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ATC-Wake Safety and Capacity Analysis

(ATC Wake D3_9)

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Short Description:

The overall objective of this study is to evaluate and quantify possible safety and capacity improvements when using the ATC-Wake system. Safe and appropriate separation minima for single runways (approaches, departures) and closely spaced parallel runways are determined. A variety of combinations of leader and follower aircraft, and under different wind conditions, are evaluated. The safety and capacity benefits of the ATC-Wake system are assessed through an analysis of WAVIR assessed separation minima for different wind conditions, combined with (cross) wind climatology, in order to derive the expected runway throughput improvements when using the ATC-Wake system. The ATC-Wake Safety and Capacity Analysis comprises the following activities:

- The definition of risk requirements and capacity aims;
- The execution of a qualitative safety assessment of the ATC-Wake operational concept;
- The development of a mathematical model for the behaviour of humans (controllers, pilots) working with new wake vortex avoidance systems;
- The extension of an existing wake vortex induced risk assessment model and toolset;
- The development and implementation of the ATC-Wake Separation Mode Planner;
- The execution of a quantitative safety assessment (through fast-time simulations);
- The validation of the safety assessment;
- The evaluation of safe separation distances and runway throughput improvements.

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List of Acronyms

AMAAI	Modelling toolset for the Analysis of In-trail Following Dynamics
AMAN	Arrival Manager
APA	AVOSS Prediction Algorithm
ASAT	Airspace Simulation and Analysis for TERPS
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
AVOSS	Aircraft Vortex Spacing System
BADA	Base of Aircraft Data
CDG	Charles de Gaulle
CFMU	Central Flow Management Unit
CRM	Collision Risk Model
CSPRA	Closely Spaced Parallel Runway Arrivals
DFS	Deutsche Flügsicherung
DFW	Dallas Forth Worth
DMAN	Departure MANager
DP	Deceleration Point
EC	European Commission
ECAC	European Civil Aviation Conference
EDR	Eddy Dissipation Rate
E-OCVM	European Operational Concept Validation Methodology
ERCR	Extended Roll Control Ratio model
ESARR	Eurocontrol Safety Regulatory Requirements
EWVCT	European Wake Vortex Concept of operations Team
FAA	Federal Aviation Administration
FAC	Follower Aircraft
FAP	Final Approach Point
FAR-WAKE	Fundamental Research on Aircraft Wake Phenomena
FMS	Flight Management System
GMU	George Mason University
HMI	Human Machine Interface
ICAO	International Civil Aviation Organisation
IGE	In Ground Effect
IFR	Instrument Flight Rules
ILS	Instrument Landing system
IMC	Instrument Meteorological Conditions
I-WAKE	Instrumentation for WAKE vortex detection, warning, and avoidance
IST	Information Society Technology
JAR	Joint Aviation Requirements
LAC	Leader Aircraft
NASA	National Aeronautics and Space Administration
NGE	Near Ground Effect
NLR	National Aerospace Laboratory NLR
NM	Nautical Mile
NOWVIV	Nowcasting Wake Vortex Impact Variables
OM	Outer Marker
PRR	Performance Review Report
RAPM	Reduced Aircraft Pilot Model
R/T	Radio Telephony
SHAPe	Simplified Hazard Area Prediction
SMGCS	Surface Movement Guidance and Control Systems
SRA	Single Runway Arrivals
SRD	Single Runway Departures
SRU	Safety Regulation Unit
STATFOR	STAtistics and FORecast service
TAAM	Total Airport and Airspace Modeller

TCAS	Traffic Collision Avoidance System
THR	(Runway) Threshold
TMA	Terminal Manoeuvring Area
TOPAZ	Traffic Organization and Perturbation AnalyZer
TWR	Tower
UKMO	United Kingdom Meteorological Office
UNW	UNified Wake
USA	United States of America
VDR	Validation Data Repository
VESA	Vortex Encounter Severity Assessment
VFR	Visual Flight Rules
VFS	Vortex Forecast System
VMC	Visual Meteorological Conditions
WAKEVAS	Wake Vortex Avoidance System
WAVIR	Wake Vortex Induced Risk Assessment
WP	Work Package
WRU	Wake Roll Up

Foreword

An important factor limiting today's airport capacity is the phenomenon of wake vortices generated by aircraft in flight. To avoid aircraft entering the zone of turbulence of another aircraft during the approach phase, minimum separation criteria between aircraft were published in the 1970's. These separations are expressed in terms of longitudinal distances and have since served to provide acceptable safe separations between aircraft at all major airports through the use of radar. An integrated Air Traffic Control (ATC) wake vortex safety and capacity system (including a controller Human Machine Interface (HMI) used in combination with new modified wake vortex safety regulation is expected to provide the means to significantly enhance airport capacity.

The main objective of the ATC-wake project is to develop and build an innovative platform integrated into the Air Traffic Control (ATC) systems with the aim of optimising safety and capacity. This platform will have a test bed environment role:

- To assess the interoperability of this integrated system with existing ATC systems currently used at various European airports;
- To assess the safety and capacity improvements that can be obtained by applying this integrated system in airport environments;
- To evaluate its operational usability and acceptability by pilots and controllers.

The local installation of an integrated system at European airports will require new safety regulation, since the present wake vortex safety recommendations and best practices do not take new modified ATC systems into account.

The main expected exploitable project outputs is the integrated ATC Wake Vortex safety and capacity platform, which contains as further exploitable elements:

- Wake Vortex Prediction and Monitoring Systems;
- Wake Vortex Safety and Separation Predictor;
- Weather forecasting, now-casting and monitoring systems;
- Wake Vortex Predictors and monitors;
- Fast-Time ATC Simulator (upgraded with 'wake vortex modules');
- Controller Human Machine Interface (HMI).

In addition to these exploitable project outputs, new modified wake vortex safety regulation will be proposed. This will strongly enhance the introduction of new systems and procedures to alleviate the wake vortex problem.

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ATC Wake Project Manager

Executive Summary

With the steady increase in air traffic, civil aviation authorities are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the separation distance between aircraft at take-off and landing without compromising safety. One major limiting factor is that aircraft always give each other a wide berth to avoid eachother wake turbulence. With the aid of smart planning techniques, however these distances can be safely reduced, significantly increasing airport capacity. The IST project ATC-Wake aims to develop and build an integrated system for ATC (Air Traffic Control) that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports.

As motivation for the use of ATC-Wake, the WP3 on Safety and Capacity Analysis has evaluated the potential safety and capacity improvements. It has been shown that **runway throughput and delay improves noticeably when the ATC-Wake system is used**. Depending on the occurrence of favourable crosswind conditions, the increase in runway throughput is about 2% for the ATC-Wake SRD operation and 5% for the ATC-Wake SRA operation (at a generic airport with average wind conditions). Introduction of a new ATC system cannot be done without **showing that minimum safety requirements are met**. ATC-Wake risk assessments intend to be compliant with ESARR4 requirements posed by EUROCONTROL’s Safety Regulation Unit (SRU). Guidelines for the development of new wake vortex safety regulation have been given (using a WV risk management framework developed in S-Wake).

The safety assessment of the ATC-Wake operation has been performed in three steps. First, as part of the qualitative safety assessment, potential hazards and conflict scenarios related to use of ATC-Wake have been evaluated. Second, through use of the ‘classical’ WAVIR tool, indicative separation minima dependent on crosswind conditions have been determined. As these indicative separation minima do not yet account for crosswind uncertainty, as part of the third step, the setting of requirements for the ATC-Wake system components was further investigated. It appears that the especially the Monitoring and Alerting system and Meteorological Forecast and Now-casting systems are crucial and sufficient accuracy and reliability shall be guaranteed.

WAVIR simulations for the SRA operation indicate that reduced separation of 2.5 Nm might be applied safely in ATC-Wake Mode provided that crosswind is forecasted to be above a certain limit. During ATC-Wake arrivals, the Monitoring and Alerting component will anticipate potential wake encounters in time (and generate an alert); nevertheless if the meteorological forecast information is not accurate and stable enough, this might be achieved at the cost of a relatively large number of missed approaches. The simulations indicate that, provided that certain requirements are met, about 30% of the approaches might be performed with 2.5 Nm aircraft separation in case ATC-Wake is used.

WAVIR simulations for the SRD operation also indicate that reduced separation of 90 seconds can be applied safely in ATC-Wake Mode, provided that crosswind is forecasted to be above a certain limit. If the accuracy of the wind forecast information is too low, the Monitoring and Alerting component could provide a relatively large number of alerts. A potential issue is that immediately after take off, i.e. at relatively low altitude, it will not be feasible for the pilot to turn away from the wake vortex of a preceding aircraft. Provision and use of meteorological now-casting information by the controller will be very beneficial during the second departure phase, in order to support the pilot to prepare for a potential encounter in case of a sudden change of the wind conditions.

Qualitative safety assessment of the ATC-Wake operation

For the operations outlined in the ATC-Wake operational concept, a qualitative safety assessment was performed for single runway departures, single runway arrivals and closely spaced parallel runway arrivals. It was concluded that for these operations there exist some conflict scenarios that may bear potential SAFETY BOTTLENECKS, i.e., the risk may be above a maximum tolerable probability. No definitive answers on the acceptability of the risks were attained in the qualitative safety assessment, as the results included extensive uncertainty bands. Therefore, the analysis was supported with a subsequent quantitative safety assessment with support of mathematical models for aspects of the ATC-Wake operations. Some safety bottlenecks have been identified, enabling adaptation and enhancements of the ATC-Wake operation. The scenarios are:

- Wake vortex encounter during departure;
- Wake vortex encounter during single runway arrival;
- Missed approach during single runway arrival;
- Wake vortex encounter during arrivals on CSPRs;
- Missed approach during arrivals on CSPRs;
- Higher traffic rates in TMA, holding, sector, or on runway;
- Turbulence;
- More landings in crosswind;
- Transitions between ICAO and ATC-Wake Separation Mode;
- Effects on ICAO Separation Mode.

For some of these scenarios, potential enhancements have been proposed, which have been addressed by ATC-Wake operational experts in *WP4 Operational Feasibility* (D4_7).

Development of human operator models

Models for the performance of human operators during single runway arrivals have been developed (in particular for the ATC supervisor, arrival sequence manager, initial approach controller, intermediate approach controller, tower controller and aircraft crews). The models describe monitoring, interaction with ATC-Wake systems and decision making of the controllers and aircraft crews. The human operator performance models have been developed and included in an integrated model, representing the performance of human operators, related aircraft movements, meteorological influences and technical systems (surveillance systems, communications systems and ATC-Wake systems).

Validation of the quantitative safety assessment

To validate the safety assessment method, a number of activities have been carried out:

- A comparison between two wake vortex evolution models (VFS and VORTEX) was made, taking into consideration conditions far and close from the ground. The models seem to predict different behaviour of vortices even for cases without crosswind, i.e. further investigation might be needed in order to better understand this phenomena.
- A comparison between available wake encounter models with different complexity was made, including validation against computed maximum bank angles observed during wake encounter flight simulations. A fair agreement of the results was noted.
- A newly developed Petri-Net (PN) aircraft flight path evolution model was validated against the AMAAI toolset developed for the analysis of in-trail following aircraft. It was concluded that the PN model provides sufficiently accurate results for use in WAVIR.

Quantitative safety assessment methodology

For the quantitative assessment of the wake vortex induced risk related to the ATC-Wake operation with reduced separation, there are three main issues to consider:

- The controller working with the ATC-Wake system has to instruct the pilot to initiate a wake vortex avoidance manoeuvre, in case an ATC-Wake warning/alert is raised.
- If one or more ATC-Wake system components provide wrong or erroneous advice, there will be a higher risk on the presence of (severe) wake vortices. The consequences might be CATASTROPHIC, because reduced separation is applied.
- The separation distance/time will vary along the flight track, and will usually not be exactly the same as the separation minima advised by the Separation Mode Planner.

The 'classical' WAVIR methodology, which originates from S-Wake, has been used to assess wake vortex induced risk. To cope with all the above issues, WAVIR has been extended with a graph and decision theory based structure. A variety of mathematical models and techniques (including fault trees, discrete and continuous Bayesian Belief Nets and vines, and Petri Nets) are introduced to incorporate the role of humans working with ATC-Wake. The details of the model are described in ATC-Wake D3_5b.

Evaluation of safe separation distances and capacity

To determine the crosswind threshold values, above which reduced separation for all aircraft combinations may be applied, three simulation studies have been carried out:

- Single runway arrivals;
- Single runway departures;
- Closely spaced parallel runway arrivals.

Indicative separation minima have been determined for all three operations, and an initial assessment of throughput improvements has been made using analytical models based on aircraft spacing, queuing models and sequencing approximation methods. These indicative separation minima for the three operations are given in the Table below. A crosswind climatology based on 400000 observations at 10 European airports has been used.

Indicative separation minima per crosswind interval for the ATC-Wake operations

	Proposed separation					**Crosswind**
Crosswind interval	SRD operation	SRA operation	CSPRA operation (non-segregated)	CSPRA operation (segregated)	CSPRA operation (semi-segregated)	Crosswind probability per interval
$0 \le u_c \le 1$m/s	ICAO	ICAO	2.5NM	2.5NM	2.5NM	0.080
$1 \le u_c \le 2$m/s	ICAO	ICAO	ICAO	2.5NM	ICAO	0.208
$2 \le u_c \le 3$m/s	120s	2.5NM	ICAO	2.5NM	ICAO	0.206
$3 \le u_c \le 4$m/s	90s	2.5NM	ICAO	2.5NM	ICAO	0.164
$4 \le u_c \le 5$m/s	90s	2.5NM	*ICAO*	3.0NM	3.5NM	0.118
$5 \le u_c \le 6$m/s	60s	2.5NM	*ICAO*	3.0NM	3.5NM	0.081
$6 \le u_c \le 8$m/s	60s	2.5NM	3.0NM	2.5NM	2.5NM	0.053
8m/s $\le u_c$	60s	2.5NM	2.5NM	2.5NM	2.5NM	0.090

Since 2005, application of the European Operational Concept Validation Methodology (E-OCVM) and the use of the Validation Data Repository (VDR) is required by all new EC/EUROCONTROL ATM related projects. E-OCVM provides a common approach to validation of operational concepts as a pre-requisite for industrialisation and operational introduction. *A Safety Case, Human Factors Case, Benefits Case and Technology Case will need to be produced before the ATC-Wake system can be used at European airports.* In this respect, a full Safety Case shall take into account the local airport weather climatology and specific local ATC/pilot procedures for wake vortex mitigation.

