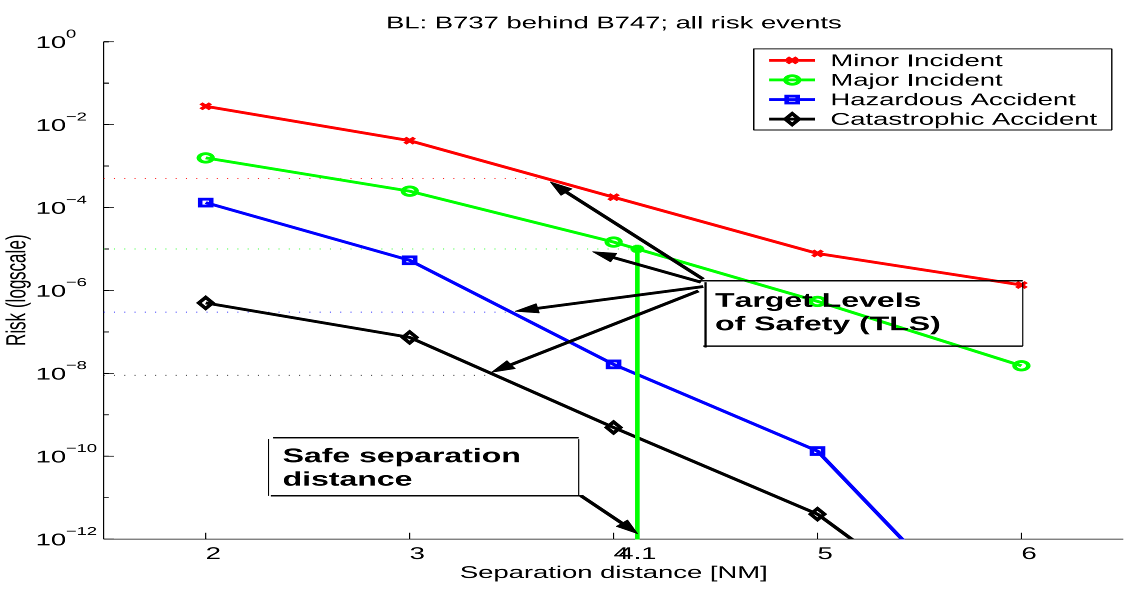

Figure 3.1 Risk management procedure to derive safe and appropriate separation minima

4 Probabilistic safety assessment model

To determine the metrics for the possible wake vortex induced risk events, an appropriate safety assessment model is required. In view of the uncertainties of the wake vortex phenomena, a *probabilistic* approach is followed (Refs. 22, 23, 40). This probabilistic model should enable evaluation of wake vortex safety under various operational and weather conditions. It should also be possible to evaluate the current practice as well as promising new concepts, such as new operational improvements, aerodynamic aircraft designs, or weather related separation minima. The approach should be able to cover different kinds of runway configurations. Considering these requirements, three probabilistic sub models are integrated within a stochastic framework:

- Wake vortex evolution model
- Wake encounter model
- Flight path evolution model

For the evaluation of wake vortex induced risk, it is necessary to develop a mathematical model to characterise wake vortex induced incident/accident probabilities. The basic elements of the Wake Vortex Induced Risk assessment (WAVIR) methodology and the numerical method to assess wake vortex induced incident/accident risk are given in the remainder of this section.

4.1 Overview of the safety modelling relations and dependencies

The incident/accident risk, in terms of minor incident, major incident, hazardous accident, and catastrophic accident probability, provides the information necessary for *regulatory authorities* to judge the acceptability of risk. However, pilots/crew and passengers will have a different perception of safety (in relation to actual encounters with wake vortices). Therefore, to also support the acceptability of risk assessment results by pilots/crew and passengers, the concept of *encounter severity* is introduced. Clearly, the more “severe” the encounter, the larger the incident/accident risk. The issue of appropriate *encounter severity metrics* (or *hazard criteri*a) has been studied in some detail (Refs. 7, 13, 14, 49, 52). Although it appears to be a subjective matter, the following two metrics have been chosen to classify individual encounters:

- Maximum attained bank angle;
- Encounter altitude.

To assess the numerical values of the selected risk metrics (in terms of risk event probabilities per aircraft movement (e.g. per approach or per departure), an incident/accident prediction model is proposed (see Section 4.5). It describes and characterises the probabilistic relation between individual (simulated) encounters and the risk of an incident or accident. The relations and dependencies between the different sub-models are visualised in Figure 4.1.

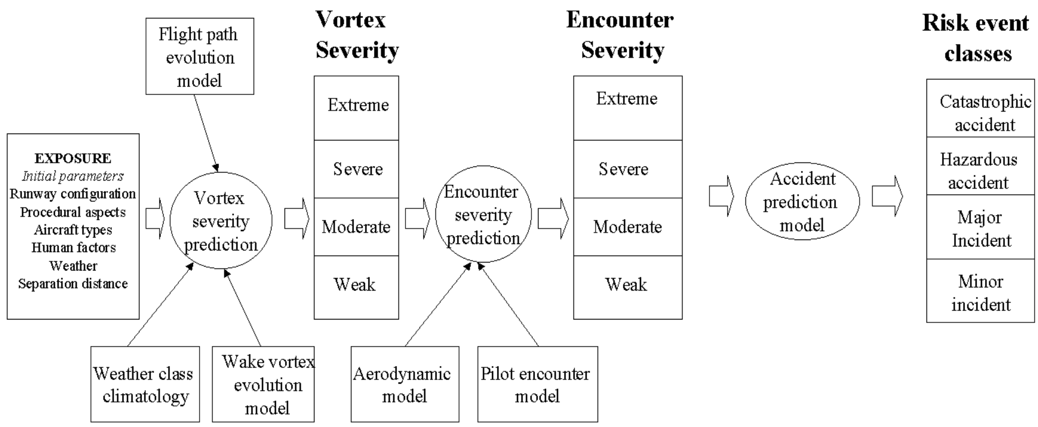

Figure 4.1 Overview of modelling relations and dependencies

4.2 Wake evolution model

Wake vortices are an inevitable consequence of the generation of lift. The thin shear or vorticity layers emanating from the trailing edge of a wing generally roll-up into two concentrated vortices within about 10 to 30 wing-spans behind the aircraft. The lateral distance between the vortices will be somewhat smaller than the wing span. The (initial) strength of the vortices shed depends on the weight (W), the wing span (b) and the flying speed (V) and altitude of the vortex generating aircraft:

$\Gamma = W/\{\rho V b s\}$,

where ρ is the air density and s is a factor smaller than one (bs is the lateral distance between the vortices). Figure 4.2 gives an impression of the induced flow angles across the vortex pair behind a Boeing 747-400 aircraft on final approach. Two cases, for two typical core sizes are shown, and wake decay has been neglected. The large flow angle upsets pose a potential risk for other aircraft entering the wake. In a quiet atmosphere and out of ground effect, the vortex pair will sink slowly due to mutual induction of the two - counter-rotating - vortices. A sink rate of about 1.5 to 2.5 m/s is found for aircraft on final approach. The motion of the vortices is influenced by the ambient wind and their decay is influenced by turbulence and the stability of the atmosphere. Vortex motion and decay are significantly influenced when the wake vortices come close to the ground, at altitudes below about one wing span. Accurate prediction of the locations and strengths of the vortices is a key to avoid wake vortex encounters and necessary in any attempt to safely reduce separation distances under specific weather conditions.

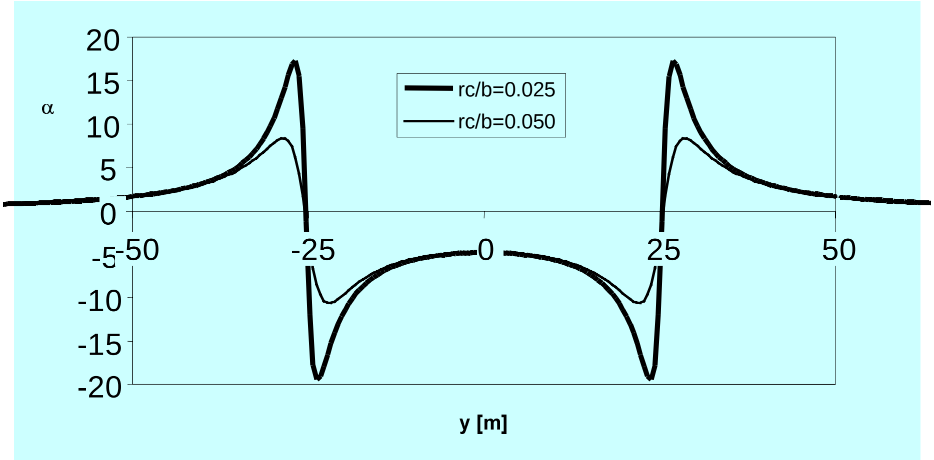

Figure 4.2 – Typical flow angles in the wake of a B747-400 aircraft on final approach for two typical vortex core sizes (rc is the vortex core size and b is the wing span)

A method based on the model of Corjon & Poinsot has been chosen to represent the behaviour of wake vortices (Refs. 24, 25, 50). Different deterministic decay models exist, and have been integrated with the WAVIR methodology. The models of Greene (Ref. 55), Donaldson & Bilanin, and Sarpkaya all account for the effects of stratification and atmospheric turbulence (Refs. 41, 43). Within this study the Sarpkaya decay model has been used (following recommendations from WP1). Main input parameters are the Brunt-Väisälä frequency and the Eddy Dissipation Rate. Reference 12 describes the probabilistic wake evolution model in detail.

4.3 Wake encounter model

Although the official policy in ATM is to avoid them, wake encounters are reported quite often by airline pilots; the NATS database, for example, contains many voluntary pilot reports. Most of these encounters are not severe. Typically, induced bank angles remain smaller than 20 degrees, but there are exceptions. The aerodynamic forces and moments on an aircraft that passes through a wake vortex pair will cause upset aircraft movements depending on the controllability of the aircraft and the strength and orientation of the vortex pair with respect to the flight path of the aircraft approaching the vortices. The aircraft may enter only one or both vortices and a large variety of resulting aircraft movements is possible, especially when wake intercept angles are small, leading to long wake encounter times. If an aircraft comes close to a vortex core it will experience a large rolling moment. Simple strip method analysis shows that for an aircraft being able to fly stable in the vortex core of an equal sized aircraft, the wake strength should have decayed by at least a factor two. Even more decay is needed for smaller aircraft flying in the wake of larger aircraft. Methods to predict wake-induced forces and moments have been developed in S-Wake and have been validated against wake encounter wind-tunnel data from NLR in a previous EU project, WAVENC (Ref. 36) and against flight tests (S-Wake WP2, Ref. 56).

A probabilistic wake encounter model that estimates the response of an aircraft during a wake encounter has been developed (Ref. 13). Two deterministic models have been integrated with the WAVIR methodology: an Extended Roll Control Ratio (ERCR) model and a Reduced Aircraft/Pilot Model (RAPM). The ERCR model is a 1 Degree of Freedom (DOF) model based on the method of Tatnall (Ref. 47). It only considers roll, taking into account the effect of the vortices on the wing only: horizontal and vertical stabiliser are not considered. The RAPM is a 5 DOF model of ONERA, supplemented with a simplified roll-control pilot model developed by DLR. It enables assessment of both loss of height and maximum attained bank angle during an encounter. The use of the RAPM is restricted to: flight conditions close to the initial conditions (final approach), relatively short encounter, predominant roll effect, initial undisturbed flight, encounter not close to the ground. An encounter classification scheme based on maximum bank angle and altitude of an encounter has been developed for different simulated encounters:

1. *Extreme*: aircraft disturbance resulting in temporary or total loss of control, with an increased possibility of a catastrophic accident in case of an encounter close to the ground.
2. *Severe*: aircraft disturbance resulting in a severe maximum bank angle (possibly higher than 30 degrees) and a critical flight state, where the pilot initiates a go around with considerable corrective recovery actions required, and an increased possibility of a hazardous accident.
3. *Moderate*: aircraft disturbance with approach limits likely exceeded, resulting in a moderate maximum bank angle (possibly in between 10 and 30 degrees), where the pilot initiates a go around without exceptional skills required, and an increased possibility of a major incident.
4. *Weak*: a slight to moderate aircraft disturbance (no approach limits exceeded), resulting in a weak maximum bank angle (less than 10 degrees), with considerable pilot action required, can be experienced. An increased possibility of a minor incident with moderate disturbance.

4.4 Flight path evolution model

A probabilistic flight path evolution model to represent the flight tracks of several generic aircraft types, as listed in Table 4.1, has been improved (Ref. 3). This model represents the flight tracks of aircraft operations in the vicinity of an airport. To validate the flight path evolution model, actual flight track data from Schiphol airport (obtained with the FANOMOS flight track registration system) has been analysed. Three flight phases have been analysed and modelled: approaches (including final approach, flare, free roll, and ground run), missed approaches, and departures. A correlation analysis of aircraft flight track data (obtained with FANOMOS) has been carried out (and it was shown that the lateral and vertical dimensions are correlated under certain conditions). A mathematical model is proposed that can take into account this correlation. Important parameters to determine the initial vortex strength are the aircraft mass on approach, the wingspan, and the aircraft type dependent Final Approach Speed (FAS) (see Table 4.1 and references 3 and 26).