During the validation activities, it appeared that both real (measured) data as well as a sufficiently validated aircraft performance and dynamics model for *departures* are not yet available. Sufficient validation of the ATC-Wake single runway departure safety assessment results was therefore not possible. It is therefore recommended to extend the well known AMAAI toolset (developed for EUROCONTROL) for the analysis of in trail following aircraft during arrivals with a module dedicated to departure operations. Wake vortex evolution models and wake encounter models for departures also appeared not sufficiently validated.

In view of the above, actual implementation of the ATC-Wake operation at European airports is envisaged around 2010 at the earliest. It is recommended to involve airport authorities and ATC centres for gathering the required data to build the Safety Case.

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1 Introduction

1.1 Scope

With the steady increase in air traffic, civil aviation authorities are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the separation distance between aircraft at take-off and landing without compromising safety.

One major limiting factor is that aircraft always give each other a wide berth to avoid eachothers wake turbulence. With the aid of smart planning techniques, however these distances can be safely reduced, significantly increasing airport capacity.

Aircraft create wake vortices when taking off and landing, restricting runway capacity. These vortices usually dissipate quickly, but most airports opt for the safest scenario, which means the interval between aircraft taking off or landing often amounts to several minutes. However, with the aid of accurate meteorological data and precise measurements of wake turbulence, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains of up to 10%, which has major commercial benefits. The IST project ATC-Wake aims to develop and build an integrated platform for ATC (Air Traffic Control) that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. The present minimum separation of six nautical miles for small aircraft (coming in behind a larger one), and three nautical miles for larger aircraft is designed to counter the problems aircraft can encounter in the wake of larger types. If these fixed distances can be reduced in favourable weather conditions without compromising safety, then an airport’s aircraft-handling capacity increases accordingly. For approaches, the aim is to manage separation distances down to 2.5 nautical miles, in perfect weather conditions, for all aircraft types regardless of size. For departures, the aim is to reduce the time separation between departing aircraft to 90 seconds (in favourable wind conditions).

The ATC-Wake system integrates weather and wake sensors, weather forecasting, wake-vortex prediction system, aircraft-spacing predictors and the air-traffic-controller interface. When used with planned new European harmonised safety regulations, it should be able to provide airports and aircraft handling organisations with significant increases in accuracy and aircraft-handling capacity, while maintaining safety.

The ATC-Wake decision-support system and procedures will help air traffic controllers decide how long the intervals should be. These procedures are based on laser technology called Lidar, which monitors the movement of dust particles through the air. This system is used to continually monitor wake turbulence on runways. This turbulence data is combined with meteorological data to generate recommendations for intervals, which are displayed on the air traffic controller's screen. The recommendations are also used in planning systems at air traffic management.

1.2 Objectives

The overall objective of this study is to evaluate and quantify possible safety and capacity improvements when using the ATC-Wake system. Safe and appropriate separation minima will be determined for single runways (approaches, departures, mixed mode operations) and closely spaced parallel runways. A variety of combinations of leader and follower aircraft, and under different wind conditions, will be evaluated. The safety and capacity benefits of the ATC-Wake system will be assessed through an analysis of WAVIR assessed separation minima for different wind conditions, combined with (cross) wind climatology, in order to derive the expected runway throughput improvements when using the ATC-Wake system. This comprises as activities:

- The definition of risk requirements and capacity aims;
- The execution of a qualitative safety assessment of the ATC-Wake operational concept;
- The development of a mathematical model for the behaviour of humans (controllers, pilots) working with new wake vortex avoidance systems;
- The extension of an existing wake vortex induced risk assessment model and toolset;
- The development and implementation of the ATC-Wake Separation Mode Planner;
- The execution of a quantitative safety assessment (through fast-time simulations);
- The validation of the safety assessment;
- The evaluation of safe separation distances and runway throughput improvements.

A Functional Hazard Assessment of the use of (on-board) instrumentation for wake detection warning and avoidance system used in conjunction with the (ground based) ATC-Wake system has been performed as part of the I-Wake project.

1.3 Approach

The overall approach taken is to start with the derivation of capacity aims, using a series of analytical tools and simulation platform developed by EUROCONTROL for providing performance predictions for the future ATM system. Several scenarios with capacity increases will be simulated, with the aim to derive targets for reduction of delays and increase in accommodated flights in the major European airports around 2010 and 2015.

Introducing and/or planning changes to the ATM system cannot be done without showing that minimum safety requirements will be satisfied. This will be done through a safety assessment. In this respect, the wake vortex risk requirements for the ATC-Wake safety assessments will be derived from (i.e. intend to be compliant with) the ESARR 4 requirements posed by EUROCONTROL's Safety Regulation Commission (SRC).

The ATC-Wake safety assessment will be performed in two steps. The first step consists of a qualitative safety assessment, so as to identify the hazards and safety bottlenecks associated with the proposed operation. This allows for an improvement of the ATC-Wake concept, which will then be analysed quantitatively through the use of the NLR WAke Vortex Induced Risk assessment (WAVIR) methodology and toolset. This second step includes estimation of the newly proposed ATC-Wake (reduced) separation minima under favourable operational and weather conditions.

Evaluation of wake vortex separation distances have historically been conducted using three approaches: (1) Experimental flight test data, (2) Historic operational data, and (3) Analytical models. As the ATC-Wake system and operation is still in the design phase, this study follows the third approach. The intention is to build sufficient safety confidence, enabling the decision makers to decide on operational testing and implementation.

The evaluation of the wake vortex safety involves the evaluation of the accident risk in the ATM system, which inhibits stochastic behavior. The probabilistic safety analysis must (and will) be conducted for a traffic mix of aircraft under different weather conditions flying flight paths with statistical variations, taking into account stochastic models of wake vortex generation, wake vortex encounter, and aircraft/pilot and controller responses.

Both in Europe and the United States, newly proposed Concept of Operations for reduced wake vortex separation depend heavily on the use of wake vortex prediction and detection information, with explicit roles and responsibilities for the pilots and controllers working with such wake avoidance systems. The WAVIR tool-set, which has been applied in S-Wake to assess the (wake vortex) safety related to current practice single runway arrivals, is therefore extended with human performance models (based Bayesian Belief Networks and Petri Nets) using expert opinion from active pilots and controllers.

Following derivation of the newly proposed ATC-Wake (reduced) separation distances, the potential runway throughput improvements are calculated using analytical models.

1.4 Document structure

Section 2 provides an overview/state-of-the-art on existing safety and capacity assessments methods and tools, including improvements needed and foreseen. Capacity aims and wake vortex risk requirements are described in Section 3. A summary of the proposed ATC-Wake concept and system architecture is contained in Section 4. The Section 5 describes the risk assessment methodology used. The results from the qualitative safety assessment, quantitative safety assessment, and the runway throughput improvement analysis are described in Sections 6, 7, and 8 respectively. Section 9 provides the conclusions and recommendations. The appendices provide results of the quantitative safety assessments for single runway arrivals, single runway departures and closely spaced parallel runways.

2 Overview / state-of-the-art

2.1 Systems and concepts of operation for reduced separation

Wake vortices are a natural by-product of lift generated by aircraft and can be considered (or viewed) as two horizontal tornados trailing after the aircraft. A trailing aircraft exposed to the wake vortex turbulence of a lead aircraft can experience an induced roll moment that is not easily corrected by the pilot or the autopilot. ATC separation standards, designed for the worst-case scenario, have been introduced to ensure operation without a wake vortex hazard. Wake vortex separation standards have a significant impact on airport departure and arrival capacity especially at the busiest hub airports. For this reason both the USA WakeNet Conops Team and the European Wake Vortex Conops Team (EWVCT) are developing technologies and procedures for increased arrival and departure rates at airports through reduced separation *without* an impact on safety.

In Europe, currently three new concepts of operation are under consideration by the European Commission and Eurocontrol. The near term procedure involves modification of the separation method used during arrivals: here the focus is on introducing *Time Based Separation* at airports with a large frequency of strong headwind conditions. Mid- to long term procedures focus on new ground and airborne systems (including *ATC-Wake* and *I-Wake*) based on real-time prediction and monitoring of wake vortices.

In the USA, currently three concepts of operation are under consideration by NASA and the FAA to improve runway flow capacity by reducing separation distances under certain conditions. The near-term procedure involves modification of the rules associated with closely spaced parallel runways. Here the aim is to enable dependent parallel runway arrival operations with parallel runways separated by less than current standards under favourable weather conditions. Mid-term procedures involve modification of separation times for departures. Long-term systems and procedures (including *WakeVAS*) aim to execute dynamic separation distances based on measurements of weather conditions.

2.2 Determining wake vortex separation standards

Prior to the introduction of large wide-body jets, wake vortex upsets or turbulence encounters by a trailing aircraft were considered to be “prop-wash” or “jet wash” and not considered a flight hazard. The introduction of large wide-body turbojet aircraft with increased weight and wingspan in the late 1960’s changed this perception and initiated the detailed study of wake vortices and their impact on trailing aircraft. In mid 1969 a series of flight test experiments were conducted by Boeing and the FAA to generate detailed information on the wake vortex phenomenon. By using smoke towers and probing aircraft, the wake vortices of a B747 and B707-320C were characterized.

This data provided the basis for wake vortex separation rules adopted by ICAO/FAA:

- VFR rules – following aircraft remain above of the flight path of the leading aircraft
- IFR rules – minimum radar-controlled wake separation distances were established for the following aircraft based on the weight of the lead and follow aircraft

Although under IFR rules aircraft were categorized by weight, the data from these studies identified that a more technically correct way to establish categories of aircraft is by wingspan of the trailing aircraft. This was considered impractical to implement and was dropped in favour of categorization by weight. With a few exceptions, weight exhibits relatively good correlation with wingspan.

A variety of methodologies for Determining Wake Vortex Separation Minima exist:

- Experimental Flight Test:
  The original separation distances for IFR were established based on the “worst case” wake vortex turbulence measurements from the flight test described above, at high altitude with low ambient turbulence. Due to the expectation that the increased ambient turbulence would disrupt the wake vortices, the actual distances were slightly reduced versions of these “worst case” distances.
- Historic Operational (VFR) Data Analysis:
  Historical data showing the fact that safe operations were consistently conducted between 1976 and 1994 by aircraft operating under “see-and-avoid” VFR separation rules at distances below the IFR separation regulations, was used as basis for reduction of the separation distance between aircraft lighter than the B757 to 2.5 Nm.
- Safety Assessment based on Analytical Modelling:
  An alternative procedure for determining safe separation distances uses a probabilistic approach to assess the wake vortex induced risk between aircraft. Here, the approach is to account for statistical variations, taking into account stochastic models of wake vortex generation, wake vortex encounter, and aircraft/pilot and controller responses. Simulation data from all the models is combined to determine the probability and severity of a wake encounter for a given separation time and under different operational and weather conditions.

The third method uses probabilistic risk assessment techniques to establish safe separation distances on the basis of a predefined risk requirement (*target level of safety).* As such, this method can also be used to assess the safety of newly proposed wake vortex avoidance concepts, systems, and procedures. Several issues arise:

1. What is the required safety level (risk requirement)?
2. What is the safety level of the current separation standards?
3. Are the current separation standards overly conservative?
4. Can the separation standards safely be reduced?

These questions, the existing wake vortex safety assessment methods, and the improvements needed and foreseen, are addressed in the following sub-sections.

2.3 Existing wake vortex safety assessment methods

In Europe, the required safety level for ATM operations is provided by EUROCONTROLs Safety Regulatory Requirements (ESARRs). The ESARRs concern use of a qualitative and/or quantitative risk based-approach when introducing and/or planning changes to the ATM system. Such assessment requires the following aspects of risk criteria:

- a severity classification,
- a frequency classification, and
- a risk tolerability scheme.

The ESARR 4 requirements also states that a combination of quantitative (e.g. using mathematical models and statistical analysis) and qualitative (e.g. using good working processes, professional judgement) arguments may be used to provide a good enough level of assurance that all identified safety objectives and requirements have been met.

Existing wake vortex safety assessment methods, able to assess wake vortex safety of flight operations and the associated separation minima in a quantitative way, are:

- WAVIR, developed by NLR.
- WakeScene, developed for Airbus.
- VESA, developed for Airbus.
- ASAT, developed for the FAA Flight Standards Branch.

WAVIR (WAke Vortex Induced Risk assessment) is a stand-alone risk assessment method, based on a modular approach (see the Figure below) in which vortex severity, wake encounter severity, and incident/accident risk are being determined subsequently.

Basically it is a three step approach. First evolution of the wake vortex generated by a leading aircraft is calculated at a given number of gates along the approach or departure path. From this the relative position and strength of the wake vortex can be determined at the time that a following aircraft passes the defined gates. Secondly, the effect of the wake on the passing (i.e. follower) aircraft is determined. Depending on the aircraft model used this is expressed either in a single disturbance parameter (induced roll angle) or a combination of disturbances (in the lateral and vertical axes). Finally these disturbances are translated to a certain hazard category. The set-up of the model allows Monte Carlo simulations, with varying meteorological conditions, aircraft types, etc. to estimate the frequencies of certain risk events in a certain scenario. The outcome of the risk assessment (incident/accident probability per movement) can then be compared with a target level of safety in order to establish the anticipated acceptability of the operation.

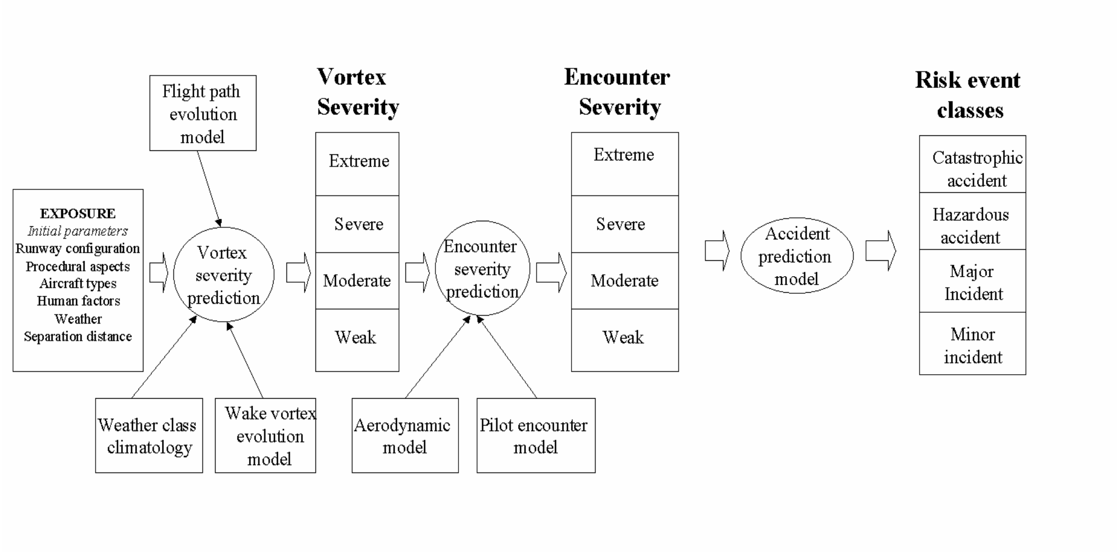


Figure 1 – Wake Vortex Induced Risk assessment (WAVIR) model

Risk requirements can be set for e.g. the encounter probability per movement or for incident/accident risk events defined on the basis of ICAO Annex 13 (for incident/ accident investigation) and the JAR 25.1309 (for aircraft system hazard categorisation).

WAVIR has been used in S-Wake to assess the wake vortex safety of current practice single runway operations. In ATC-Wake, WAVIR has been extended to the whole airport environment (including departures). The roles and reaction times of pilots and controllers working with wake vortex concepts and procedures is explicitly modelled and analysed.

The **WakeScene** (Wake Vortex Scenarios Simulation) Package also allows to assess the relative encounter probability behind different wake vortex generating aircraft within a domain ranging from the final approach fix to threshold (i.e. approach phase of flight only). WakeScene supports Monte-Carlo Simulation as well as prescribed parameter variations and generates statistical evaluations. The package consists of elements that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. The Aircraft Speed Model provides time, speed, and mass of generator and follower aircraft at the different gate positions, using point-mass aircraft models, based on the BADA database. The Flight-Path Deviation Model computes random deviations from nominal glide path which are derived from measured flight path deviations. A Meteorological Data Base comprises a one-year statistics of meteorological conditions for the Frankfurt terminal area which were produced with the weather forecast model system NOWVIV. Based on vertical profiles of environmental conditions and aircraft parameters, the Probabilistic Two-Phase Wake Vortex Decay and Transport Model simulates the development of wake vortex trajectories, circulation, vortex core radius, and attitude of wake vortex axes. The module Simplified Hazard-Area Prediction (SHAPe) computes the required distance between wake vortex and follower aircraft on the basis of a hazard zone around a wake vortex.

VESA (Vortex Encounter Severity Assessment) has been developed by Airbus to assess and compare aircraft reactions and the effects of vortex encounters behind various aircraft. As such, VESA support air traffic service providers and national aviation safety regulators, which need assurance of the separation standards if modifications of the current system are proposed. An application is to assess if the operational safety of the existing aircraft is maintained after the introduction of the A380. VESA uses 6 DOF aircraft simulation models and aerodynamic (strip or panel methods) to calculate the response to a wake vortex encounter. The VESA model employs both autopilot and pilot models to calculate the response in a closed loop fashion. The resulting aircraft response is then used to determine the encounter severity. The VESA concept focuses on the *comparison* of probabilities to exceed certain hazard levels for aircraft combinations.

ASAT (Airspace Simulation and Analysis for TERPS) is a collection of models and simulations that can be used to analyze safety and risk factors for a large range of aviation scenarios. ASAT has recently been extended with the AVOSS Prediction Algorithm (APA), so as to assess the probability of a wake encounter behind a variety of leader aircraft and under different weather conditions. APA is based on Sarpkaya's "out of ground effect" decay model, and therefore not valid for encounters close to the ground. The heart of the system consists of the high fidelity engineering flight dynamics models of three Boeing aircraft (737, 767, and 747) against which the lesser models normally used in the high speed simulations are frequently checked. Model performance is also driven by empirical data collected in flight simulators and flight tests. In addition to these aircraft simulation models ASAT comprises models of aircraft avionics (FMS, autopilot, etc.) based on real equipment, models of ground navigation aids, etc. In this respect the simulation models resemble the models as for instance used in auto-land certification. Through the use of APA, the simulation tool can also generate and track wake vortices and identify encounters between wakes and aircraft in the scenario. As such ASAT/APA can also be used for wake vortex risk assessments of new concepts and procedures.

2.4 Existing capacity analysis methods and tools

For estimation of potential capacity improvements, when using the ATC-Wake system and supporting operational concept, it is important to distinguish the following metrics:

- Unconstrained demand: the expansion of air traffic demand as expected and desired by the airspace users to maintain and develop growth of their businesses.
- Accommodated demand: the maximum number of flights that can be scheduled by users under given capacity conditions, taking all ECAC network effects into account.
- Un-accommodated demand: those flights, which are unable to obtain slots in desired airports at the desired time of the day (i.e. flights which will not even be scheduled).
- Reduction of delays: improvement in average delay per flight for an airport.

EUROCONTROL has developed a series of tools and simulation platforms useful for providing performance predictions for the future ATM system, in terms of delay at the European level given a number of potential scenarios concerning the evolution of both capacity and demand. These tools represent the only such European-wide environment capable of faithfully replicating the operations of the CFMU and resultant network interaction. It is possible to assess the impact on ATFM delay and system access at a chosen time horizon resulting from changes in the “supply-side” (airport capacity limits).

TAAM (Total Airspace and Airport Modeller) is an ATC fast-time simulator, able to simulate ground, terminal area and en-route operations. TAAM provides details about aircraft movements, including departure and arrival flow rates, delays, runway utilisation and occupancy times, taxi in and taxi out times, and also gate delays.

In addition to these two simulation platforms, a variety of analytical models for capacity estimation exist worldwide. These analytical models are based on aircraft spacing models, queuing models, and sequencing approximation methods for the arrival and departure flows. Such models might be useful for estimation of the runway throughput improvements, when using ATC-Wake in combination with an AMAN or DMAN.

2.5 Verification and validation of risk assessments

Wake vortex safety assessment methods will most likely be used by authorities for the approval of new ATM systems, concepts and procedures, as well as newly designed high capacity aircraft. in this respect it is important to verify and validate both the overall approach taken and the sub-models included. Unfortunately, at present no validated wake vortex safety assessment method exists. In fact, it is presently not fully known how the various model assumptions and simplifications in the models described in Section 2.3 affect the risk assessment results. Therefore, part of the research will have to focus on the comparison of the models used with historical data, flight simulator data, and validated flight path evolution models. In this respect, the following sources are relevant:

- NLR Aviation Safety database;
- Wake encounter flight simulator data (e.g. from *S-Wake*);
- Databases with wake vortex measurements (e.g. from *Memphis*, *Dallas Forth Worth*);
- AMAAI modelling toolset for the analysis of in-trail following dynamics during arrivals.

Comparison of simulation results with these data sources will provide an indication which simplifications are allowable, and where models are sensitive to the modelling structure and parameters.

3 Capacity aims and risk requirements

3.1 Capacity aims

Capacity increase may impact the overall air transport network – using “delay” and “access” as the measures of performance impact. EUROCONTROL has developed a series of analytical tools and simulation platforms useful for providing performance predictions for the future ATM system. The aim of such tools is to provide a consolidated performance prediction in terms of delay at the European level given a number of potential scenarios concerning the evolution of both capacity and demand. The analytic environment is indicated in Figure 2.

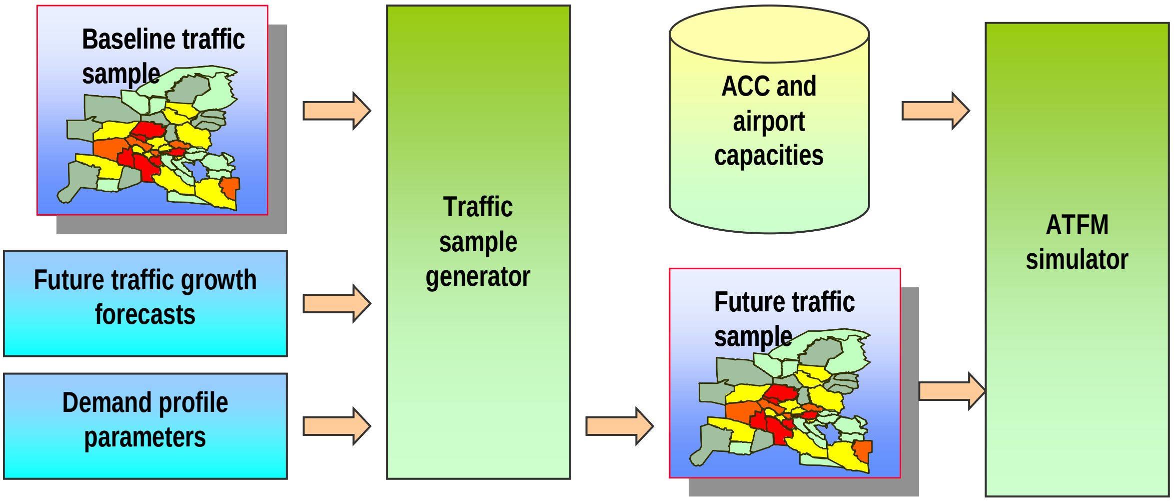


Figure 2 – EUROCONTROL simulation platform for ATM performance predictions

At the heart of the analytic environment is an ATFM simulator that simulates the slot allocation process of the CFMU. The model therefore takes as input both ‘supply-side’ (capacity) and demand-side (individual flight plans) data and allocates departure slots in the same way as the CFMU. These tools represent the only such European-wide analytical environment capable of faithfully replicating the operations of the CFMU and resultant network interaction. Using the above framework, it is possible to assess the impact on ATFM delay and system access at a chosen time horizon resulting from changes in the “supply-side” (airport capacity limits). As the time horizon for performance analysis becomes more protracted, the quality of the predictions concerning traffic growth and capacity provision necessarily decrease. More than ever-such performance predictions should be considered in the framework of a ‘what-if’ rather than as a prediction of the future state of the ATM network. Nevertheless, the principal aim is not to attempt to provide detailed performance predictions, but rather to provide indications of the potential sensitivity of the ATM network to changes in the balance between demand and supply (flight numbers, available capacity).

The process is illustrated in Figure 3. Basically, the methodology consists of 7 steps:

- Step A Development of the Baseline Scenarios
- Step B Traffic Growth Forecasts (STATFOR)
- Step C Traffic Augmentation Methodology
- Step D Airport capacities and un-accommodated demand
- Step E En-route capacity evolution
- Step F Airport capacity scenarios study
- Step G Performance predictions

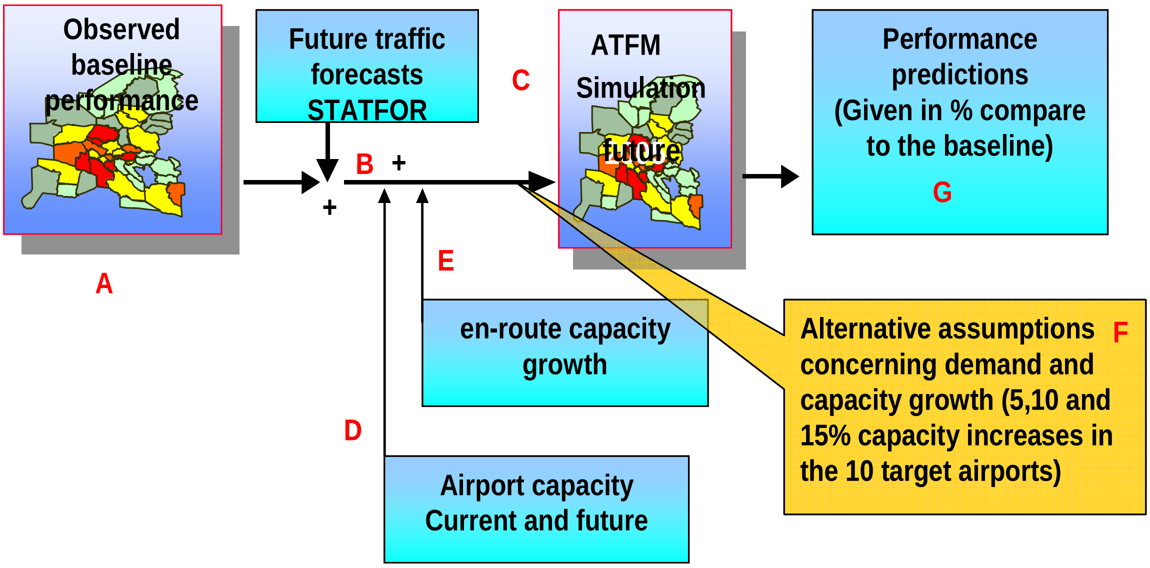


Figure 3 – EUROCONTROL methodology for determining airport capacity aims

Figures 4, 5 and 6 present unconstrained, accommodated, and un-accommodated demand until 2020 for the 10 major airports (Paris-CDG, Frankfurt, London Heathrow, Amsterdam, Madrid, Brussels, Copenhagen, Zurich, Rome and London Gatwick).