Table 4.1: Aircraft data

#	**Generic category**	**ICAO CAT**	**Mass on approach [kg]**	**Wingspan [m]**	**FAS [kts]**
6	Light turbo prop	L	4000	14.0	100
5	Medium turbo prop	M	20000	30.0	106
4	Regional jet	M	34000	30.0	128
3	Medium jet	M	60000	36.0	138
2	Wide body jet	H	130000	45.2	135
1	Large jumbo jet	H	245000	60.0	150

Within this study the aircraft are assumed to follow an ILS approach along a 3 degrees glide path. The wake vortex induced risk will be evaluated at several positions along the approach (see also Table 4.2). As an example, with a Reference Datum Height (RDH) of 52 ft, the glide path is assumed to intercept the runway 300 m beyond the runway threshold

Table 4.2: Longitudinal positions where wake vortex severity is evaluated and their relation between distance to runway threshold and height along the glide path.

Label	x1	x2	x3	x4	x5	x6	x7
Distance (m)	0	200	400	1000	2000	7408	13813
Distance (Nm)	0.00	0.11	0.22	0.54	1.08	4.00	7.46
Height (m)	16	26	37	68	121	404	740
Height (ft)	52	86	120	223	395	1324	2425

Position x6 and x7 correspond to the Outer Marker (OM) and Final Approach Point (FAP) at London Heathrow. The other points are taken close to the runway threshold, since the initial safety assessment showed that the risk is highest near the runway threshold (Refs. 6, 8).

The aircraft speeds, controlled by ATC, are airport dependent. Within this study the aircraft speed at London Heathrow airport has been determined in close co-ordination with NATS. For the standard deviation a value of 10 kts is taken for speeds higher than 200 kts, and 5 kts otherwise. For the aircraft types the speed profiles representing an approach on London Heathrow Airport are shown in Figure 4.3. The basic assumptions are:

- Initially – down to an altitude of 4000ft - a speed of 210 kts
- A reduction of speed to 160 kts to be achieved at the Final Approach Point FAP located at 7.5Nm before the runway threshold.

- A speed of 160 kts to the Outer Marker (OM) located at 4Nm before the runway threshold.
- A reduction of speed to the Final Approach Speed to be achieved at the Deceleration Point (DP) located at 2.5 Nm before the runway threshold.

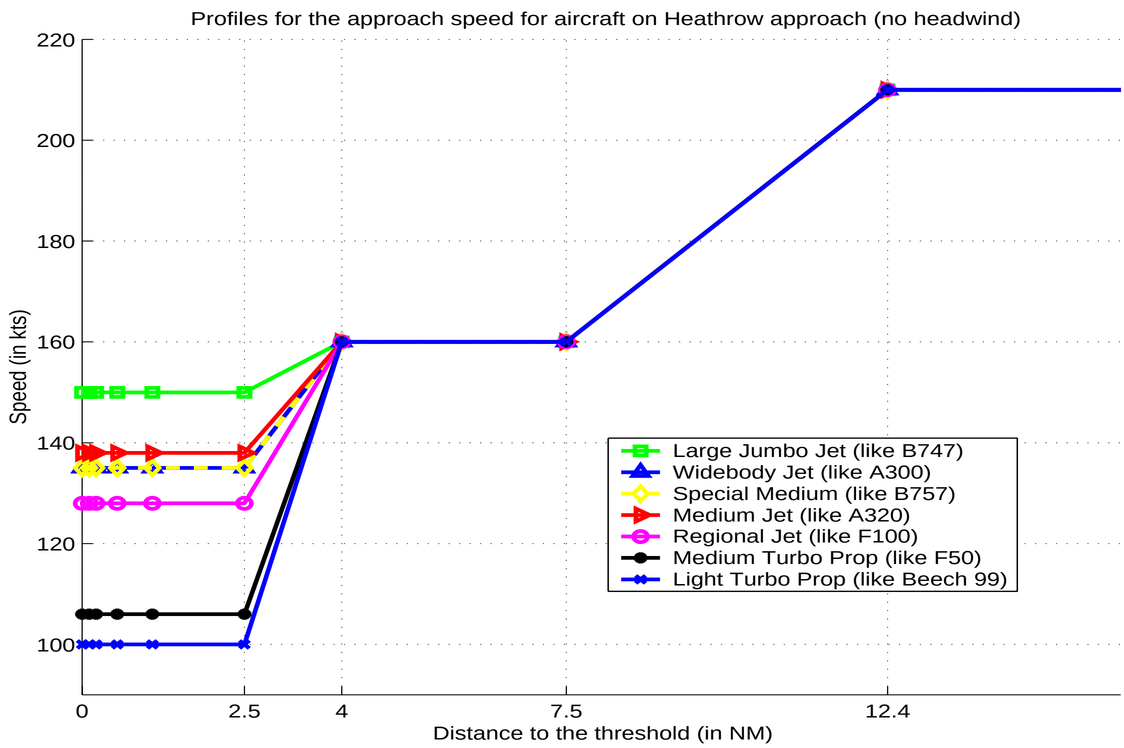

Figure 4.3 Speed profiles for aircraft on Heathrow approach

4.5 Incident/accident risk prediction model

The incident/accident prediction model relates the severity of individual wake encounters to the severity of the possible risk events, through a probabilistic relation that includes the initial encounter altitude. This probabilistic relation is based on a transition probability matrix and probability distributions for the loss of height. The probability distributions enable assessment of the catastrophic accident risk probability, on the basis of the assumption that the loss of height shall be larger than the initial encounter altitude. In order to also assess the other three risk events (*Minor Incident*, *Major Incident*, and *Hazardous Accident*), the transition probability matrix is defined. This matrix gives the fractions of the simulated wake encounters that result in the three (non-catastrophic) risk events, provided that the loss of height is less than the initial aircraft altitude at the start of an encounter (Refs. 4, 8). The probability distributions for the loss of height during an encounter (and consequently height above ground at the end of an encounter) are to be determined using wake encounter simulations with the Reduced/Aircraft Pilot Model (RAPM) (see references 4, 8).

As an example, Table 2 shows that *Weak encounter*s will most likely result in a *Minor Incident*, whereas *Severe Encounters* and *Extreme Encounters* may result in a *Hazardous Accident*. Appropriate values for the transition probabilities can be determined using encounter data from incident/accident data collection activities (such as being collected at Heathrow airport). Note that, in the following, it is also assumed that certain transition probabilities are zero (see also Table 2). For example, Weak Encounters will never result in a Major Incident or Hazardous Accident and Extreme Encounters will never result in a Minor Incident. The values in Table 2 are elicited through expert judgement and recommended for use within the S-Wake project.

Table 2 Transition Probability Matrix (individual elements are denoted by e.g. $P_{T\,(WEAK \rightarrow MAJOR)}$*)*

Risk Event / **Encounter Severity**	Minor Incident	Major Incident	Hazardous Accident	Catastrophic Accident
Conditional event	*Loss of height smaller than encounter altitude*			*Loss of height is larger than the initial aircraft encounter altitude (i.e. crash)*
Weak	**1.0**	0	0	
Moderate	**0.6**	**0.4**	0	
Severe	0	**0.6**	**0.4**	
Extreme	0	**0.2**	**0.8**	

The four risk metrics (minor incident, major incident, hazardous accident, catastrophic accident) are determined through integration of the four instantaneous risk curves (conditional on the position along the flight track) over the entire aircraft movement (e.g. approach or departure).

4.6 Numerical procedure to evaluate incident/accident risk

The assessment of the safety level is carried out in seven steps:

1. The parameters in the wake vortex evolution model are identified (the parameter distributions are based on empirical data and/or state-of-the-art literature). In addition a set of relevant longitudinal positions along the proposed aircraft flight path x is determined.
2. Monte Carlo simulations with the wake vortex evolution model are run (for the cases that the follower aircraft encounters the wake vortices at longitudinal position x). Lateral and vertical positions, strength, and core radius of the wake vortex pair are obtained at the time instant when the vortex pair has the same longitudinal co-ordinate as the trailer aircraft. This time instant is computed with the flight path evolution model, which incorporates the wind speed in longitudinal direction (i.e. influence of head- / tailwind on aircraft ground speed).
3. The results from step 2 are analysed. Based on this analysis a dedicated probability density fitting procedure is identified that accounts for dependencies between the lateral and vertical

position co-ordinates, the strength, and the core radius of the wake vortex pair. A probability density fitting procedure is carried out and the joint distribution of the wake vortex position, strength, and core radius is obtained. For this purpose, pattern recognition and Bayesian sampling methods and techniques are used (Ref. 4).

4. Monte Carlo simulations are carried out to simulate the wake vortex encounter. In this step the joint distribution from step 3 and distributions of the position of the trailer aircraft are used. This step provides encounter severities, plots with probabilistic maximum attained bank angles and vertical loss of height along the proposed aircraft flight path.
5. The wake-induced incident/accident risk to follower aircraft at various positions x along the flight path is evaluated. To do so, the risk is related to the follower aircraft and its trajectory, using the incident/accident prediction model described in Section 3.6. This step provides the *instantaneous* risk curves (minor incident, major incident, hazardous accident, catastrophic accident) showing the risk to follower aircraft along the proposed aircraft flight path.
6. The wake-induced incident/accident risk is obtained by integrating over x the risk obtained in Step 5. This step, which is repeated for different separation distances, provides the four incident/accident risk curves as functions of separation distance.
7. Application of the risk management procedure – based on the requirement that all four Target Level of Safety values should be fulfilled – provides the required separation minima under different operational, weather and wind conditions.

5 Incident/accident risk assessment and evaluation

5.1 Introduction

Two wake vortex safety assessments are carried out, in order to assess the relation between wake vortex induced risk and required separation minima for single runway approaches:

- Initial safety assessment, with the WAVIR methodology (and tool) available at the start of S-Wake (developed as part of NLR's basic research programme) (Refs. 5, 6, 7);
- Extended safety assessment, with the improved WAVIR methodology (and tool) that incorporates the sub-models as improved/developed in S-Wake (Ref. 8).

The aim of the initial safety assessment is to identify those factors that contribute most to the risk of a wake vortex induced incident/accident. For this purpose, an extensive sensitivity analysis is carried out, where the impact of aircraft size, navigation performance, procedural aspects, and weather and wind conditions is investigated. Each of these aspects is varied one at a time to study the effect of each parameter on the incident/accident risk. The results are used to give early modelling feedback and to focus the study with the extended WAVIR method on the most promising and influencing aspects. The aim of the extended safety assessment is to apply the improved WAVIR methodology to investigate the wake vortex induced risk related to single runway approaches at Heathrow airport, in order to compare or validate the results against the WP5 Heathrow Data Base analysis. A wide variety of aircraft combinations and weather and wind conditions are analysed, using meteorological data for Heathrow airport.

5.2 Definition of scenarios

The scenarios are defined in agreement with the operational procedures prescribed for single runway approaches at London Heathrow (contained in the UK Air Information Pilot (Ref. 46)). Aircraft are routed according to a Final Approach Fix, which is located at 7.5DME from the threshold, then to 4 DME (which could be interpreted as the Outer Marker), then to touchdown. Procedures require that aircraft should fly at 210kt during the approach phase. ATC will request speed reductions to within the band 160kt to 180kt on, or shortly before, the closing heading to the ILS, and 160kt when established on the ILS to 4DME; all speeds to be flown as accurately as possible". The only exception is Concorde, for which the speed limit is 200kt. For all four runways, 27R, 27L, 09R and O9L, the final approach phase from 4DME to touchdown is the same: After intercepting the glidepath at 2423ft above threshold (2500ft alt) descent according to the glidepath commences from 7.5 DME. Procedures dictate that all aircraft should attempt to maintain a continuous descent to the FAF without recourse to level flight. Four DME/Localisers are used, one for each runway. They are zero ranged to the runway thresholds.

Different combinations of leader and follower aircraft are investigated. Most relevant are:

- Leader aircraft: Large Jumbo Jet (ICAO Heavy) and Medium Jet (ICAO Medium);
- Follower aircraft: Large Jumbo Jet, Medium Jet, Regional Jet, and Light Turbo Prop;

Especially a combination of cross- and tailwind is expected to be dangerous. Strong headwind will be beneficial for the relative vertical position of encountering aircraft and the wake vortex. Tailwind has an opposite effect: vortices will be transported in the same direction as the follower aircraft is flying thereby decreasing the vertical distance between vortex and aircraft. There is no need to analyse strong tailwind conditions, since runways are usually approached with headwind conditions. Wind scenarios are given in Figure 5.1.

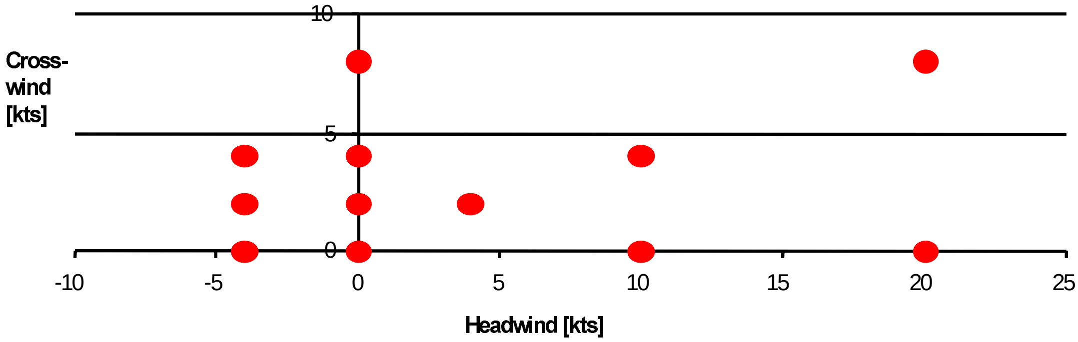

Figure 5.1: Investigated head- and crosswind scenarios

Frequency distributions of Eddy Dissipation Rate (EDR) and Brunt-Väisälä frequency (N) at various height levels have been determined using London Heathrow meteorological data from UK Met Office (Refs. 8, 28). The EDR data comes from the processed Flight Data Recordings (FDR) data (collected in S-wake WP5) and the Brunt-Väisälä frequency data is obtained with a model representing the London Heathrow climatology. Figures 5.2 and 5.3 show the frequency distribution of the Eddy Dissipation Rate and the Brunt-Väisälä frequency (N^2) at various height levels along the approach glide path. This has been used in the Sarpkaya wake evolution model.