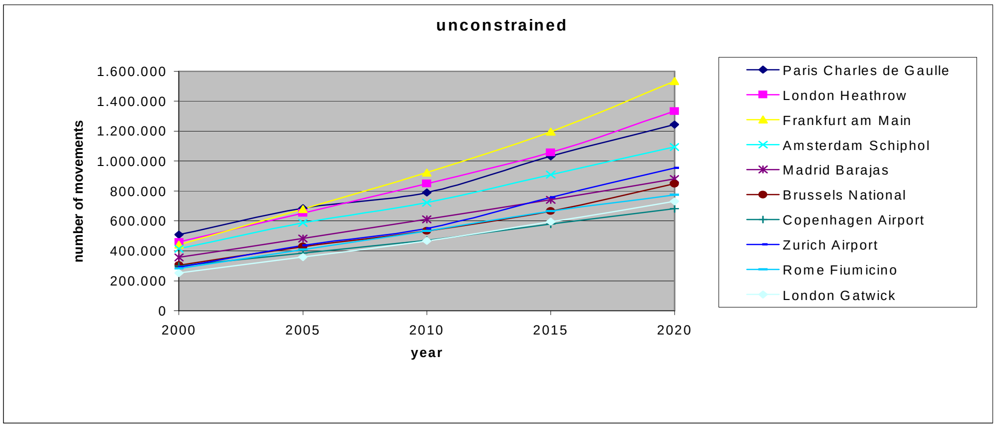


Figure 4 – Unconstrained demand forecast

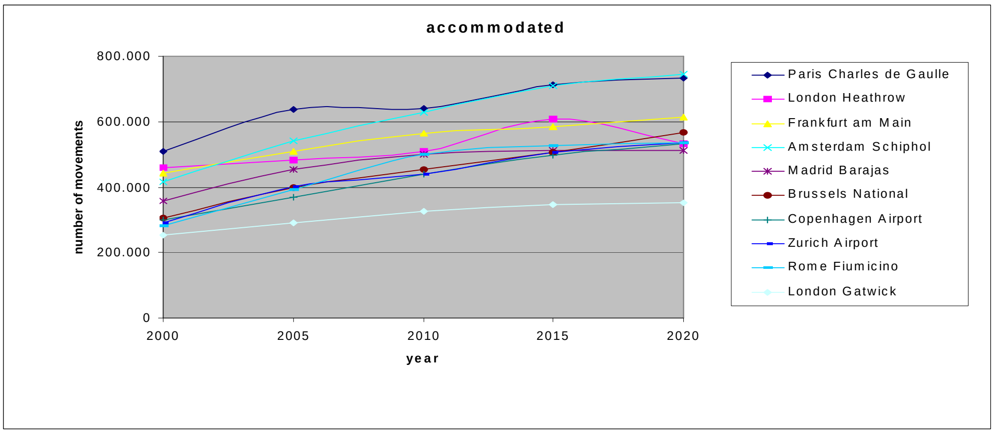


Figure 5 – Accommodated demand forecast

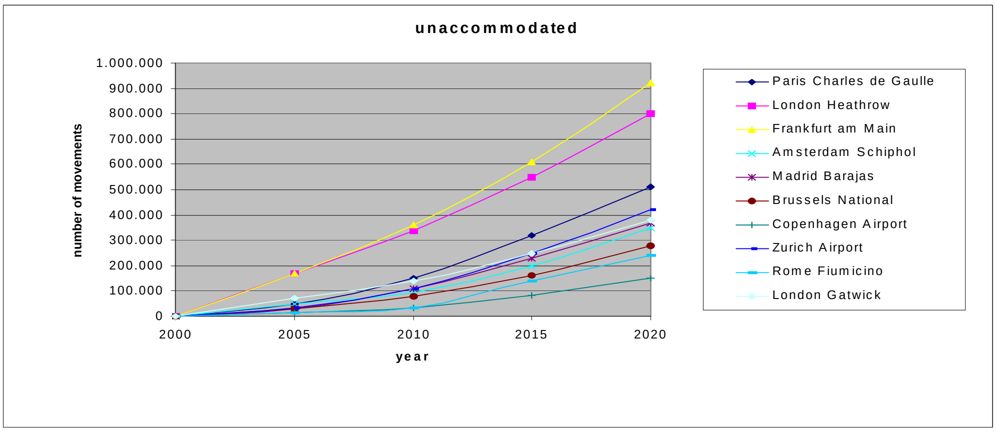


Figure 6 – Un-accommodated demand forecast

Several scenarios with 5%, 10% and 15% additional (over and above that of the “do-nothing” scenario) capacity increases in 10 target airports have been simulated. The following future traffic samples were built:

- 2010 and 2015 samples with airport capacity increases corresponding to those known to EUROCONTROL (baseline case).
- 2010 and 2015 with a 5% increase in capacity surplus for the target airports.
- 2010 and 2015 with a 10% in capacity surplus for the target airports.
- 2010 and 2015 with a 15% incapacity surplus for the target airports.

Figures 7 and 8 below gives the resulting reduction of the airport delays (red bars) and the en-route delays (yellow bars) for the whole ECAC region for 2010 and 2015 respectively. At the ECAC level, for 2010 a significant reduction in airport delays at the global level can be observed: 8.5% for 5% and 26% for 15% compare to the “do nothing” scenario. We note that the En-Route delay remains almost constant. For 2015, an increase of 15% of the capacity in the 10 target airports implies a reduction of 32% of the airport delays on the ECAC zone.

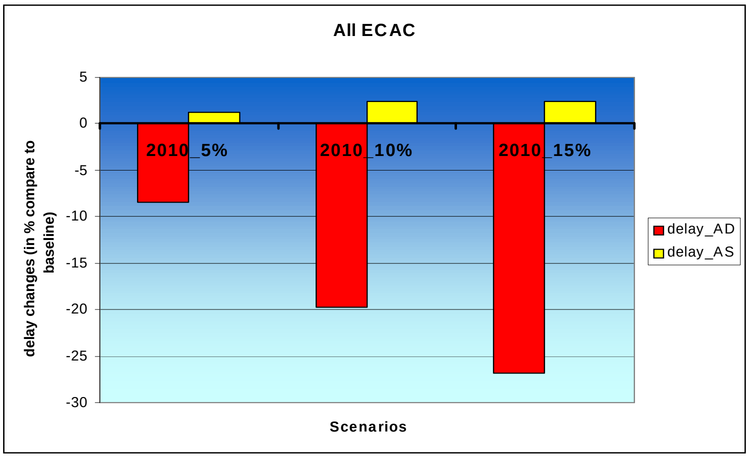


Figure 7 – Airport delay change for 2010

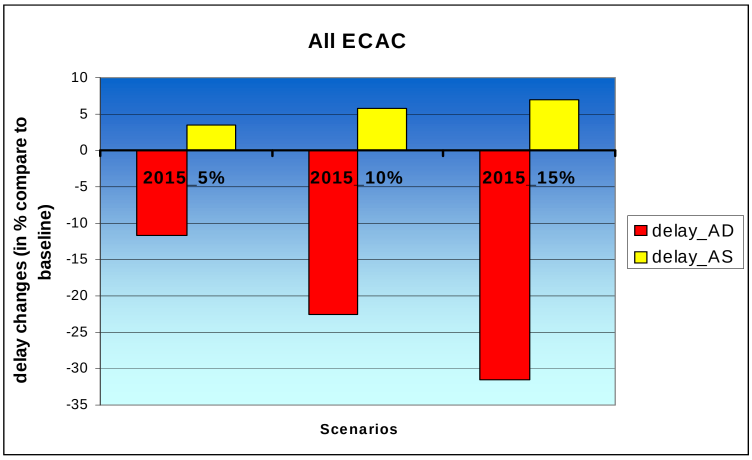


Figure 8 – Airport delay change for 2015

Figure 9 shows the benefit of the capacity increases for each of 10 major European airports for 2010. The red bars represent the improvement in average delay per flight; this improvement is given in percentages of reduction compared to the baseline and the scale is the red one on the left. The yellow curves represent the increase in demand accommodated, in simple words the flight surplus. This demand increase is also given in percentage of change compared to the baseline and the scale is the yellow one on the right side of the graph. We can observe that the capacity increases in those airports manifest themselves in two different ways: the delay reduction and more accommodated flights. The combination of these two effects depends on the characteristics of each airport, relating mainly to the daily traffic distribution and the significance of the lack of capacity. In general terms, we usually observe that the higher the number of new accommodated flights, the lower is the delay reduction. If we look more in detail, we can note that for a big part of the airports studied, the capacity increase implies essentially a reduction of delay with a very limited impact in terms of accommodated flights. For 9 of 10 airports (the exception being Madrid), the additional number of flights that can be accommodated is less then 3% and often close to 0.

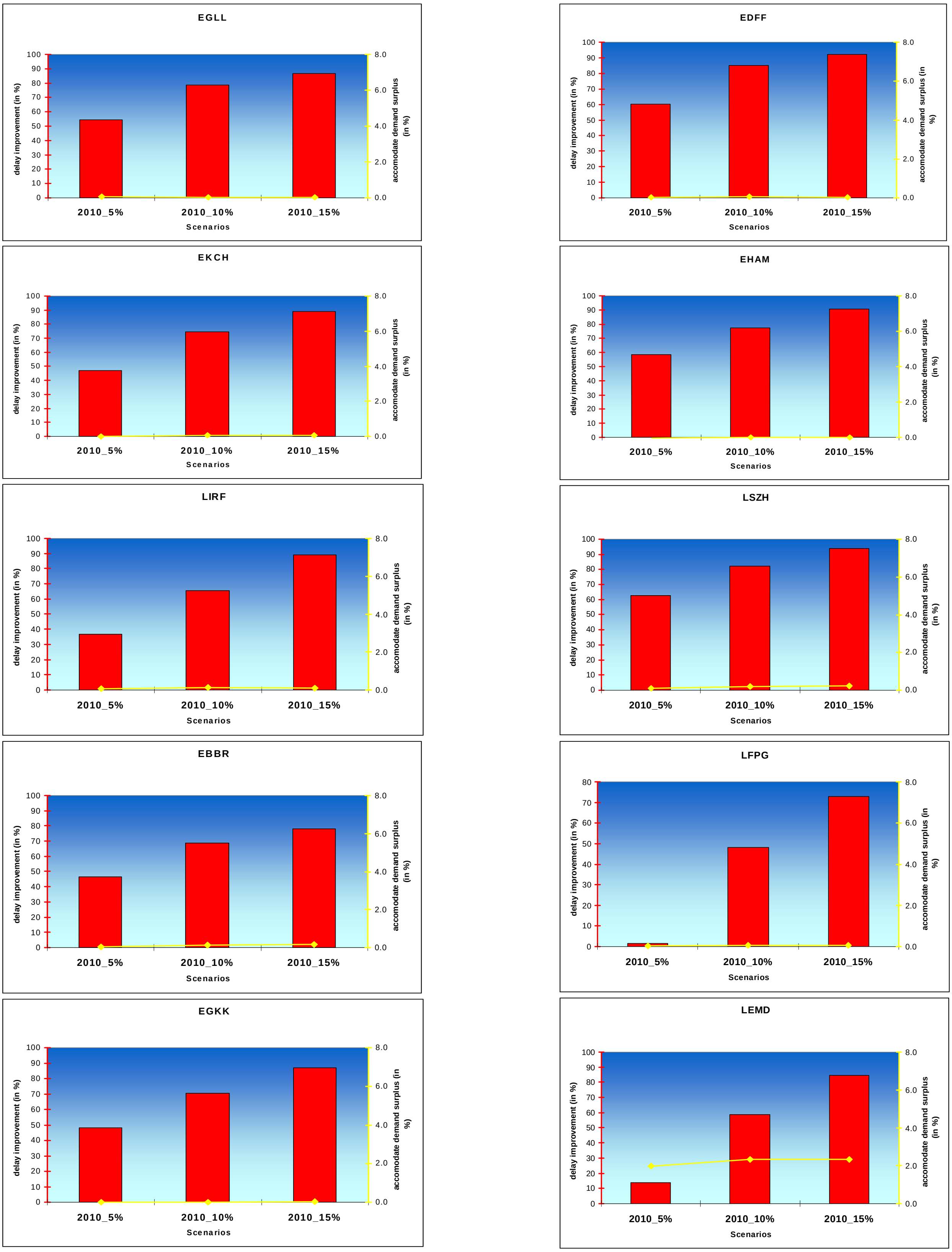


Figure 9 – Benefits of capacity increases for the 10 major airports for 2010

The benefits in terms of delay reductions can easily be translated into cost. For this purpose, the figures contained in the PRR4 can be used. The average airport delay prediction for 2015 is over 5 min per flight with a predicted traffic over 40,000 flights a day. The benefit of increasing the capacity in some airports is significant and often, a few gains in capacity can allow a huge delay reduction (this is due to the exponential shape of the delay sensibility to the traffic). This shows that by working on a limited number of airports, the average airport delay can be reduced significantly.

Table 1 – Costs of delays

	Cost of delay (in € per min of delay)
ATFM delay	**40 to 66**
Reactionary delay	**28**
Total direct cost	**68 to 94**
Indirect cost undergo by the society (passengers…)	**46 to 60**

Note: PRC assumes that each minute of primary delay is responsible for 0.5 minute of reactionary delay.

3.2 Risk requirements

3.2.1 Overview of ATC-Wake approach

Introducing and/or planning changes to the ATM system cannot be done without showing that minimum risk requirements will be satisfied. This can be done through a qualitative and/or quantitative safety assessment. The main issue is the choice of the safety criteria. The risk assessments in the ATC-Wake project intend to be compliant with the ESARR 4 requirements posed by EUROCONTROL's Safety Regulation Commission (SRC). Following the ESARR4, a safety assessment requires the following risk criteria aspects:

- A severity classification,
- A frequency classification,
- A risk tolerability scheme.

The ESARR 4 requirements also states that a combination of *quantitative* (e.g., mathematical model, statistical analysis) and *qualitative* (e.g. good working processes, professional judgement) arguments may be used to provide the required level of assurance that safety objectives and requirements have been met. To assess safe and appropriate separation minima, a quantitative assessment will need to be performed. In the ATC-Wake qualitative safety assessment, the ESARR 4 severity classification, will be used. Five severity classes are distinguished: accident, serious incident, major incident, significant incident, no safety effect. The definitions of occurrence, accident, and incident are specified in the ESARR2.

For execution of the quantitative safety assessment, the Wake vortex risk management framework defined in the S-Wake project will be used. Here, incident/accident risk *probabilities* will be determined followed by a comparison with risk criteria. The following classification, which is based on ICAO Annex 13 for incident/ accident investigation and JAR 25.1309 for aircraft system hazard categorisation, will be used:

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

The method proposes that all four risk requirements are to be satisfied, i.e. the most stringent requirement will determine the required separation minima (see Table 2).

Table 2 – Risk requirements (per *queued* aircraft movement)

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}

This approach supports two commonly accepted rationales for acceptance of a new system (or procedure) 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.

Nevertheless, this approach still needs to be further harmonised with the ESARR4.

3.2.2 Elaboration of ESARR4 requirements

ESARR 4 documentation has been used to derive appropriate risk criteria for use in the ATC-Wake qualitative safety assessment. In this respect, the results intend to be compliant with the ESARRs. The severity classification is taken directly from the ESARR4 (Table 3). The frequency classification has been derived from the ESARRs to judge the acceptability of a number of *conflict scenarios* that may occur.

Table 3 – ESARR 4 severity classification scheme in ATM

Severity class		Examples of effects on operation
Number	**Term**	
1	ACCIDENT	• One or more catastrophic accidents. • One or more mid-air collisions. • One or more collisions on the ground between two aircraft. • One or more Controlled Flight Into Terrain. • Total loss of flight control. No independent source of recovery mechanism, such as surveillance or ATC and/or flight crew procedures can reasonably be expected to prevent the accidents.
2	SERIOUS INCIDENT	• Large reduction in separation (e.g., a separation of less than half the separation minima), without crew or ATC fully controlling the situation or able to recover from the situation. • One or more aircraft deviating from their intended clearance, so that abrupt manoeuvre is required to avoid collision with another aircraft or with terrain (or when an avoidance action would be appropriate).
3	MAJOR INCIDENT	• Large reduction (e.g., a separation of less than half the separation minima) in separation with crew or ATC controlling the situation and able to recover from the situation • Minor reduction (e.g., a separation of more than half the separation minima) in separation without crew or ATC fully controlling the situation (without the use of collision or terrain avoidance manoeuvres).
4	SIGNIFICANT INCIDENT	• Increasing workload of the air traffic controller or aircraft flight crew, or slightly degrading the functional capability of the enabling CNS system. • Minor reduction (e.g., a separation of more than half the separation minima) in separation with crew or ATC fully controlling the situation and fully able to recover from the situation.
5	NO SAFETY EFFECT	No hazardous condition, i.e., no immediate direct or indirect impact on the operations.

Frequency classification

In the qualitative safety assessment, frequency classes need to be defined for severity outcomes of conflict scenarios. The severity and frequency classes together are used to define risk tolerability. The ESARR 4 requirements do not specify these frequency classes, but only provide the maximum tolerable probability of ATM directly contributing to an *accident* of a Commercial Air Transport aircraft. The ESARR 4 requirements currently leave freedom to define the details of risk criteria that are required to conduct a safety assessment, such as maximum tolerable probabilities of incidents and risk budgets of conflict scenarios. According to the ESARR 4 requirements, the maximum tolerable probability of ATM directly contributing to an accident of a Commercial Air Transport aircraft is 1.55×10^{-8} accidents per flight hour or 2.31×10^{-8} accidents per flight. These maximum tolerable probabilities are based on:

- historical accident data in the ECAC region over the period 1988 to 1999,
- a target for the maximum ATM direct contribution to the total number of accidents of 2%, which is based on historical data for accidents with at least one ATC primary cause and a factor that accounts for allowance of variations in the scope of source data (ATS, ASM and ATFM in addition to ATC), for statistical error, and for adopting a conservative approach to offer additional protection to the future,
- requirement that the number of accidents in 2015 may not be higher than in 1999,
- an annual traffic increase of 6.7% for the period 1999 to 2015.

The scope of the current qualitative safety assessment is wider than accidents and incidents with a *direct* ATM contribution, such as used in the ESARR 4 requirements. It is not limited to occurrences where at least one ATM event or item was judged to be *directly* in the causal chain of events, but aims to cover ATM *direct and indirect* occurrences. However, a maximum tolerable accident probability of ATM indirectly contributing to an accident of a Commercial Air Transport aircraft has not been specified by the ESARR4 requirements. It is now proposed to use the target of 1.55×10^{-8} accidents per flight hour or $2.31x10^{-8}$ accidents per flight is for the maximum tolerable probability for accidents with *direct and indirect ATM contributions.* This is a conservative approach, which obviously implies that the ESARR4 requirements are satisfied.

The target levels of safety are expressed in occurrences per flight. The current qualitative safety assessment does not consider the risk of a whole flight, but considers the risk of the ATC-Wake operations. As such it is needed to determine what budget of the total ATM related risk of $2.31x10^{-8}$ accidents per flight can be provided to the presently assessed operations. In the ATC-Wake qualitative safety assessment the risk is evaluated per conflict scenario. For this purpose, it is assumed that the ATM related risks of a whole flight can be represented by 25 conflict scenarios, and that each has an equal risk budget. Using these assumptions the maximum tolerable probability of an ATM related accident is about 1×10^{-9} accidents per conflict scenario. In line with risk criteria of JAA, in the qualitative safety assessment it is assumed that the maximum tolerable probabilities of serious and major incidents are, respectively, a factor 1×10^{2} and 1×10^{4} higher than for accidents. The frequency terms and the associated probabilities as derived in this section are shown in Table 4.

Table 4 – Frequency categories used in this study

Frequency category	**Probability of occurrence**
PROBABLE	Higher than 10^{-5} per conflict scenario
REMOTE	Between 10^{-7} and 10^{-5} per conflict scenario
EXTREMELY REMOTE	Between 10^{-9} and 10^{-7} per conflict scenario
EXTREMELY IMPROBABLE	Lower than 10^{-9} per conflict scenario

4 ATC-Wake systems and operation

4.1 ATC-Wake: two modes of operation

For the definition of the ATC-Wake operational concept and procedures, the principle of *evolution not revolution* has been retained. As far as possible, existing concepts and procedures for arrivals and departures have been reused. In this context, the proposed evolution of ATC-Wake operations impacts on working methods, in order to allow:

- Safe and efficient use of wake vortex detection and prediction information;
- Determination and implementation of appropriate separation between aircraft;
- Sequencing of approach and runway operations in a seamless way.

Depending on weather conditions influencing Wake Vortex transport out of so-called arrival or departure critical areas, two modes of aircraft separation have been defined:

- ICAO standard separation;
- ATC-WAKE separation.

To implement a concept with 2 modes of operation, four ATC-Wake components are introduced (Table 5), which will interface with existing ATC systems (see Table 6).

Table 5 – ATC-Wake System Components

ATC-Wake Separation Mode Planner	Determines the applicable separation mode (ICAO mode or ATC-WAKE mode) and advises about minimum aircraft separation distance. The advisory includes the expected time for future mode transitions, and an indication of the aircraft separation minimum applicable
ATC-Wake Predictor	Predicts for individual aircraft the WV behaviour (“Wake Vortex Vector”) in the pre-defined arrival or departure area(s). The WVV is part of the critical area (e.g. ILS Glide Slope) potentially affected by the wake vortex
ATC-Wake Detector	Detects for individual aircraft the WV position, extent (“vortex vector”) and – if possible – also strength in the pre-defined arrival or departure area(s)
ATC-Wake Monitoring and Alerting	Alerts ATCO in case of : • significant deviation between WV detection and WV prediction information which raises the risk of WV encounter • failure of one or several WV components

Table 6 – Existing ATC Systems interfacing with ATC-Wake components

ATCo HMI	Provides the traffic situation picture and automated support for various ATCO tactical roles (Approach, Tower).
Arrival Manager	Determines automatically optimum arrival sequence and provides advises for realising this sequence. Communicates forecast sequence upstream to en-route and / or approach ATSUs
Flight Data Processing System	Keeps track of every flight information and updates, in particular the flight plan, the trajectory prediction, ETA and ETD, aircraft type and equipment.
Surveillance System	Provides and maintains the air traffic situation picture using all available detection means (radars, air-ground data links)

4.2 ATC-Wake Users or Involved Actors

The ATC-Wake users, including their proposed roles, are given in Table 7 below.

Table 7 – ATC-Wake Users or Involved Actors

Actor	Current Responsibility	Specific/additional Role in ATC - WAKE
Airport ATC Supervisor	Monitors ATC tower and ground operations	Decides on arrival and departure separation mode and in case of ATC-Wake separation decides on the rate to be applied
Arrival Sequence Manager	In charge of arrival planning management for one or several runways, in co-ordination with adjacent ATC Units (sequencing and spacing of aircraft can be assisted by an arrival manager tool (AMAN)	Uses WV prediction information for determination of aircraft sequencing and spacing in the final approach corridor (according to the separation mode decided by the ATC Supervisor) Co-ordinates forecast sequence upstream to en-route and / or approach ATSUs
Initial Approach Controller (INI)	In charge of inbound traffic from initial approach fix (IAF). Responsible for holding stacks management.	Establishes arrival sequence based on WV.
Intermediate Approach Controller (ITM)	In charge of intermediate approach, ILS interception Establishes sequence for final approach and landing	Establishes final approach sequence based on WV prediction and informs about deviations
Tower Controller (TWR)	In charge of final approach, landing, and take-off phases	Monitors safe and optimal separations using WV detection and short term forecasting of the WV displacement. Instructs aircrew on any necessary evasive action.

Actor	Current Responsibility	Specific/additional Role in ATC - WAKE
Ground Controller (GND)	Organises and monitors aircraft and vehicles ground movements Sequences departures according to landings	Uses WV detection and short term forecasting of the WV displacement to optimise departure sequencing
Aircrew	Navigates aircraft safely	Complies with Controller's instructions to meet arrival sequence constraints based on WV prediction information Takes necessary evasive actions to avoid WV encounter if instructed by ATC or alerted by on-board equipment (I-WAKE).

4.3 Aircraft Separation Modes

Based on meteorological conditions, ATC-Wake will advise the ATC Supervisor about applicable separation mode and associated validity period (start / end). The ATC Supervisor has the responsibility to decide the minimum separation to be applied for approach or departure as well as the landing rate to be used for arrival sequencing (using AMAN or not). The time horizon to be considered for arrival sequencing is 40 min if an AMAN is used, 20 min otherwise. Based on planned traffic and meteorological conditions (wind profiles), an assessment of WV transport and decay is performed in order to advise the ATC Supervisor about the applicable minimum separation for a fixed period of time (start / end of ATC-Wake operations). The transition from ICAO to ATC-Wake separation mode will begin by considering the incoming or departing aircraft that have a planned arrival time included in the start / end time period for ATC-Wake operations. The re-planning of arrivals (if necessary) will be performed by the Arrival Sequence Manager or by AMAN and transition information will be distributed to concerned ATCOs. The time adjustments will be implemented by en-route controllers. This will be done through speed modifications, radar monitoring and/or holding patterns.

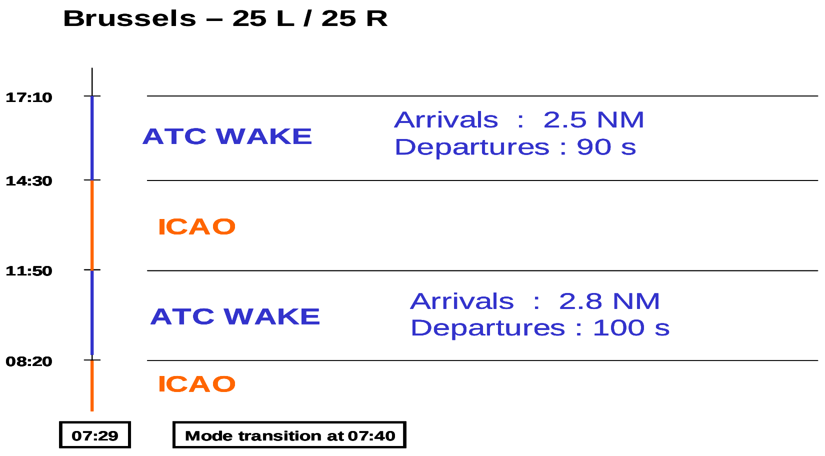
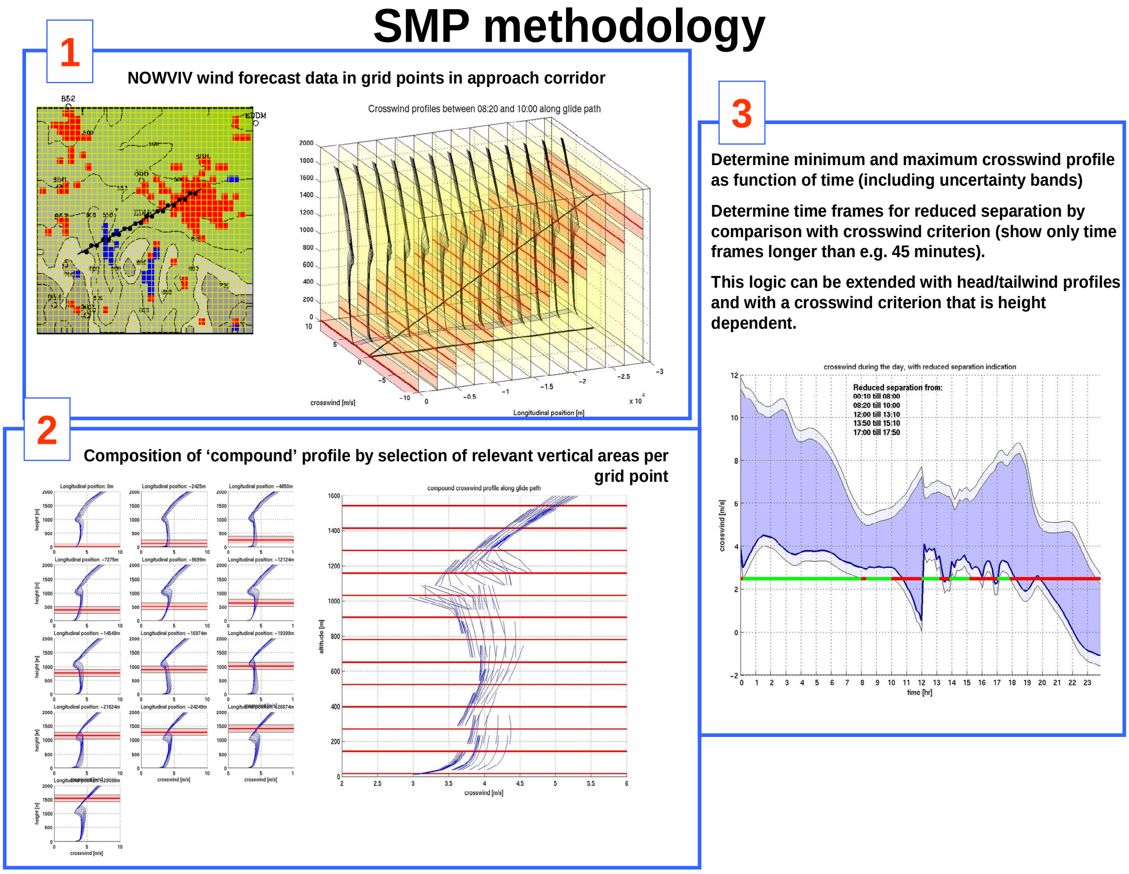


Figure 10 – Example of a Planning of Separation Modes

4.4 ATC-Wake Separation Mode Planner

To support the ATC supervisor with planning of separation modes, an ATC-Wake Separation Mode Planner (SMP) has been developed and implemented. In the proposed methodology, NOWVIV wind forecast data is used to determine time frames suitable for reduced separation. Criteria on crosswind and/or head/tailwind and associated safe separation minima are derived from safety assessment results. To enable an interfacing between the Separation Mode Planner and the WAVIR safety assessment results, a WAVIR database has been set up. This database also enables users to review WAVIR parameter settings and retrieve WAVIR results via interfaces. In the context of “safety monitoring”, such database might be used to evaluate wake vortex safety performance indicators at an airport. Results from safety monitoring activities can also be fed back in the WAVIR database to tailor the database to specific airports, and to increase the performance and reliability of the Separation Mode Planner. In this first design of the Separation Mode Planner, relatively simple wind criteria have been proposed. Depending on the benefits that can be achieved with such criteria and the requirements of the users, further study may focus on elaborating these criteria.