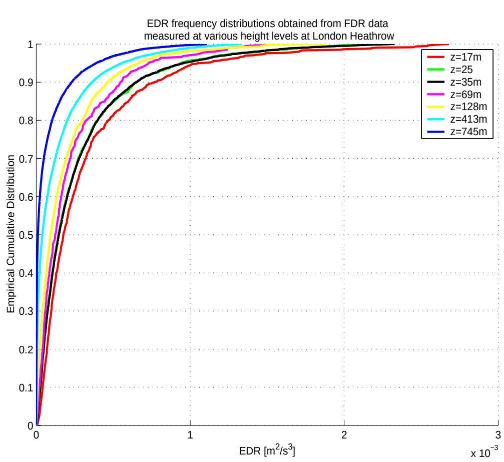

Figure 5.2 Frequency distribution of EDR at various height levels

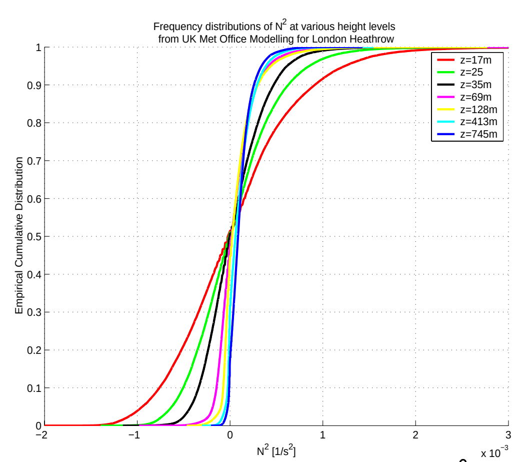

Figure 5.3 Frequency distribution of N^2 at various height levels

5.3 Initial safety assessment

A baseline accident risk assessment has been carried out (Ref. 6), where the aircraft approach a single runway under current ICAO flight regulations. A Boeing 737-400 aircraft, which is in the ICAO medium weight class, is landing behind a Boeing 747-400 aircraft, which is in the ICAO heavy weight class. This scenario – with average turbulence and average stratification – is evaluated for five different separation distances (2 Nm, 3 Nm, 4 Nm, 5 Nm, and 6 Nm). For both involved aircraft it is assumed that the approach is ILS Cat I. It is assumed that the pilot does not initiate a missed approach when experiencing a roll upset. The landing phase starts at about 28 km before the threshold, and ends at touchdown, which is 300 metres beyond threshold. Figures 5.4 – 5.7 show – for each of the defined risk events, i.e. *minor incident, major incident, hazardous accident, and catastrophic accident* – the instantaneous risk as a function of distance from the runway threshold. The results clearly show that - for this baseline scenario - the highest risk occurs near the runway threshold.

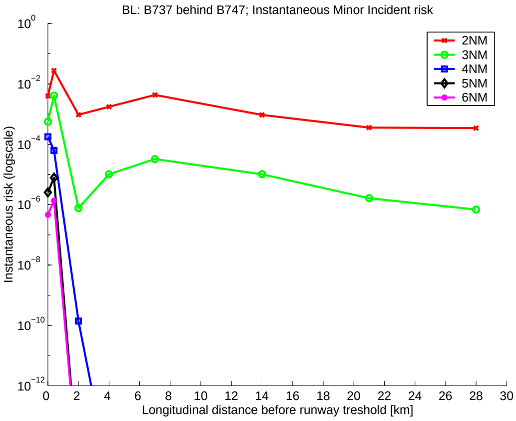

Figure 5.4 Instantaneous minor incident risk along the glide slope

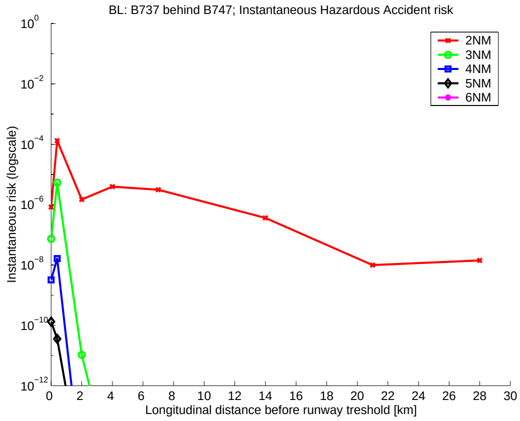

Figure 5.6 Instantaneous hazardous accident risk along the glide slope

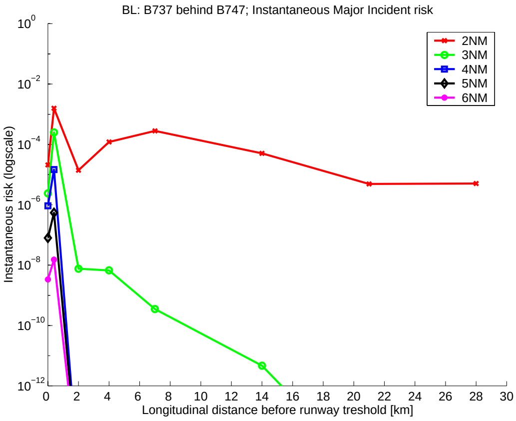

Figure 5.5 Instantaneous major incident risk along the glide slope

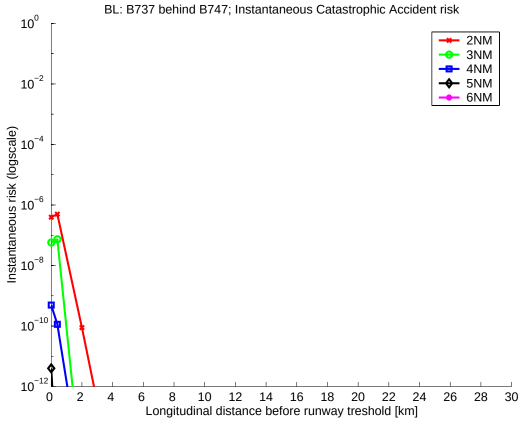

Figure 5.7 Instantaneous catastrophic accident risk along the glide slope

From a safety and capacity perspective, it is important to identify those factors that contribute most to the risk ("safety criticalities" or "safety bottlenecks"). For this reason, a sensitivity analysis – with a Boeing 737 landing behind a Boeing 747-400 – has been carried out, and the major findings are:

- For most evaluated scenarios, the highest risk is located near the runway threshold. This implies that – to reduce the risk – weather based prediction, monitoring and warning systems should focus on weather and wind effects near the runway threshold.
- The risk is most sensitive to weather and wind conditions. This implies that an increase of runway capacity might be possible if reliable and stable predictions of weather and wind effects over a time period of 20 minutes or more (necessary from operational point of view to allow scheduling for approach with prescribed separation minima) can be obtained.

Safe and appropriate separation distances have been determined for a wide variety of scenarios, involving navigation performance, atmospheric conditions, procedural aspects, and wind conditions. Figure 5.8 below gives an overview of the derived separation minima for a Boeing 737 landing behind a Boeing 747-400, under different operational, weather and wind conditions.

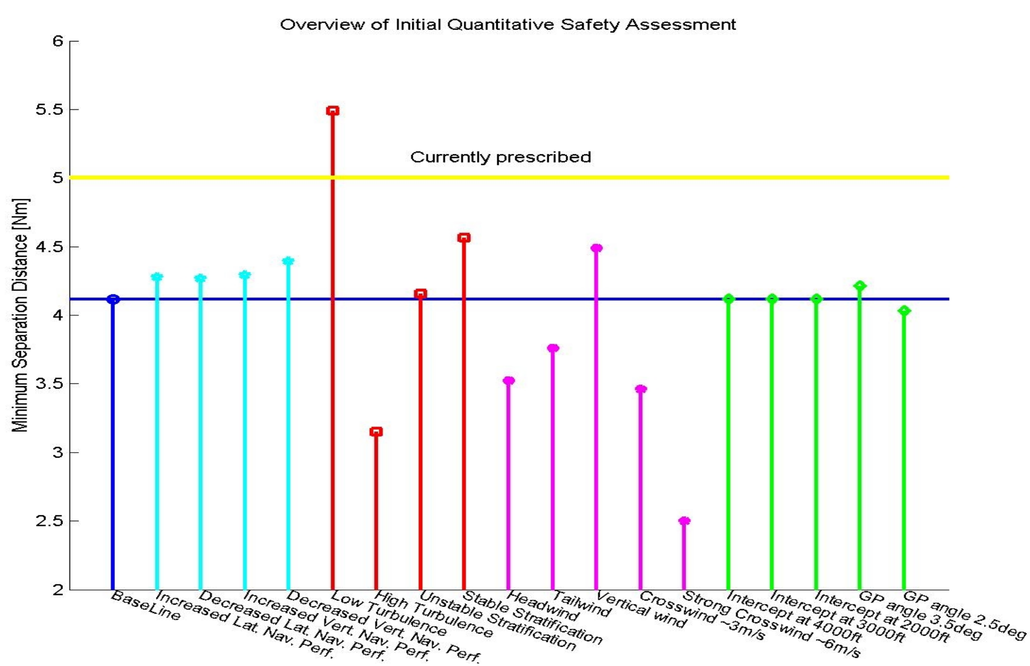

Figure 5.8 Derived Separation Minima under different operational and weather conditions

The current separation minima of 5 NM (for a Boeing 737 landing behind a Boeing 747-400) seems sufficiently safe under most conditions. An increase of capacity – might be possible, especially for high turbulence and crosswind conditions. Figure 5.8 shows that the separation distances might need to be increased under low atmospheric turbulence conditions.

5.4 Extended safety assessment

The initial safety assessment shows that the impact of the investigated ATM procedural aspects – as compared to the impact of weather and wind conditions – on wake vortex risk is relatively small. This is due to the fact that the largest risk contribution evolves from possible encounters near to the runway threshold (with consequently a small impact of e.g. different glide path angles, different glide slope intercept altitudes). This implies that the evaluated changes in ATM procedures at present will not allow safe reduction of separation distances. The results also indicate that to enhance capacity, weather and wind conditions favourable to reduce risk in the runway threshold area shall be exploited. The extended safety assessment was made with the atmospheric weather parameters according to the weather climatology of Heathrow (see figures 5.2 and 5.3). The extended safety assessment was further focused on the impact of wind conditions. Different head-, tailwind and crosswind conditions were considered (see Figure 5.1, Appendices D-G, and references 8 and 9 for the full results).

<u>Safe separation distances behind a Large Jumbo Jet (LJJ)</u>

The wake vortex induced risk for four different types of follower aircraft: a Large Jumbo Jet, a Medium Jet, a Regional Jet, and a Light Turbo Prop (behind a LJJ) is determined. Application of the risk management framework described in section 3, provides safe separation distances under different wind conditions (see Appendix B). The figures 5.9 to 5.12 show the safe separation distances for a Large Jumbo Jet, Medium Jet, Regional Jet, and a Light Turbo Prop (behind a LJJ). It appears that the situation with a small crosswind of 1 m/s is most unfavourable. As can be seen, in addition to crosswind (drifting of the vortices out of the flight corridor), also strong headwinds are efficient in reducing the risk to follower aircraft. For most scenarios, the results show that the current separation minima are sufficient.

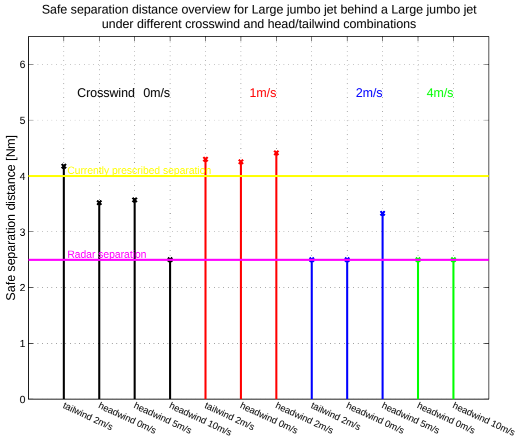

Figure 5.9 Safe separation distance for a Large Jumbo Jet behind Large Jumbo Jet

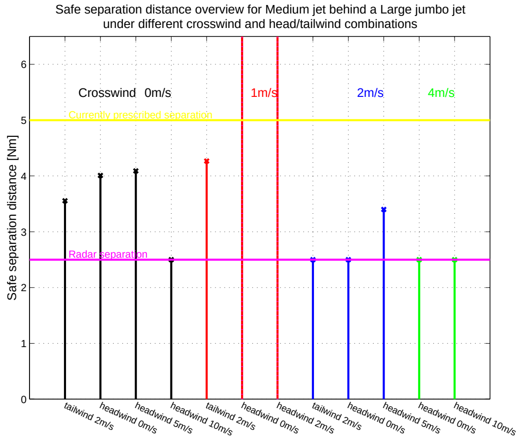

Figure 5.10 Safe separation distance for a Medium Jet behind Large Jumbo Jet

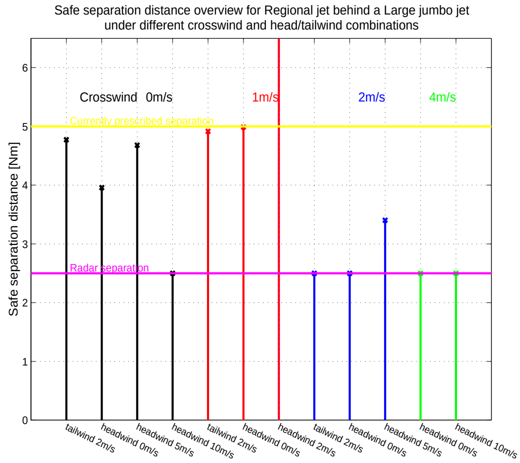

Figure 5.11 Safe separation distance for a Regional Jet behind Large Jumbo Jet

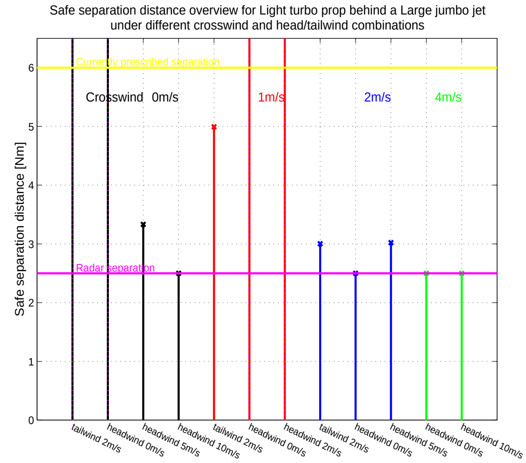

Figure 5.12 Safe separation distance for a Light Turbo Prop behind Large Jumbo Jet