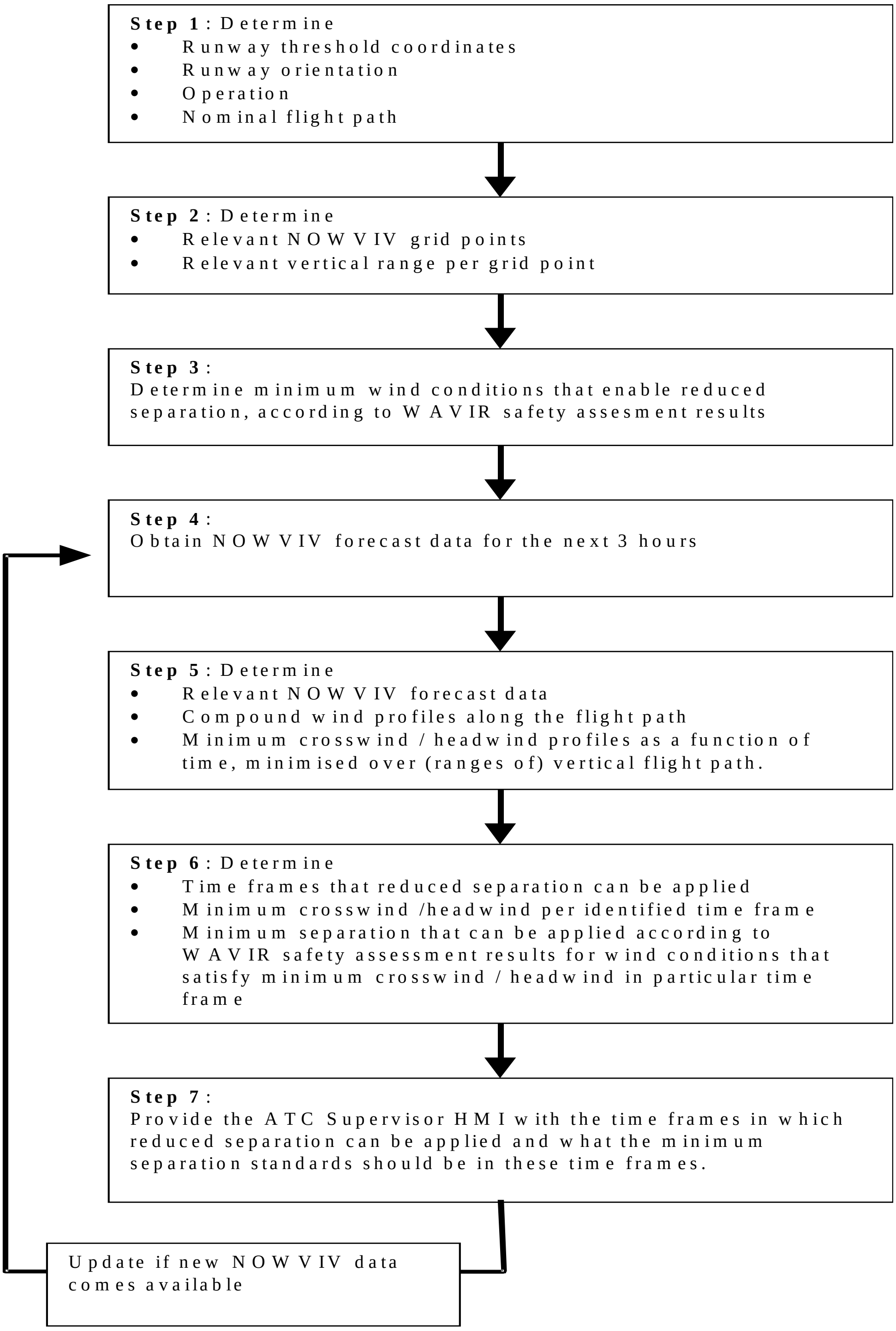
Determine minimum and maximum crosswind profile as function of time (including uncertainty bands)

Determine time frames for reduced separation by comparison with crosswind criterion (show only time frames longer than e.g. 45 minutes).

This logic can be extended with head/tailwind profiles and with a crosswind criterion that is height dependent.

Figure 11 – SMP methodology, example case for a single runway approach

The functional design of the ATC-Wake Separation Mode Planner is described in detail in D3_5A. The seven steps in the process to obtain an advice on separation mode and minima are shown in Figure 12.



Step 1: Determine
- Runway threshold coordinates
- Runway orientation
- Operation
- Nominal flight path

Step 2: Determine
- Relevant NOWVIV grid points
- Relevant vertical range per grid point

Step 3:
Determine minimum wind conditions that enable reduced separation, according to WAVIR safety assesment results

Step 4:
Obtain NOWVIV forecast data for the next 3 hours

Step 5: Determine
- Relevant NOWVIV forecast data
- Compound wind profiles along the flight path
- Minimum crosswind / headwind profiles as a function of time, minimised over (ranges of) vertical flight path.

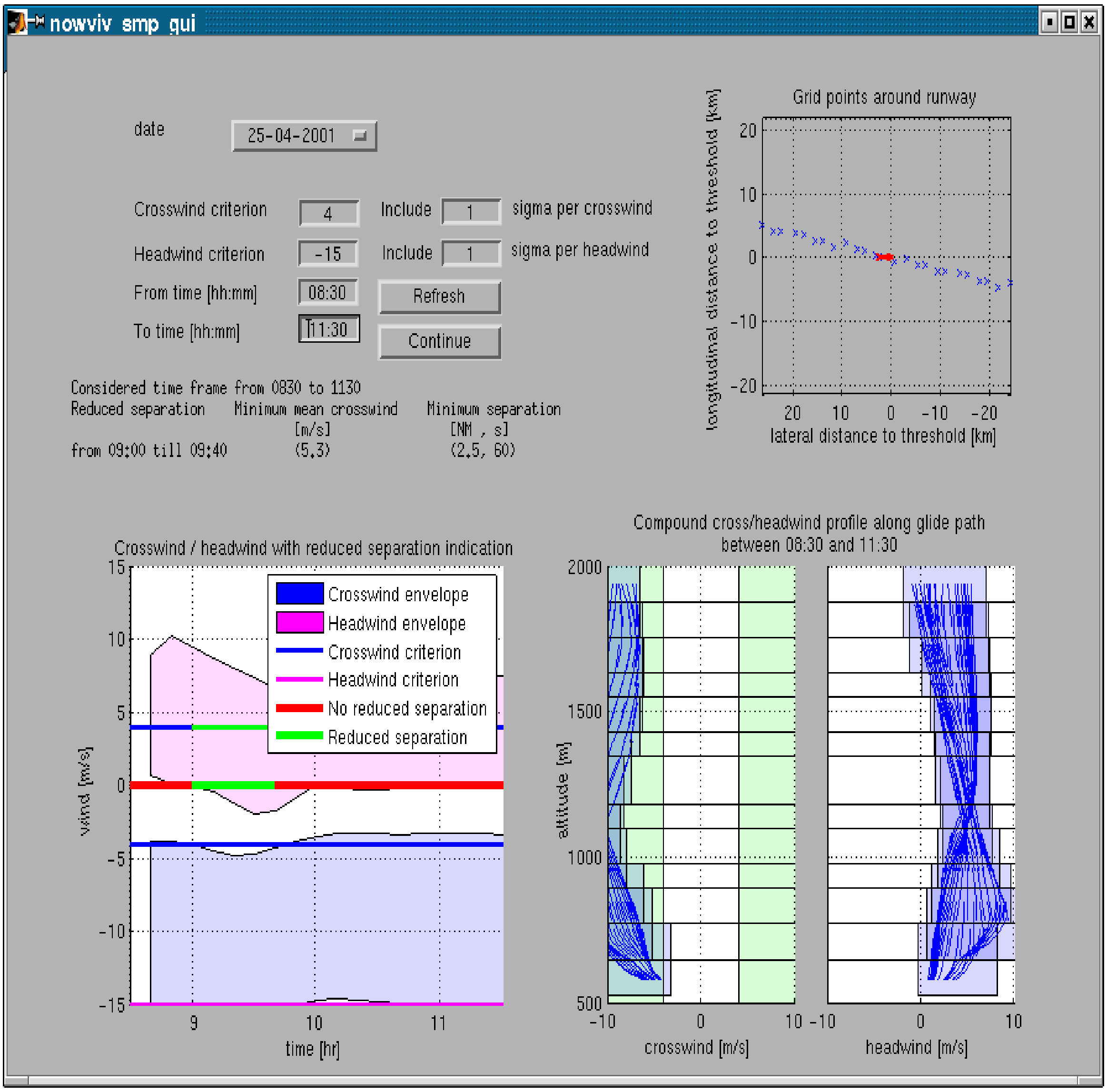
Step 6: Determine
- Time frames that reduced separation can be applied
- Minimum crosswind /headwind per identified time frame
- Minimum separation that can be applied according to WAVIR safety assessment results for wind conditions that satisfy minimum crosswind / headwind in particular time frame

Step 7:
Provide the ATC Supervisor HMI with the time frames in which reduced separation can be applied and what the minimum separation standards should be in these time frames.

Update if new NOWVIV data comes available

Figure 12 – Functional steps of the Separation Mode Planner

The proposed Graphical User Interface for the determination of the applicable Separation Mode and distance/time to be applied by the ATC supervisor is given in Figure 13 below.



date 25-04-2001

Crosswind criterion 4 Include 1 sigma per crosswind

Headwind criterion -15 Include 1 sigma per headwind

From time [hh:mm] 08:30

To time [hh:mm] 11:30

```
Considered time frame from 0830 to 1130
Reduced separation    Minimum mean crosswind    Minimum separation
                              [m/s]                 [NM , s]
from 09:00 till 09:40         (5,3)                 (2.5, 60)
```

Figure 13 – Separation Mode Planner Graphical User Interface

4.5 ATC-Wake Monitoring and Alerting

It is assumed that the Wake Vortex situation will be monitored by comparing results of prediction and detection. From ATC supervisor or operator viewpoint a typical refresh rate of such information is 30 min. In case of a discrepancy between prediction and detection information, an alert is provided to the controllers, who may instruct the pilot to initiate a wake vortex avoidance manoeuvre. To support the controllers with the monitoring and alerting procedure, Human Machine Interfaces have been developed.

The output of the ATC-Wake Predictor is the Wake Vortex Vector (WVV) of an aircraft in a so-called critical area. This information is presented as an enhancement on a Plan View Display (PVD). The PVD shows the information received from the airport radar, combined with flight track data. Because the WVV is only calculated in the critical area (an area close to the glide slope) only changes to the PVD of the Final Approach controller and Tower controller are foreseen. For the Approach controllers, the so-called "Variable Wake Vortex" HMI has been developed and tested with active controllers from five countries (see Figure 14). New is the blue coloured vector behind each aircraft, representing the WVV and varying (using information from the Predictor) along the glide slope. Also a micro-label with the distance to the preceding aircraft is proposed.

Figure 14 – ATC-Wake HMI for the approach controller

In case of an alarm, the colour of the WVV will change to orange and an audio alarm will be raised (Figure 15). The selected HMI and ATC-Wake concept have been received very well by the controllers, which certainly support the expected benefits of the concept.

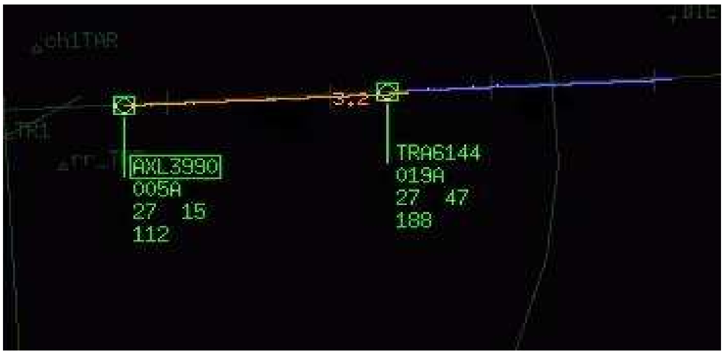


Figure 15 – ATC-Wake alarm for Tower controllers

In case of a caution of alert, the air traffic controllers shall perform the following actions:

- Caution: the other air traffic controllers shall be informed, but no instruction to the pilot is needed;
- Alert: a missed approach or turn instruction is required, and the pilot shall initiate it as soon as practicable.

4.6 ATC-Wake System Architecture

The ATC-Wake Operational System includes four new functional components, which will interface with several existing and/or enhanced ATC system components. The new components are:

- ATC-Wake Separation Mode Planner,
- ATC-Wake Predictor,
- ATC-Wake Monitoring and Alerting, and
- ATC-Wake Detector.

Existing ATC systems are: Arrival Manager (AMAN) or Departure Managers (DMAN) (if in use), Flight Data Processing System, and Surveillance Systems. Enhanced ATC systems are: Meteorological Systems, Supervisor HMI, and ATCo HMIs. For the Meteorological systems, enhancements in prediction and update rates are foreseen and the HMI's for supervisor and ATCo shall be extended with ATC-Wake symbology. Four use cases are identified: Separation mode planning, Transition between ICAO and ATC-Wake separation mode, Approach phase, and Departure phase. Figure 16 shows all relations between the different components.