<u>Safe separation distances behind a Medium Jet (MJ)</u>

The wake vortex induced risk for four different types of follower aircraft: a Large Jumbo Jet, a Medium Jet, a Regional Jet, and a Light Turbo Prop (behind a MJ) is determined. Application of the risk management framework described in section 3, provides safe separation distances under different wind conditions (see Appendix C). The risk analysis showed that radar separation can be applied for Medium Jet and Large Jumbo Jet follower aircraft under all wind conditions. The figures 5.13 and 5.14 show the safe separation distances for a Regional Jet and a Light Turbo Prop (behind a MJ) respectively. Again, in addition to crosswind, strong headwinds are also very efficient in reducing the risk to follower aircraft. In general, the results show that the current separation minima are sufficient.

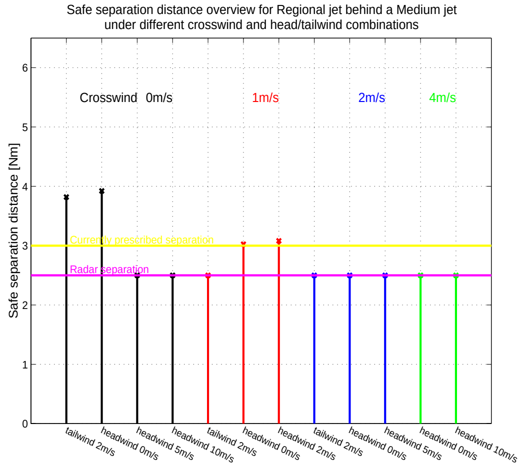

Figure 5.13 Safe separation distance for a Regional Jet behind Medium Jet

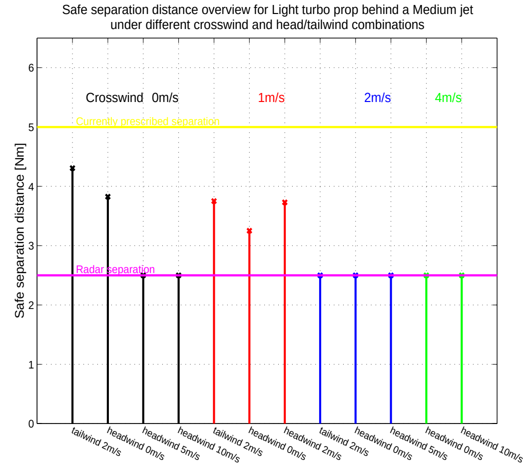

Figure 5.14 Safe separation distance for a Light Turbo Prop behind Medium Jet

Most unfavourable wind conditions

To analyse the wake vortex induced risk related to unfavourable wind conditions in more detail, figures providing the safe separation distances for specific unfavourable wind conditions are given below. A variety of follower aircraft behind two leader aircraft have been analysed. Most unfavourable is a combination of small crosswind (1 m/s) with a negligible to small headwind (of 2 m/s). More specifically, it appears that without crosswind and with negligible head- or tailwind, the current ICAO separation minima behind the Large Jumbo Jet might not suffice.

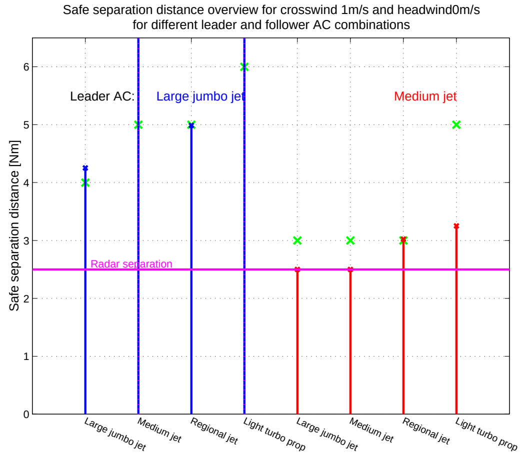

Figure 5.15 Safe separation distance for a small crosswind of 1 m/s

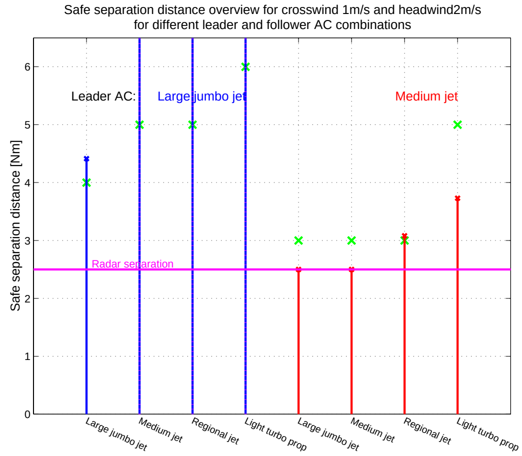

Figure 5.16 Safe separation distance for a crosswind of 1 m/s and a headwind of 2 m/s

Favourable wind conditions

To analyse the wake vortex induced risk related to favourable wind conditions in more detail, figures providing the safe separation distances for specific favourable wind conditions are given below. A variety of follower aircraft behind two leader aircraft have been analysed. Most favourable are a crosswind higher than 2 m/s and/or a strong headwind of more than 10 m/s.

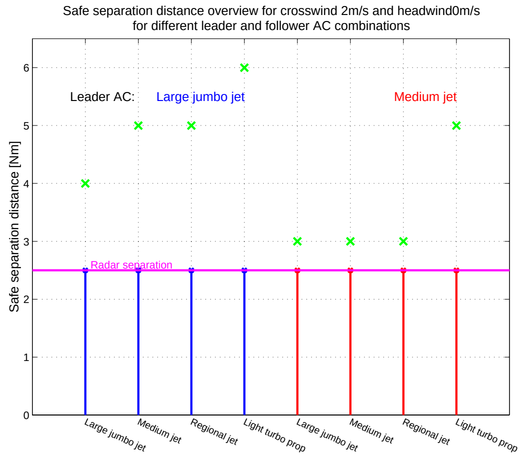

Figure 5.17 Safe separation distance for a crosswind of 2 m/s

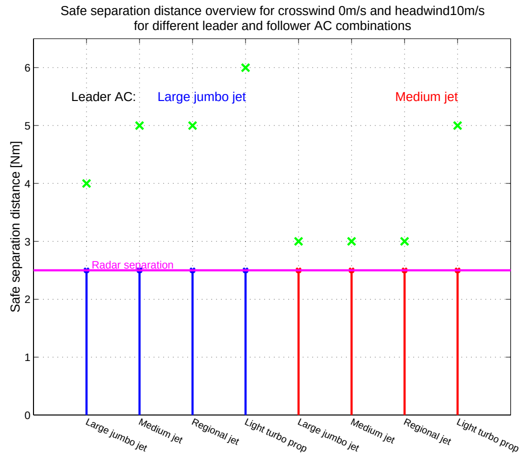

Figure 5.18 Safe separation distance for a headwind of 10 m/s and no crosswinds

5.5 Validation of the safety assessment

The Manager of S-Wake Work Package 5 (WP5), NATS, has been collecting voluntary pilot reports since 1972 (Ref. 15). However, it is not known how close the reported rate of encounters is to the actual rate of encounters. In addition, only limited information is available from the reported encounters on the severity of the encounters. As a result, these data are not reliable enough for a comprehensive assessment of the current wake vortex safety levels around major airports. The first part of the WP5 programme was therefore aimed at developing, implementing and validating an algorithm for the automatic processing of Flight Data Recordings (FDRs) from all incoming BA aircraft at London Heathrow. This algorithm was developed by NLR and is known as NLR-VORTEX (Refs. 16, 17, 18). An initial validation of the WVE detection algorithm was performed by NATS, which shows that it can successfully identify WVEs from flight data (Ref. 19). Subsequently, an extensive data collection was performed for incoming flights at London Heathrow. It covered a one-year period from September 2001 to August 2002. Full details of this data collection are given in Reference 20, but it included:

- The collection of segments of FDR data from flights of BA aircraft into London Heathrow. In total 30,000 FDR flight segments were successfully gathered.
- The application of the NLR-VORTEX algorithm to the collected FDR data segments in order to:
  a) create a limited set of parameters (including Met data along the flight path) for each successfully processed FDR output segment;
  b) detect the occurrence of WVEs in the processed FDR output segments (about 210) and, in that case, store a more extended set of parameters for further analysis;
- The storage of all these data in the Heathrow Database (HDB). This enables the correlation between FDR Met data and ground based (METAR) met data, the determination of actual radar separations between trailing aircraft and the identification of the wake generating aircraft and the local atmospheric conditions when a WVE is detected. Reference 21 gives an initial specification for this database, detailing the wide range of parameters that it contains.

Unfortunately, the activities described above have faced severe technical problems. Therefore the WVE results from analysis of FDRs have to be considered as preliminary. Nevertheless, in the final phase of WP5 statistical analyses were conducted by NATS using the HDB database to investigate relationships between vortex encounter parameters and situational parameters such as time separation and wind vector (Ref. 20). As an example of the preliminary WVE results, Figure 5.19 shows a plan-view of the London Heathrow area (covering all four approach corridors) with the locations of the WVEs detected by NLR-VORTEX. The radar tracking locations of the WVE aircraft are shown as well. Clearly, WVEs occur both along the ILS flight path and along flight segments joining onto the ILS path.

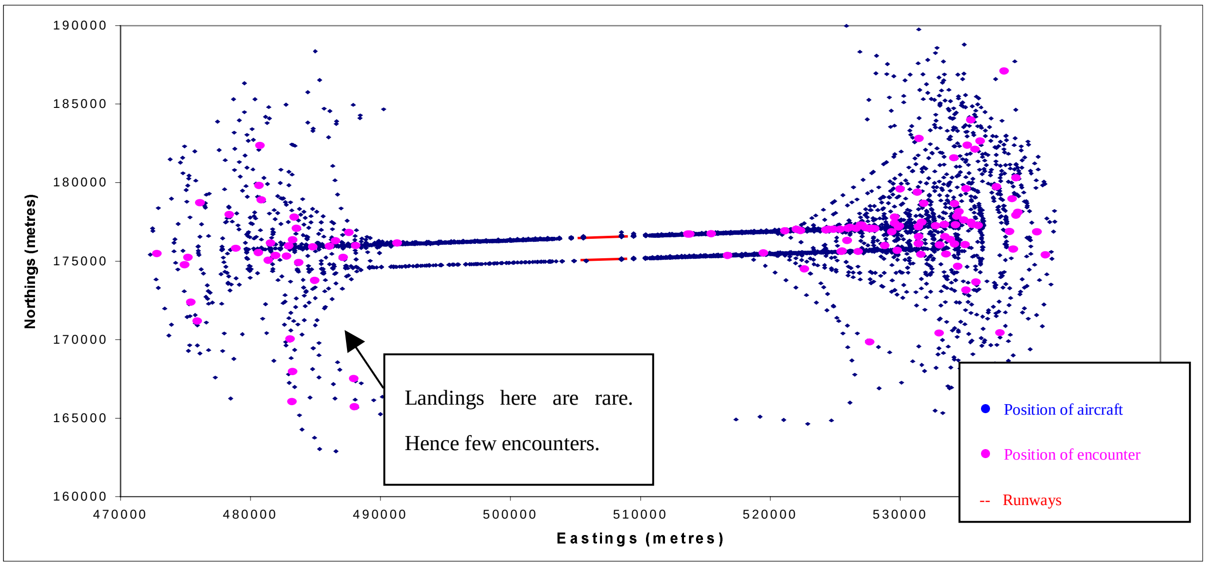

Fig. 5.19: Plan view of the London Heathrow area, with radar flight tracking and WVE positions detected by NLR-VORTEX from FDR data (preliminary result)

Further investigation of the output from NLR-VORTEX suggested that some of the identified encounters might be due to causes other than wake vortex (e.g. atmospheric turbulence). Therefore, the statistical analysis of WVEs further concentrated on data from NATS database of voluntary pilot reports.

Analysis of voluntary pilot reports

The additional analysis of voluntary pilot reports for WVEs was insufficient for WP5 to produce a robust and complete validation of the results from WP4. However, the analysis did produce two interesting results:

Result 1: The rate of WVEs appears to increase rapidly (see Figure 5.20) when aircraft are spaced more than 10 to 15 seconds below the separation minimum. The likelihood of an encounter is relatively constant when the separation is above the minimum. The precise weather conditions (e.g. level of turbulence) for all these encounters are unknown but the crosswinds are generally below 3 - 4 m/s for heights below 4,000ft (see *Result 2* below). *Result 1* does therefore confirm that the current separations (expressed in terms of time) have been set at appropriate levels, at least for the meteorological conditions in which WVEs are reported.

Indeed the separation is insufficient to eliminate WVEs completely even for separations much larger than the ICAO minima. This suggests that the current ICAO minima might not always suffice in certain meteorological conditions (see Section 5.4). *Result 1* does not, however, exclude the possibility that significantly smaller (but safe) separations are possible under certain weather conditions: see *Result 2* for example.

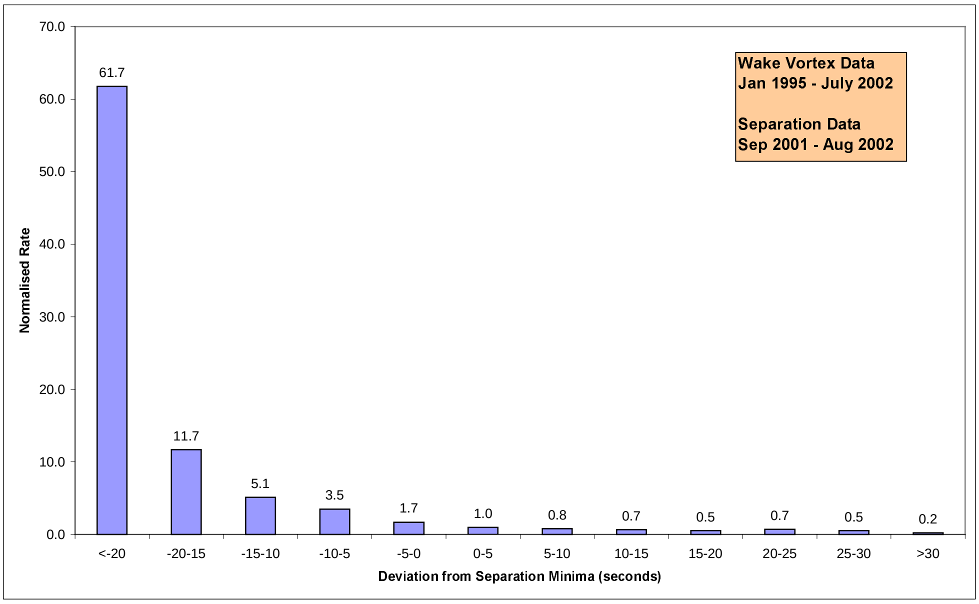

Figure 5.20 Relative WVE Rates (WVE rate for nominal separations normalised to 1) for Voluntary Reported Encounters

Result 2: For leader and follower aircraft established on the glideslope, the rate of WVEs is considerably reduced when the crosswind is above a critical level (about 3 to 4 m/s). Figure 5.20 shows the distributions of crosswinds at encounter and also the overall crosswind climatology at Heathrow as derived from the FDR data. As far as possible, the reported encounters shown in Figure 5.20 relate solely to incidents where both leader and follower aircraft were established on the ILS at heights less than 4,000ft. Although some caution must be applied to the information from voluntary pilot reports, Figure 5.21 clearly shows that the size of the crosswind seen at Heathrow is higher than the crosswind experienced at encounter for much of the time. *Result 2* also supports one of the main conclusions from WP4 i.e. that separations can potentially be reduced substantially when the crosswinds is above a critical level of 6 to 8 knots (about 3 to 4 m/s) (because vortices would be transported out of the approach corridor). WP4 suggests that the critical level may be as low as 2m/s (see section 5.4). If vortices are to be avoided for distances further away from threshold (where the approach corridor is wider) greater crosswinds will be required (as the result from WP5 suggests).

The activity in WP5 has shown that it is possible, in principle, to obtain statistical data on WVEs in an automatic manner, as well as from voluntary reports. A number of recommendations for additional work are given in Reference 20. In particular it is recommended that detailed analysis of the 210 WVEs identified from FDR data in WP5 be performed. This analysis should look at the effect of crosswind on encounter rates and examine the severity of the identified encounters.

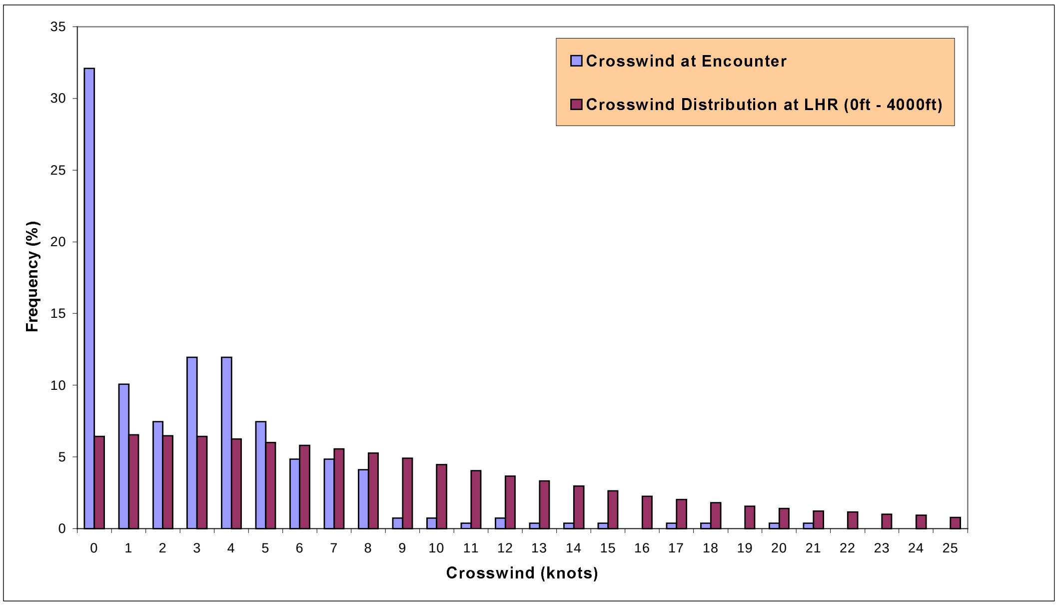

Figure 5.21 Crosswind Distribution for Voluntary Reported Encounters compared with the London-Heathrow cross-wind climatology

In the "Wake Vortex Evolution and Wake vortex encounter" (WAVENC) project, a statistical analysis of the European Turbulent Wake Reporting Log (ETWIRL) reported wake encounters was made (Ref. 58). Exploring the whole ETWIRL data-base (with about 120 reported cases) enabled a preliminary statistical analysis to be made of the conditions during wake encounter. As shown in Figure 5.22, most encounters occur during the approach phase (at reasonable low altitude). Compared with the results from S-Wake WP5 it seems that relatively few WVEs are detected by NLR-VORTEX at low altitudes. This needs to be further investigated.

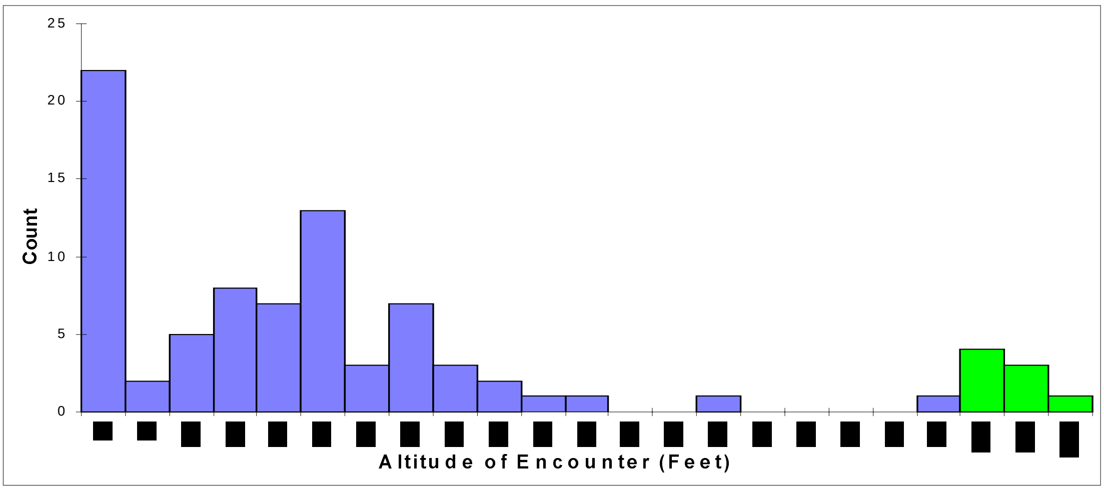

Figure 5.22: Statistical analysis of ETWIRL data-base (120 samples) with flight data recordings of wake vortex encounters (Ref. 58, courtesy RED Scientific)

5.6 Operational feedback and procedure design

The risk assessment results show that – for single runway approaches – the largest runway capacity improvement might be achieved through exploiting favourable wind conditions, in particular in the area close to the runway threshold, where wake vortex risk mitigation measures seem most effective. The results also show that procedural changes that have an effect further along the glide slope (including e.g. steeper approaches for smaller follower aircraft, different glide slope intercept altitudes, increased or decreased lateral and vertical aircraft navigation performance) are not effective in reducing the risk related to single runway approaches.

This leads to the conclusion that *warning* for unfavourable evolution of the vortices (in terms of position and strength in relation to the encountering follower aircraft) is most efficient. This can be achieved through an integrated (ground based) ATC wake vortex system that can be used by controllers, possibly supplemented by instrumentation for wake vortex detection and avoidance on-board aircraft. Note that the former is considered in the ATC-Wake project, whereas the latter is considered in the I-Wake project (both for the EC).

6 New concepts and procedures for capacity improvements

6.1 Basic principles for new concepts for reduced separation minima

Most of the attempts to overcome the wake vortex induced capacity limitations are aiming at the reduction (optimisation) of the average separation between aircraft under certain circumstances. During peak hours at highly loaded airports the approaching traffic at certain runways could be restricted solely to aircraft of similar wake vortex weight classification in order to avoid an unnecessary enlargement of the mean spacing. A group of measures for a capacity enhancement is directed to a better utilisation of the conventional separation rules, such as

- Optimising the sequence of arrivals,
- Optimising the mix of arrivals and departures, or
- Homogenisation of air traffic during busy hours.

These measures require procedural changes in the work of air traffic controllers. The problem of harmonised optimisation is quite complex and demands the development of computer based controller assistance tools (including optimum sequencing tools). The present ICAO based separation rules are generally believed to be safe. Therefore any proposal for reduction needs careful consideration and proof before it can be accepted. It also needs new technology/tools/ equipment (on-board aircraft and/or ground based), new findings from research (detailed data analysis and/or simulations), and/or new ideas for procedures. Before any reduction of separation minima can be put into operation, it has to be proven by a safety assessment that the intended changes do not degrade the existing level of safety (Ref. 10).

6.2 Measures and associated systems and procedures

All measures and associated procedures that target a reduction of spacing between aircraft can be categorised as one of: wake vortex alleviation, wake vortex avoidance, or wake encounter alleviation control. These three measures are discusses in more detail below.

Wake vortex alleviation (EU project Awiator):
All measures suitable to reduce size, strength and/or duration of the vortices. It is solely related to the leading aircraft as the vortex creator, and aimed to minimise wake turbulence at its source. Wake vortex alleviation may be achieved by passive measures such as the design and construction of special aero-dynamical aircraft shapes, which produce less wake turbulence (e.g. relying on span-wise wing load). Or, aircraft can be equipped with active moving flaps (alternate flap-settings) that feed into the aerodynamics instabilities of the wake leading to a faster decay of the vortices. Some general conclusions were made with respect to passive wake control and active wake control respectively (Ref. 10):

- For passive wake control methods that rely on modified span-wise loading, without attempting to significantly alter the instability of the wake, the following conclusions apply:
    - inboard loading creates stronger vortices, but these vortices travel more rapidly out of the flight corridor, have a shorter life-time and a larger initial core radius,
    - except for the stronger initial wake vortex strength this suggests that inboard loading could have a favourable effect on the wake vortex problem,
    - it still needs to be demonstrated if the penalties in drag, noise and flight mechanic handling of the aircraft are acceptable. This might limit available maximum benefits.
- For active wake control methods, the practical implications of flying with alternate oscillating flaps remains to be investigated though the effectiveness has already been demonstrated in sub-scale tests (water-tank). It is, however, not clear whether passenger comfort can be maintained nor what the effects might be on the aircraft wing structure.

Wake vortex avoidance (EU projects ATC-Wake, I-Wake):

All measures appropriate to avoid an encounter. It is solely related to the trailing aircraft, which is in risk of flying into the vortex of a leading aircraft. A first category of systems or procedures aims to detect, estimate, or predict the position and/or strength of vortices (e.g. using on-board and/or ground based wake sensors). With this information the trailing aircraft shall be enabled to stay outside the hazardous region but to fly as close as possible to the leading aircraft without wasting airport capacity. In any case, an operational use of these techniques will require that the relevant information on wake vortices is shared between pilots and ATC, i.e. this demands efficient communication and/or data link systems, and might include handing over the responsibility from ATC to the pilot. Among those systems are

- The Wake Vortex Behaviour Classes (WVBC) concept developed within S-Wake and aimed at characterise the wake vortex evolution
- The Wake Vortex Warning System (WVWS) defined by DFS for Frankfurt airport
- The Aircraft Vortex Spacing System AVOSS developed by NASA

They offer a kind of "real-time" adaptation of the separation distance, depending on measured and predicted local meteorological conditions

- Systems of wake vortex avoidance using on-board detection (e.g. I-wake project)
- Systems of wake vortex avoidance using ground-based detection (e.g. ATC-Wake project)

Other procedures enable reduced separations:

- HALS/DTOP procedure, also defined by DFS for Frankfurt Airport, taking advantage of the configuration of parallel runways
- The time-based separations procedure proposed by Eurocontrol

Wake vortex encounter control:
All measures to improve the capability of an aircraft to act in response to encountering a vortex. It can never be fully excluded that an aircraft unintentionally gets into contact with a vortex (or local atmospheric turbulence). Improvements of aircraft control capabilities may be achieved by constructional measures, i.e. improving aircraft's design, structure, and power in association with suitable escape procedures that have to be defined.