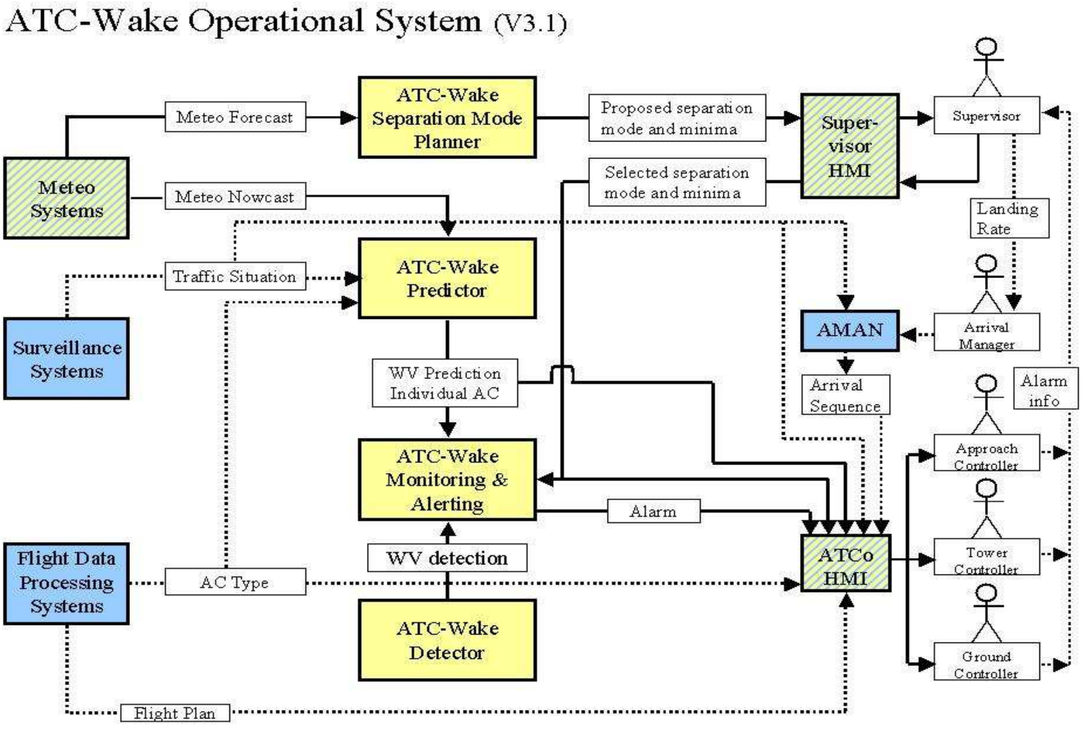


Figure 16 – Functional flow of ATC-Wake Operational System

The use of the ATC-Wake system components, including the ATC-Wake Predictor and ATC-Wake Detector, are described in more detail in D1_5 (System Requirements), D2_12 (System Design and Evaluation) and D4_7 (Evaluation of Operational Feasibility).

5 Risk assessment methodology

5.1 Overview of qualitative risk assessment methodology

The risks associated with the ATC-Wake operation have been assessed with NLR's Qualitative Safety Assessment methodology. This methodology is based on structured use of operational experts' judgement, supplemented with historical data, if available.

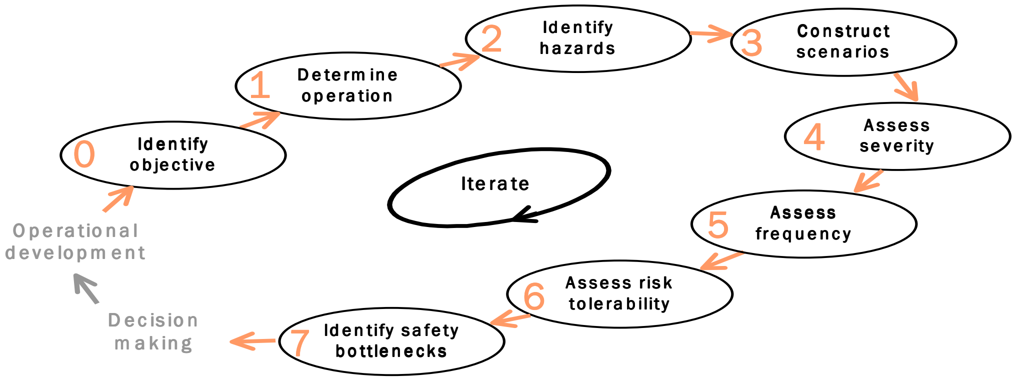


Figure 17 – Stepwise overview of the qualitative safety assessment methodology

In step 0 the objective of the study is determined, as well as the safety context, the scope and the level of detail of the assessment. The actual safety assessment starts by determining the operation that is assessed (step 1). Next, hazards associated with the operation are identified (step 2), and clustered into conflict scenarios (step 3). Using severity and frequency assessments (steps 4 and 5), the risk associated with each conflict scenario is classified (step 6). For each conflict scenario with a (possibly) UNACCEPTABLE risk, safety bottlenecks are identified (step 7), which can help operational concept developers to find improvements for the operation. Should such an improvement be made, a new cycle of the safety assessment should be performed to investigate whether all risks have decreased to an acceptable level. A risk tolerability matrix specifies the acceptability of the risk of an occurrence for a conflict scenario, based on combination of its severity and frequency. The matrix in Table 8 will be used.

In the assessment, any operational aspect fully satisfying requirements from for instance ICAO and EUROCONTROL are assumed to have no unacceptable risks associated with them. In particular, in some cases risks are assessed using comparisons to the current operations. In these cases, it is assumed that the current operation has a TOLERABLE risk at most, unless the operational expert interviews indicate that this is not the case.

Table 8 – Risk tolerability matrix for accident and incidents

SEVERITY FREQUENCY	**ACCIDENT**	**SERIOUS INCIDENT**	**MAJOR INCIDENT**	**SIGNIFICANT INCIDENT**
PROBABLE	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE	TOLERABLE
REMOTE	UNACCEPTABLE	UNACCEPTABLE	TOLERABLE	NEGLIGIBLE
EXTREMELY REMOTE	UNACCEPTABLE	TOLERABLE	NEGLIGIBLE	NEGLIGIBLE
EXTREMELY IMPROBABLE	TOLERABLE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE

5.2 Overview of quantitative risk assessment methodology

5.2.1 Introduction: the WAVIR toolset

For a quantitative assessment of the wake vortex induced risk related to the ATC-Wake operation with reduced separation, there are three main issues to consider:

- The controller working with the ATC-Wake system has to instruct the pilot to initiate a wake vortex avoidance manoeuvre, in case an ATC-Wake warning/alert is raised.
- If one or more ATC-WAKE system components provide wrong or erroneous advice, there will be a higher risk on the presence of (severe) wake vortices. The consequences might be CATASTROPHIC, because reduced separation is applied.
- The separation distance/time will vary along the flight track, and will usually not be exactly the same as the separation minima advised by the Separation Mode Planner.

The 'classical' WAVIR methodology, which originates from S-Wake, is used to assess wake vortex induced risk in case the ATC-Wake system is not working (i.e. no wake vortex avoidance manoeuvre is performed by the pilot, and worst case conditions apply). This assessment of wake vortex induced risk has been performed with the WAVIR tool-set, version 2.0, which is based on probabilistic models. The model structure and user interfaces are described in D3_5b. In short, the WAVIR tool-set includes four sub-models for:

- flight path evolution
- wake vortex evolution
- wake encounter simulation
- risk prediction

To assess the risk related to the ATC-Wake operation, WAVIR is extended with a graph and decision theory based model structure. A variety of mathematical models and techniques (including fault trees, discrete and continuous Bayesian Belief Nets and vines, and Petri Nets) are introduced to incorporate the role of humans working with ATC-Wake. The details of the mathematical model are described in ATC-Wake D3_5b.

5.2.2 Assessment of wake detection, warning & avoidance manoeuvre

The execution of the ATC-Wake detection, warning, and avoidance manoeuvre (e.g. turn away from a wake vortex (during departures) or a missed approach (during arrivals)) depends - besides operational feasibility - on the probability of failure of the ATC-Wake system components. For the ATC-Wake system failures, a causal model has been constructed using Bayesian Belief Networks (BBNs). It is shown that this resulting BBN might be represented by a fault tree as given in Figure 18 (see D3_5b).

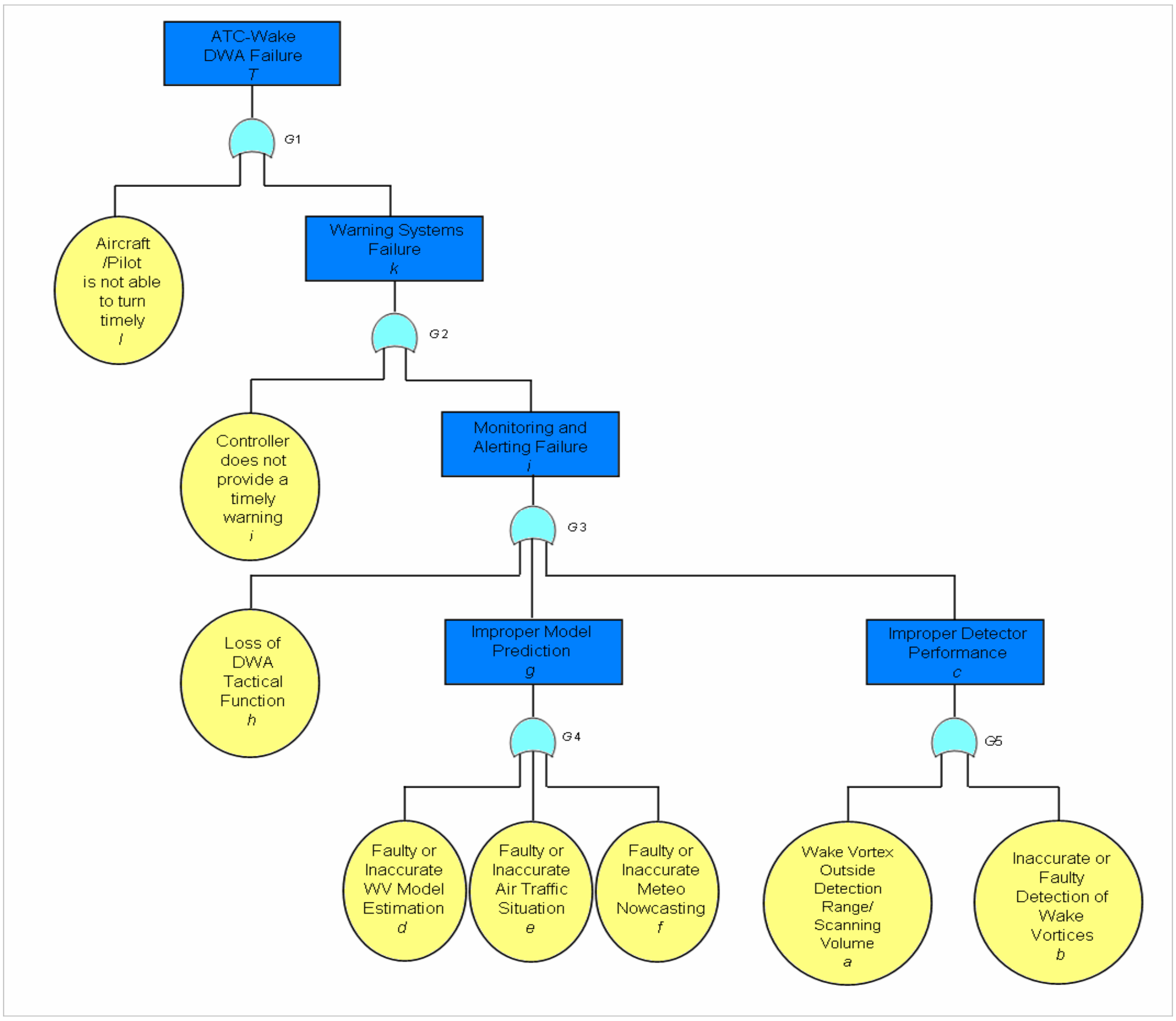


Figure 18 – Fault tree for the WV DWA probability

The nodes in this (high-level) Fault Tree representation have the following explanation:

- *ATC-Wake DWA Failure*: represents the probability of aircraft/pilot not able to initiate the ATC-Wake DWA manoeuvre (e.g. a turn away from WV of a preceding aircraft).
- *Aircraft/Pilot not able to turn timely*: represents the probability of an aircraft/pilot not able to perform the ATC-Wake DWA manoeuvre, when requested by the controllers.

- *ATC-Wake Warning Failure*: represents the probability not providing a timely warning to the flight crew when one should be given. As a result, it is possible that a pilot reacts later to a wake encounter when one should occur.
- *Controller does not provide a timely warning:* represents the probability of the ATCo not providing an alert, when it is advised by the Monitoring and Alerting system
- *Monitoring and Alerting Failure*: represents the probability of not providing a timely warning to the air traffic controllers when one should be given. As a result, the ATCo might NOT be able to initiate/instruct the pilot to perform an evasive action.
- *Loss of DWA Tactical Function*: represents the probability of an undetected loss of the Monitoring and Alerting Function. In case of a Detected Loss, the ATCos are aware that NO cautions/alerts will be given and a transition will be made to the ICAO Mode (the separation will increase, and the DWA manoeuvre will not be necessary).
- *Improper Model Prediction*: represents the probability that the predictions of Wake Vortex locations and strength are inaccurate/wrong.
- *Inaccurate or Faulty WV Model Estimation*: represents the probability that the predictions of wake vortex locations and/or strengths made by the WV Model, on the basis of aircraft data and meteorological data, are inaccurate/wrong. As a result, incorrect information is passed to ATC-Wake Predictor, causing improper functioning
- *Inaccurate or Faulty Air Traffic Situation*: represents the probability that the air traffic situation provided by the surveillance systems is inaccurate or wrong. As a result, incorrect information is passed to the Predictor, causing improper functioning.
- *Inaccurate of Faulty Meteo Nowcasting*: represents the probability that the meteorological conditions (i.e. now-casting data) provided by the meteorological systems are inaccurate or wrong. As a result, incorrect information is passed to the ATC-Wake Predictor, causing improper functioning.
- *Improper Detector Performance*: represents the probability that the ATC-Wake Detector (e.g. LiDAR) performs significantly less than the air traffic controllers expect (while they are not aware of the inaccuracies) (i.e. inaccurate/wrong alerts are given);
- *Wake Vortex Outside Detection Range/Scanning Volume*: represents the probability that the ATC-Wake Detector does not detect the wake vortices of the leading aircraft, because these are outside the scanning volume of the ATC-Wake Detector.
- *Inaccurate or Faulty Detection of Wake Vortices*: represents the probability that the ATC-Wake Detector does not detect wake vortices of the leading aircraft accurately, when these are inside the planned scanning volume of the ATC-Wake Detector(s).

5.2.3 Assessment of the ATC-Wake aircraft separation time

In reality, the actual separation time will differ from the advise provided by the Separation Mode Planner. This is related to e.g. role of the humans in the decision making process as well as aircraft performance.

The spread of inter-arrival times at Atlanta runway 27 was analysed by the George Mason University in 2002. The resulting number of occurrences observed at Atlanta runway 27 is provided in Figure 19 below.