6.3 Model to assess maximum runway capacity

In order to evaluate the relationship between the value of separation minima and capacity, a general model of capacity computation has been developed (Refs. 9, 10). This model covers any runway configuration and operations. The capacity of the runway is defined as the average maximum number of aircraft that can use the runway per hour. By use is meant land only, take-off only or land and take off depending on the way the runway is operated. The separation between 2 aircraft depends on the types of aircraft so that the number of aircraft that can land or depart depends on the sample of traffic, characterised by the distribution between the different types of aircraft. To obtain the capacity a random long sequence of aircraft (N) corresponding statistically to this distribution of traffic is generated, the minimum required time for the whole sample to be taken into account is computed, and then the computation of capacity is deduced.

Separation requirements
The operational requirements define air separation requirements and ground separation requirements, the actual separation to be applied being the maximum of those requirements. The **air separation requirements** are defined to prevent an aircraft from encountering the wake vortices of the preceding aircraft. The present air separations are defined by ICAO separation minima at arrival and departure. Those minima depend on the type of aircraft involved. ICAO classifies aircraft in 3 categories, as a function of their MTOW (Maximum Take-off Weight).

Table 6.1 ICAO separation requirements at arrival

		Trailing aircraft		
		Light MTOW < 7t	**Medium** 7t ≤ MTOW<136t	**Heavy** 136t ≤ MTOW
Leading aircraft	**Light**	*	*	*
	Medium	5 NM	3 NM	*
	Heavy	6 NM	5 NM	4 NM

* means that no separation constraint related to wake vortices is required

Table 6.2 ICAO separation requirements at departure

		Trailing aircraft		
		Light MTOW < 7t	**Medium** 7t ≤ MTOW<136t	**Heavy** 136t ≤ MTOW
Leading aircraft	**Light**	*	*	*
	Medium	120 s (180 s)	*	*
	Heavy	120 s (180 s)	120 s (180 s)	*

* Values in brackets are for the case that aircraft take off from an intermediate part of the runway

A take-off or landing authorisation can't be delivered as long as the preceding plane does not cross the end of the runway in service or started a turn. Therefore the **ground separation requirements** are related to the runway occupancy time. At departure the runway occupation time includes the plane alignment time and the take-off phase. The proper take-off phase includes a constant acceleration phase and a climb at a constant angle of 5° at the take-off speed. The runway occupation time at arrival includes the landing phase, that is the approach, with a touch down point uniformly distributed over a given interval, the deceleration phase from the approach to the taxiing speed, and the taxiing phase. In the configuration of two dependent runways, the runway occupation time is not relevant, because while the leading aircraft is operating on the first runway, the follower can operate on the second one. The actual time separations to apply between 2 aircraft are computed by taking into account air and ground separation requirements, and a buffer corresponding to position errors. Three exploitation configurations are considered: Arrival only, Departure only, or Arrival-Departure-Arrival sequences.

Aircraft Performances

The separation times between aircraft depend on their performances as seen before. The ICAO classification considers 3 classes of aircraft for wake vortices: light, medium, and heavy. In order to have classes with more homogeneous performances the medium category is split into 2 categories, one corresponding to MTOW less and greater than 40t and denoted respectively by medium light (ML) and medium heavy (MH). In order to represent the diversity of the planes in a given class, and the dispersion in the performances, the aircraft performances are represented by a uniform distribution in a given range.

Runway layout

The configuration for a single the runway is defined by its length, the number of turnoffs, their distance from threshold and their nature, i.e. high-speed turnoff or not. In the case of dependent runways, the only relevant data is the length of the runways.

Impact of air separation matrix variations

The ICAO air separation minima may be changed in the simulation in order to assess the influence on capacity.They are given in Nm in the arrival matrix and in seconds in the departure matrix. Figure 6.1 shows the evolution of capacity for a variation in separation varying from -2 Nm to 2 Nm, for a typical mix [13% 72% 15%] and a typical runway configuration.

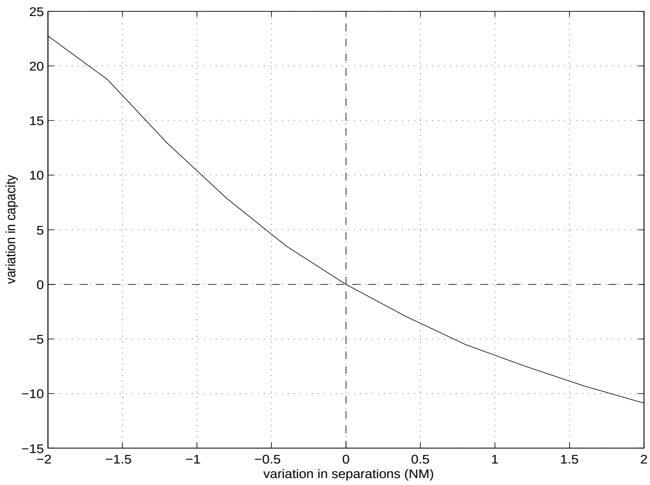

Figure 6.1 Evolution of capacity in function of arrival separations

For separations ICAO -1NM the percentage of cases where air separation prevails on ground separation decreases to 90%, for ICAO-2 NM this percentage is 40%. The results indicate that a decrease of 0.5 NM of separation standard will imply an increase of 5 aircraft per hour, a reduction of 1 NM leads to an increase in capacity of 10 aircraft per hour, for the considered traffic mix.

6.4 Impact of new systems and procedures on runway capacity

The idealised model described in the preceding section has been used for estimating the capacity improvement that may be obtained through implementation of a number of new procedures or systems that have been described in the preceding parts: the Wake Vortex Warning System, the HALS/DTOP procedure and the AVOSS. Note that all those procedures apply to arrivals. The Wake Vortex Warning System and HALS/DTOP are or will be implemented at Frankfurt Airport. Under most favourable conditions an increase by up to four additional landings per hour may be expected with HALS/DTOP or the Wake Vortex Warning System at Frankfurt airport. However, the average increase in capacity will be lower due to additional conditions that need to be fulfilled before the procedures can be applied. In contrast to the scenarios that are evaluated within S-Wake, Frankfurt is operating closely spaced parallel runways, which might be a cause for improvements as far as wake turbulence separation is concerned.

Aircraft Vortex Spacing System AVOSS

It is difficult to evaluate the capacity benefits of this system, because no precise data on the separation applied as functions of weather conditions are available. The figures presented here are from NASA. An average increase of 5% in runway throughput was calculated using the AVOSS spacing outputs, with daily values ranging from 2% to 11%. With four landing runways in use the DFW airport typically lands about 110 aircraft per hour. A 5% gain implies 5 or 6 aircraft more. Since the benefit of a wake spacing system varies with the traffic mix, the AVOSS spacing criteria was applied to a traffic mix representing Miami with a high fraction of heavy aircraft. The potential arrival rate increase was about 12%.

6.5 Some conclusions and recommendation about new concepts

New procedures and systems are at present under development for addressing the problem of runway capacity, limited by the spacing requirements between aircraft due to vortices. A rather extensive inventory and examination of new concepts has been made (see reference 10):

- Systems for wake vortex avoidance using knowledge of wake vortices evolution: WVBC (Wake Vortex Behaviour Classes) as developed within S-Wake, WVWS (Wake Vortex Warning System) defined by DFS for Frankfurt Airport; the NASA Aircraft VOrtex Spacing System AVOSS; and systems using on-board detection (e.g. I-Wake) or ground based prediction, detection and monitoring systems (e.g. ATC-Wake).
- Reduced separation procedures for closely parallel runways: HALS/DTOP procedure, also defined by DFS for Frankfurt Airport.
- Procedures to enhance airport capacity during head-wind conditions e.g. by using a the time-based separation strategy as proposed by Eurocontrol,
- Active and passive wake vortex alleviation systems, including low vortex aircraft design (e.g. AWIATOR).
- Active control to reduce the effects of an encounter.

The new concepts are not all at the same stage of development or maturity: some are at the stage of feasibility study, some are already at a pre-operational evaluation phase. For the most advanced and well defined (e.g. WVWS, HALS/DTOP, AVOSS) it has been possible to assess the impact on landing capacity. For others it is difficult to assess the potential benefits, but the analysis of the time based separation strategy (see Appendix A and references 8, 9, 10) shows obvious benefits for runway capacity in case of strong head wind conditions. Passive control (e.g. low vortex aircraft design) is still at an early stage of definition, and is further investigated in C-Wake and AWIATOR. I-Wake will provide detailed results about the benefits of on-board wake detection systems and ATC-Wake will provide detailed results about the benefits of ground based wake prediction and detection systems.

Capacity improvement figures have been derived for some of the above concepts. As a conclusion it seems that implementing local procedures that take advantage of particularities of an airport (and associated with new wake detection devices, either on board or ground based) may lead to an increase of capacity of magnitude of up to 10 to 20% (Refs. 9, 10).

Within the "Aviation Safety Targets for Effective Regulation" (ASTER) project, the following four wake vortex measures have been analysed with respect to costs and benefits (Ref. 57):

- Ground based prediction, detection, warning and avoidance systems;
- Airborne prediction, detection, warning and avoidance systems;
- High Approach Landing System / Displaced Threshold Operation (HALS / DTOP);
- Wake reduction at the wing of the aircraft.

The calculation results in the highest Net Present Value (NPV) for wake reduction at the aircraft, followed by ground based systems and HALS / DTOP. Airborne systems have a negative NPV. However, wake reduction at the aircraft wing is also the alternative with the largest uncertainties as regards technical feasibility, total costs and overall effect on capacity. Based on the results from the cost benefit analysis, the installation of *ground based* systems at major European airports was most encouraged (Ref. 57).

7 Conclusions and recommendations

7.1 Conclusions

With the steady increase in air traffic, there is an urgent need to use existing and newly proposed technologies in an efficient way. This document describes work undertaken in WP4 “Probabilistic Safety Assessment” of the project S-WAKE for the European Commission. The study comprises a quantitative safety assessment of wake vortex induced risk related to single runway approaches under current practice flight regulations. A probabilistic approach has been followed to evaluate wake vortex induced risk related to different separation distances between landing aircraft on a single runway. The model is based on a stochastic framework that incorporates sub models for wake vortex evolution, wake encounter, and flight path evolution, and relates severity of encounters to possible risk events (incidents/accidents) that might occur.

The Wake Vortex Induced Risk assessment (WAVIR) methodology has been applied to study, for single runway approaches, procedural aspects and the impact of weather and wind conditions. An extensive risk assessment – with different aircraft landing behind a Large Jumbo Jet and a Medium Jet – has been carried out. The impact of weather and wind conditions (e.g. turbulence, stratification, crosswinds and head- and tailwinds) and procedural aspects (e.g. glide slope intercept altitudes, navigation performance, glide path angles) on incident/accident risk has been evaluated. The risk assessment results show that the largest runway capacity improvement might be achieved through exploiting favourable wind conditions, in particular in the area close to the runway threshold, where wake vortex risk mitigation measures are most effective. The results also show that procedural changes that only have an effect further along the glide slope (e.g. steeper approaches for smaller aircraft, different glide slope intercept altitudes, increased or decreased navigation performance) are not sufficiently effective to reduce the wake turbulence risk related to single runway approaches.

A risk management framework (consisting of risk events, risk metrics, and risk requirements) has been proposed. The risk requirements are based on the Target Level of Safety approach, and are derived using historical incident data on actual wake encounters. The framework has been reviewed by the FAA and EUROCONTROL within the frame of their Action Plan 3 "Air traffic modelling for separation standards", and is currently being elaborated in the ATC-Wake project.

S-Wake WP1 weather climatology analysis showed that the prediction of wind climatology is relatively easy and can therefore probably be used in an operational system. This leads to the conclusion that *warning* for unfavourable evolution of the vortices (in terms of position in relation to the encountering follower aircraft) is most efficient. This can be achieved through an integrated (ground based) ATC wake vortex system that can be used by controllers, possibly supplemented by instrumentation for wake vortex detection and avoidance on-board aircraft.

New concepts and procedures have been evaluated with respect to their potential for capacity improvements. Measures targeted at reduction of the spacing between aircraft have been categorised as aiming at wake vortex alleviation, wake vortex avoidance, or wake encounter alleviation control, and evaluated accordingly. It was concluded that implementing local procedures that take advantage of particularities of an airport (including favourable wind conditions occurring with a relatively high frequency) associated with new wake alleviation systems may lead to an increase of capacity of magnitude of up to 10 to 20 %. This initial assessment of airport capacity gains (with a runway capacity model from ONERA) thus suggests that that in principle substantial gains in airport capacity can be obtained.

7.2 Recommendations

From a safety and capacity perspective, it is of importance to locate those factors that contribute most to the incident/accident risk related to wake turbulence. For this reason, a sensitivity analysis has been carried out, and the major findings are:

- The highest wake vortex induced risk is clearly located near the runway threshold. This implies that - to reduce the risk - weather based prediction, monitoring and warning systems should focus on weather and wind effects near the runway threshold.
- The risk is most sensitive to wind conditions. This implies that an increase of runway capacity might be possible if reliable and stable predictions of wind conditions over a time period of 20 minutes or more (necessary from an operational point of view to allow scheduling for approach with prescribed separation minima) can be made. In this respect, crosswind and strong headwinds are most favourable to increase runway capacity.

With respect to validation, it is recommended to analyse the data collected within the Heathrow Data Base (HDB) in more detail. So far, only partial sets of encounter data have been analysed and compared with the results from the probabilistic safety assessment. Further validation activities shall focus on specific elements of the individual sub-models (e.g. wake evolution in *ground effect*), thereby taking into account validity, applicability and limitations of these sub-models (e.g. the reduced/aircraft pilot model does also *not* perform well *close to the ground*). The relation between encounter severity (bank angle versus loss of height) and the four risk events is a key element that needs to be further validated with actual encounter data as well. In support of acceptance of the WAVIR methodology, it will also be necessary to closely co-ordinate the application with European interest groups responsible for the safety of operation (besides the European Commission also including EUROCONTROL groups (Refs. 59, 60).

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Appendix A WAVIR workflow and integration in ISTaR

The figure below shows the WAVIR workflow, which has been integrated within NLR's Information System for SafeTy and Risk analysis (ISTaR), enabling access through its SPINEware based user- interface.

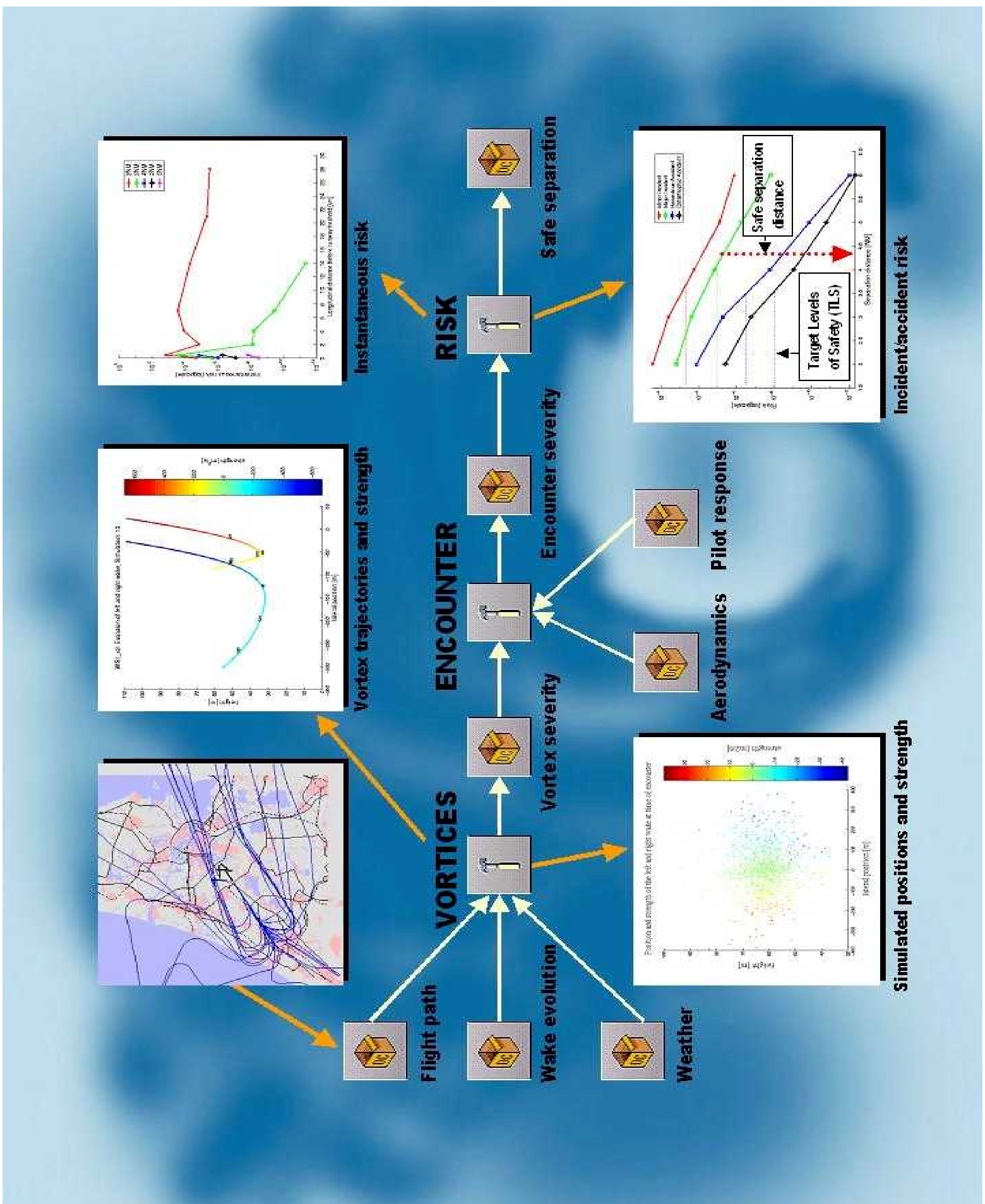

Figure A.1 WAke Vortex Induced Risk (WAVIR) assessment Tool

Appendix B Safe separation distances behind a Large Jumbo Jet aircraft

Figures B.1 – B.4 show the safe separation distances for four types of aircraft behind a Large Jumbo Jet under different crosswind and head/tailwind conditions.

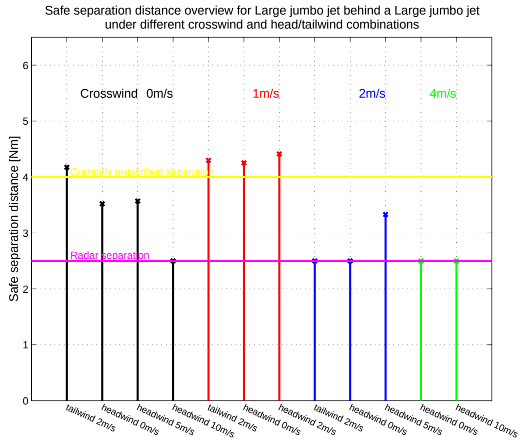

Figure B.1 Safe separation distance for a Large Jumbo Jet behind Large Jumbo Jet

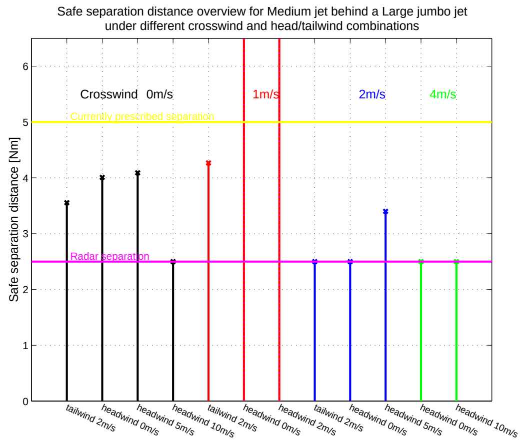

Figure B.2 Safe separation distance for a Medium Jet behind Large Jumbo Jet

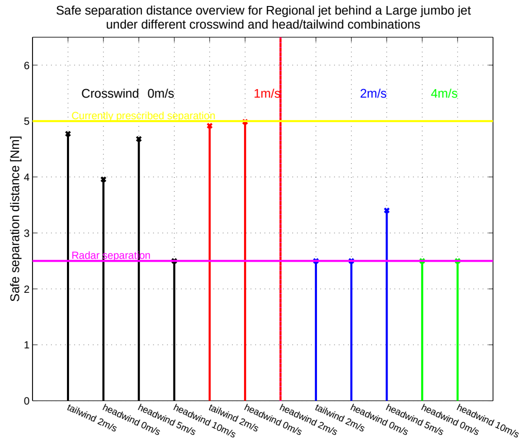

Figure B.3 Safe separation distance for a Regional Jet behind Large Jumbo Jet

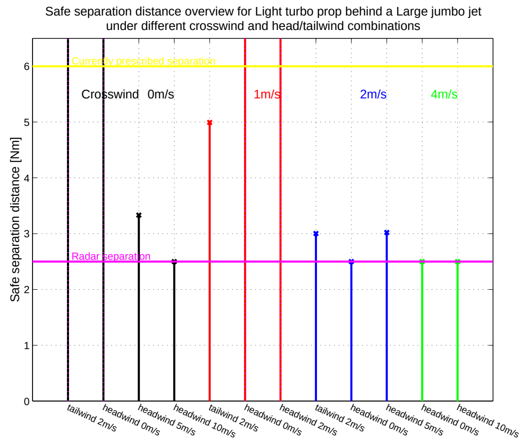

Figure B.4 Safe separation distance for a Light Turbo Prop behind Large Jumbo Jet

Appendix C Safe separation distances behind a Medium Jet aircraft

Figures C.1 – C.4 show the safe separation distances for four types of aircraft behind a Medium Jet under different crosswind and head/tailwind conditions.

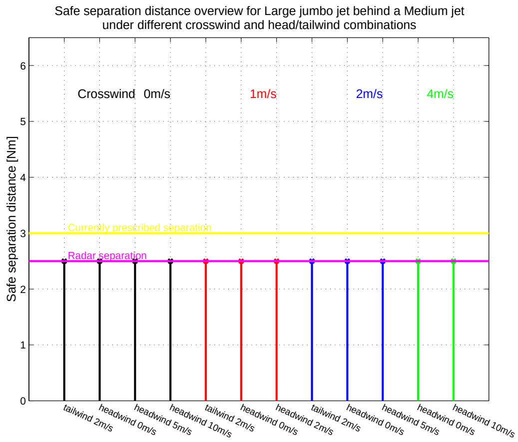

Figure C.1 Safe separation distance for a Large Jumbo Jet behind Medium Jet

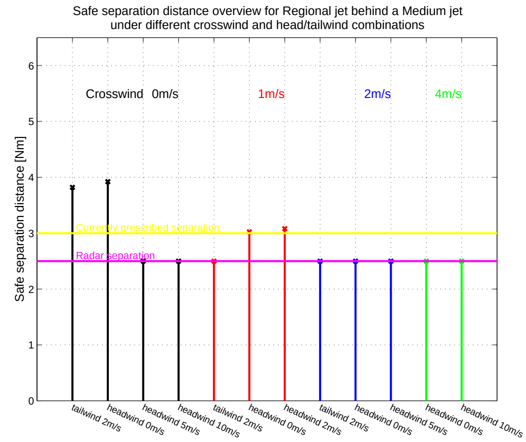

Figure C.3 Safe separation distance for a Regional Jet behind Medium Jet

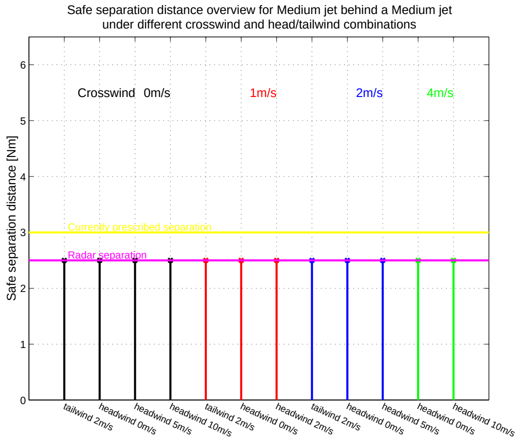

Figure C.2 Safe separation distance for a Medium Jet behind Medium Jet

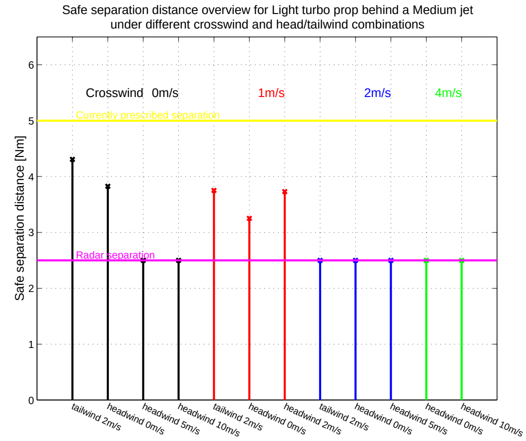

Figure C.4 Safe separation distance for a Light Turbo Prop behind Medium Jet

Appendix D Safe separation distances with head- or tailwind conditions

Figures D.1 – D.4 show the safe separation distances for different combinations of aircraft with no crosswind conditions, and different head/tailwind conditions.

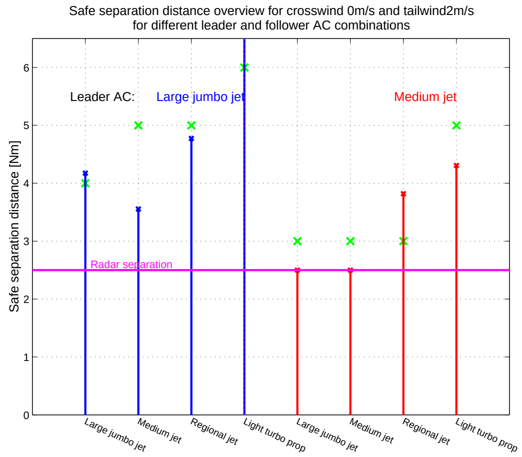

Figure D.1 Safe separation distance for a small tailwind of 2 m/s and no crosswind

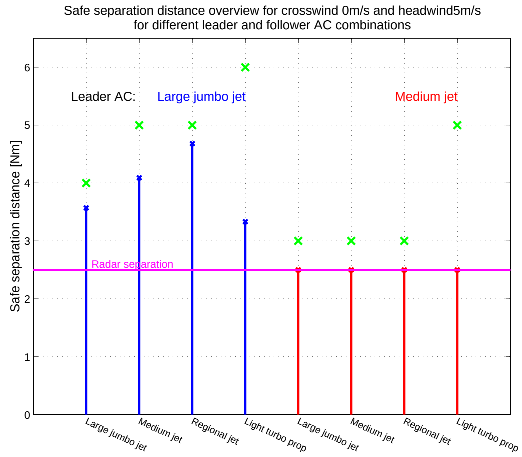

Figure D.3 Safe separation distance for a headwind of 5 m/s and no crosswind

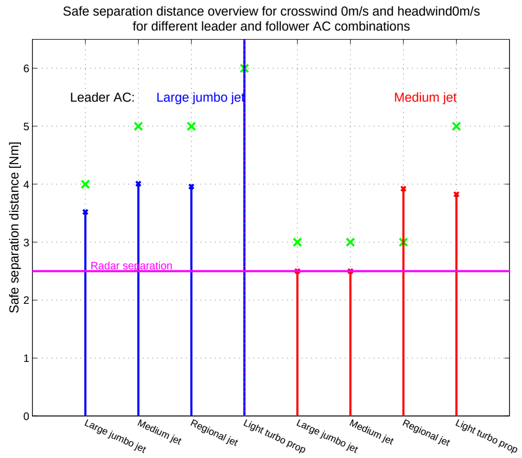

Figure D.2 Safe separation distance for a the situation without any wind

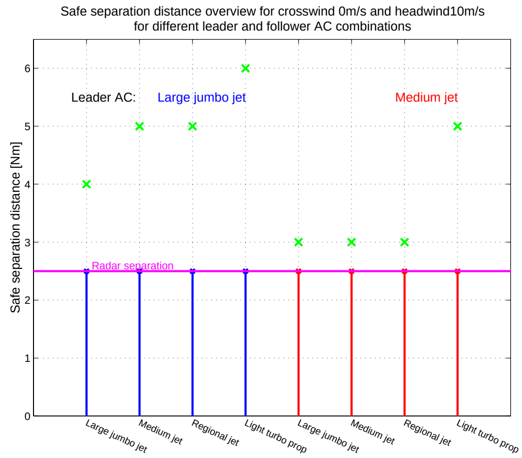

Figure D.4 Safe separation distance for a headwind of 10 m/s and no crosswind

Appendix E Safe separation distances for different crosswind conditions

Figures E.1 – E.4 show the safe separation distances for different combinations of aircraft with no head/tailwind conditions, and different crosswind conditions.

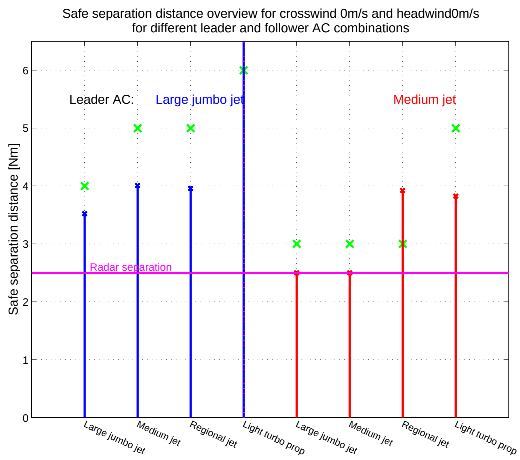

Figure E.1 Safe separation distance for the situation without wind conditions

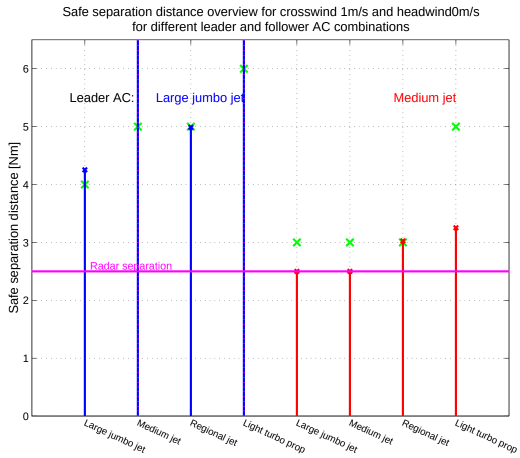

Figure E.2 Safe separation distance for a small crosswind of 1 m/s

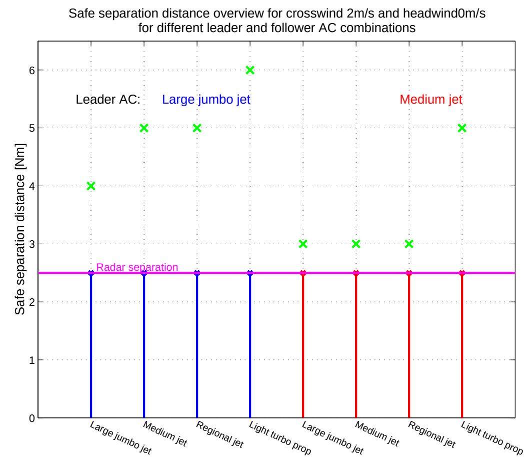

Figure E.3 Safe separation distance for a crosswind of 2 m/s

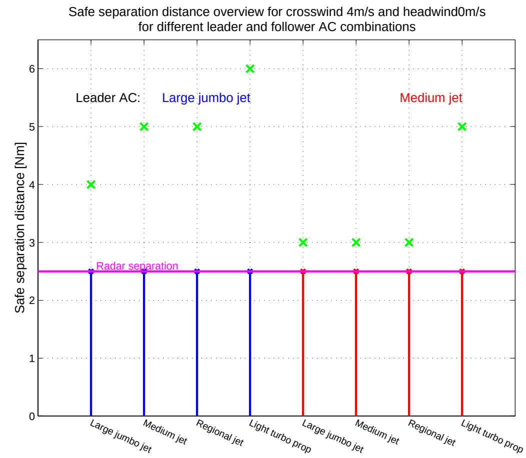

Figure E.4 Safe separation distance for a crosswind of 4 m/s

Appendix F Safe separation distances for small tailwind conditions

Figures F.2 – F.4 show the safe separation distances for different combinations of aircraft with some tailwind conditions, and compared with the situation without any wind conditions (F.1).

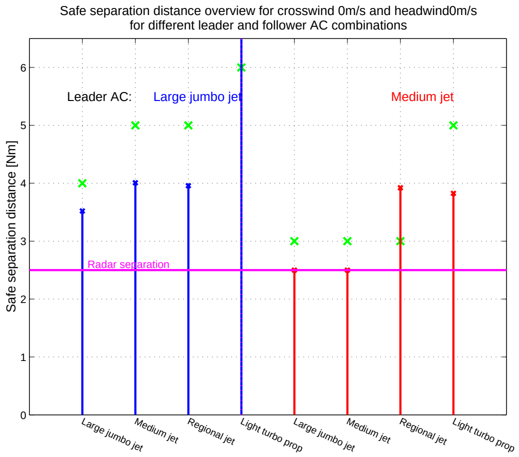

Figure F.1 Safe separation distance for the situation without wind conditions

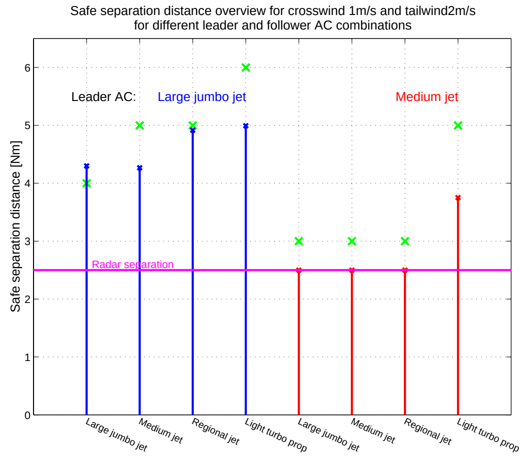

Figure F.3 Safe separation distance for a tailwind of 2 m/s and a crosswind of 1 m/s

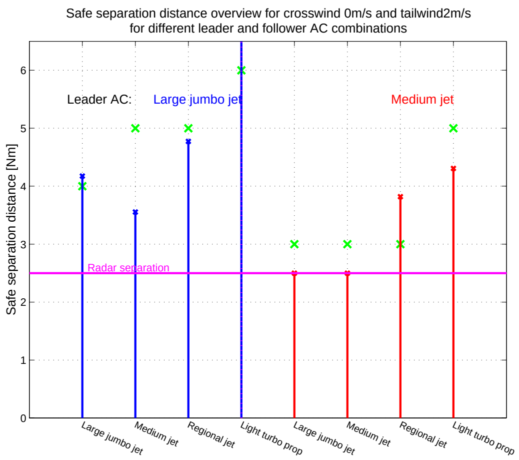

Figure F.2 Safe separation distance for a tailwind of 2 m/s and no crosswind

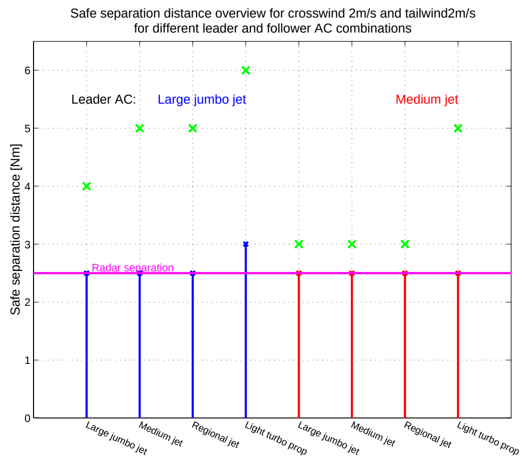

Figure F.4 Safe separation distance for a tailwind of 2 m/s and a crosswind of 2 m/s

Appendix G Safe separation distances for combinations of head- and crosswind

Figures G.2 – G.4 show the safe separation distances for different combinations of aircraft with cross and head wind conditions, and compared with the situation without any wind (G.1).

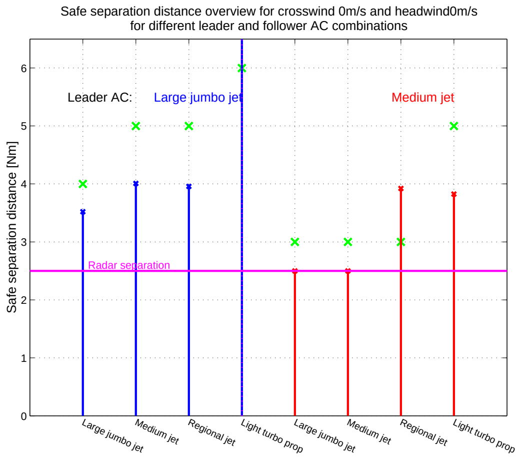

Figure G.1 Safe separation distance for the situation without wind conditions

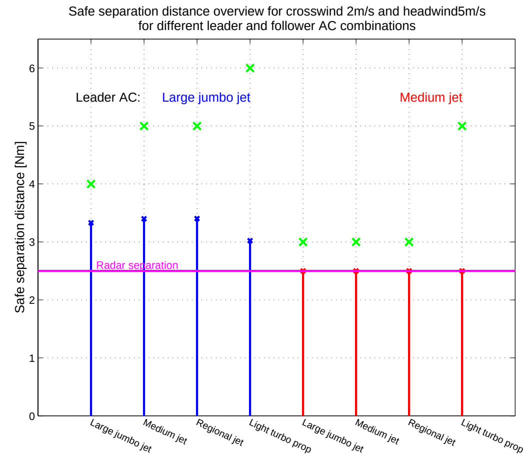

Figure G.3 Safe separation distance for a crosswind of 2 m/s and a headwind of 5 m/s

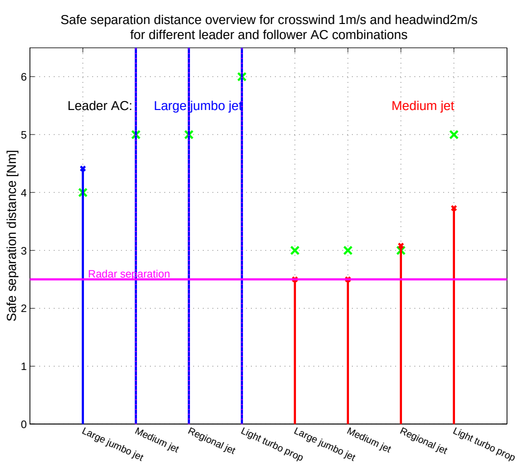

Figure G.2 Safe separation distance for a crosswind of 1 m/s and a headwind of 2 m/s

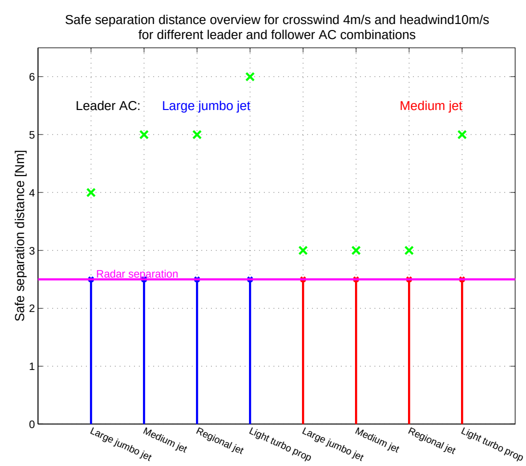

Figure G.4 Safe separation distance for a crosswind of 4 m/s and headwind of 10 m/s