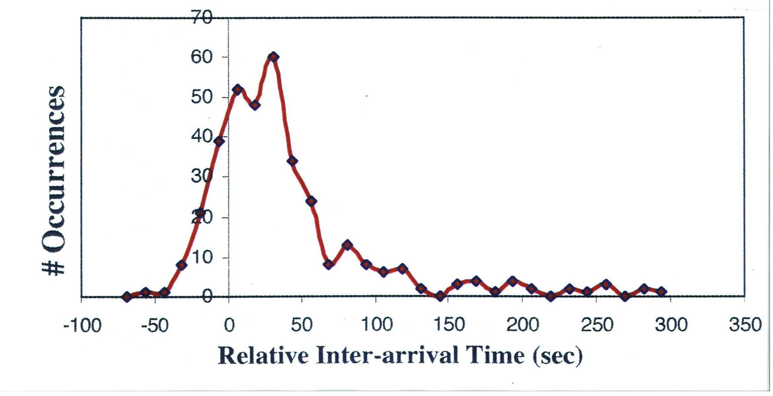


Figure 19 – Spread of inter-arrival times observed at Atlanta runway 27 (source GMU)

The relatively large spread of observed inter-arrival times at the runway threshold is related to the variations in initial separation distances between leader and follower aircraft at the Final Approach Point (FAP) and the variation of aircraft speed during the approach.

A model of the intermediate approach controller performance, which is based on Petri Nets, has been used to determine the initial separation between the leader and the follower aircraft at the FAP. This initial separation is composed of a nominal separation plus a stochastic variation due to control actions up to the FAP. The latter contribution is described by a variation time chosen from a Rayleigh distribution shown in Figure 20, which is independent from wind conditions, aircraft types or required separation distance.

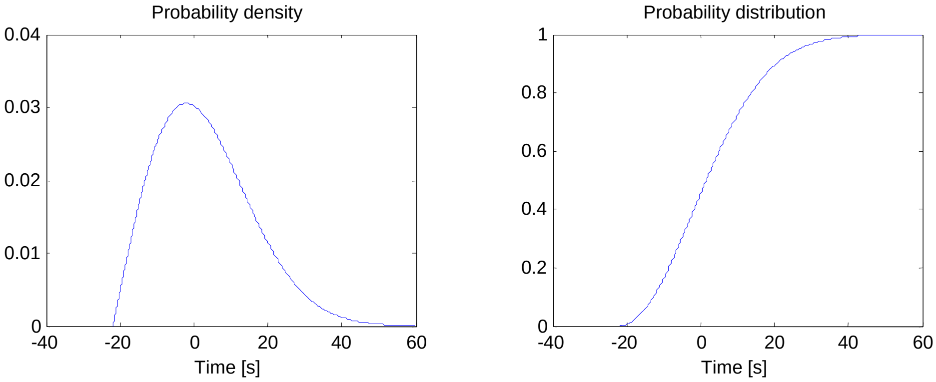


Figure 20 – Probability density function (left) and probability distribution (right) of the difference between the actual and planned separation times at the FAP

For departures, the stochastic initial aircraft separation time at the start of roll can be modelled through the use of a causal model, e.g. based on BBNs (see Figure 21).

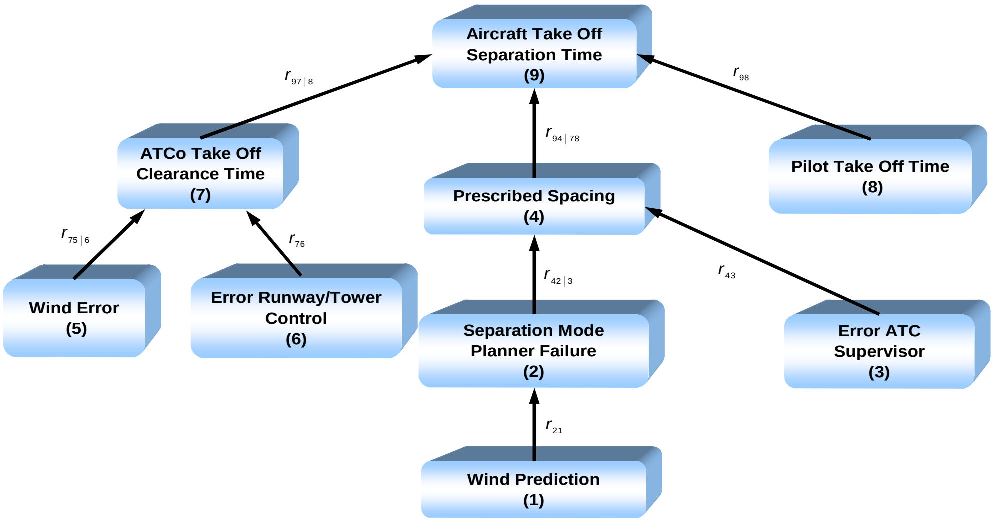


Figure 21 – BBN for the initial aircraft separation time during ATC-Wake departures

The explanation of the nodes in the BBN is given in Table 9. The probability distributions for the nodes in the BBN have been derived from the results of interviews with seven pilots and two controllers (see ATC-Wake D3_6b for the full details). This BBN can be used to analyze the influence of the stochastic variables in Table 9 on the initial aircraft separation time.

Table 9 – Explanation of the nodes in the BBN for the Aircraft Separation Time

Stochastic variable	Explanation
Aircraft TO Separation Time	Time difference between start of roll of the leader and the follower aircraft
ATCo Take Off Clearance Time	Time difference between start of roll of the leader and take off clearance of the ATCo for the follower aircraft
Pilot Take Off Time	Time difference between take off clearance of the ATCo and the start of roll of the aircraft
Prescribed Time Spacing	Separation Time prescribed by the ATC supervisor (in ATC-Wake Mode)
SMP Failure	Time difference between output of the SMP (i.e. Separation Time Advise) and the actual Wind Now-casting
Wind forecast error	Meteorological system wind profile forecast error at reference height (10 m altitude)
Wind now-cast error	Meteorological system wind profile now-cast error at reference height (10 m altitude)
Error runway/ tower controller	Time difference between Separation Time prescribed by the ATC Supervisor and Take Off Clearance Time
Error ATC supervisor	Time difference between SMP Separation Time and Separation Time prescribed by the ATC Supervisor

In both cases (arrivals and departures), the resulting stochastic distribution for the initial separation time can be used as input for the 'classical' WAVIR tool in order to assess the incident/accident risk in relation to the advise provided by the SMP (see also Appendix A).

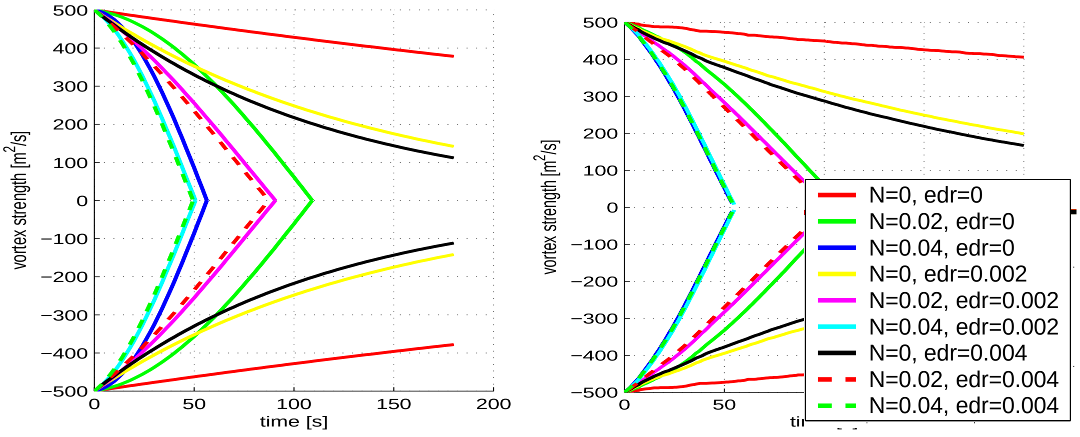
5.3 Validation and verification of the sub-models

5.3.1 Wake vortex evolution models

As shown by LIDAR measurements in real aircraft wakes the wake vortex transport and decay is very sensitive to the ambient weather conditions (winds, turbulence, atmospheric stability are all spatial-temporal variables). This complicates the prediction of wake vortex transport and decay and also the validation of the models against measured LIDAR data, for which the actual ambient weather conditions at the measurement site are only approximately known. Parametric studies with CFD methods and analysis of LIDAR measurements have nevertheless helped to understand the prime transport and decay mechanisms of vortex pairs in different weather conditions, cross-wind shear conditions and vortex interaction with the ground. This enabled the development of simplified wake vortex evolution models such as the simple point vortex method VORTEX, the multiple point vortex methods VFS and P-VFS (Vortex Forecasting System, VFS, and its probabilised version P-VFS.

A somewhat different approach is followed in the P2P method, which implicitly takes into account the variability/uncertainty of weather. A comparison of VFS and VORTEX models was made in a parametric study (deterministic). Both conditions far and close from the ground were considered. All the models use slightly different initialisation, modelling assumptions, model constants and treatment of vortex interaction with the ground. Though each of the models has been carefully tested and verified by the modellers (usually against the same LIDAR data sets), the differences between the model predictions are sometimes considerable, especially for conditions close to the ground. Figure 22 shows as an example a direct comparison between the VFS and the VORTEX model for a range of (non-dimensional) Eddy Dissipation Rates (denoted with EDR) and stratification conditions (denoted by the Brunt-Väisälä parameter N). In these simulations the initial vortex strength was 500 m^2/s, their lateral spacing was 50.6 m and there was no wind.

Both methods use Sarpkaya's EDR decay model for atmospheric turbulence, albeit with a different value for modelling constant C (C=0.45 for VORTEX and C=0.3 for VFS). This reflects the amount of uncertainty in measured LIDAR and/or corresponding weather data that were used for the model validations. It explains why with the VORTEX model the vortices decay faster (and sink less) under turbulence (EDR) conditions than with the VFS model. The predicted stratification effects are quite similar for both models. In conclusion, out of ground effect, both models behave very similar if the same value for modelling constant C would have been used.

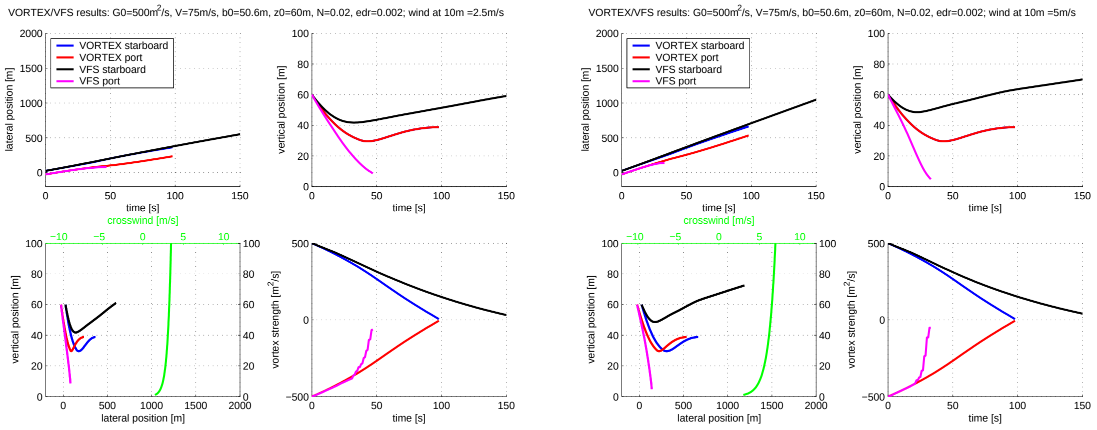


a) VORTEX model **b) VFS model**

Figure 22 – Comparison of VORTEX & VFS predictions for vortices out of ground effect

Close to the ground the situation is more complex because within VORTEX and VFS quite different models for the treatment of ground proximity are employed. The VORTEX model employs mirror vortices (below the ground) for the primary vortices only and when the primary vortices reach the so-called rebound height ($0.6b_v$) secondary counter rotating vortices are introduced directly below the primary vortices, at a height of $0.1b_v$ above ground. The strength of the secondary vortices is taken as a constant fraction (appropriate value somewhere between about 0.3 and 0.7) of the strength of the primary vortices. Corresponding mirror images of the secondary vortices are not taken into account however, so proper ground reflections are not fully satisfied.

The VFS model uses a different approach for the introduction of secondary vortices close to the ground. A comparison of VORTEX and VFS predictions for vortices created near the ground is given in D3_4. It was concluded that both models predict quite different behaviour of vortex trajectories even for cases without cross-wind. For cases with cross-wind the VORTEX model predicts weak effects on vortex tilting whereas the VFS model predicts much more pronounced vortex tilting and delay of vortex decay for the downwind and much increased vortex decay for the upwind vortex due to wind shear effects. This is illustrated in Figure 23, for vortices created at 60m height in crosswind.



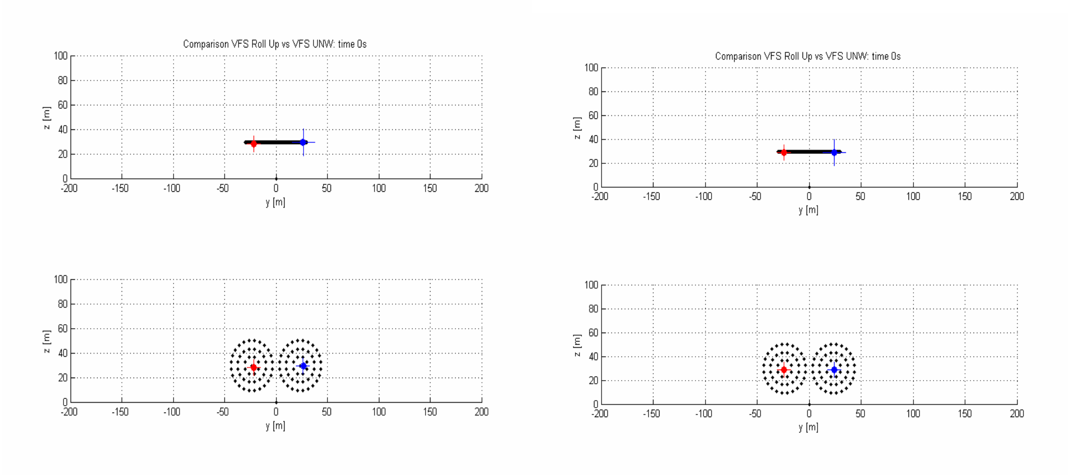
a) U_c= 2.5 m/s **b) U_c = 5 m/s**

Figure 23 – Comparison of VORTEX and VFS predictions for vortices created at 60m

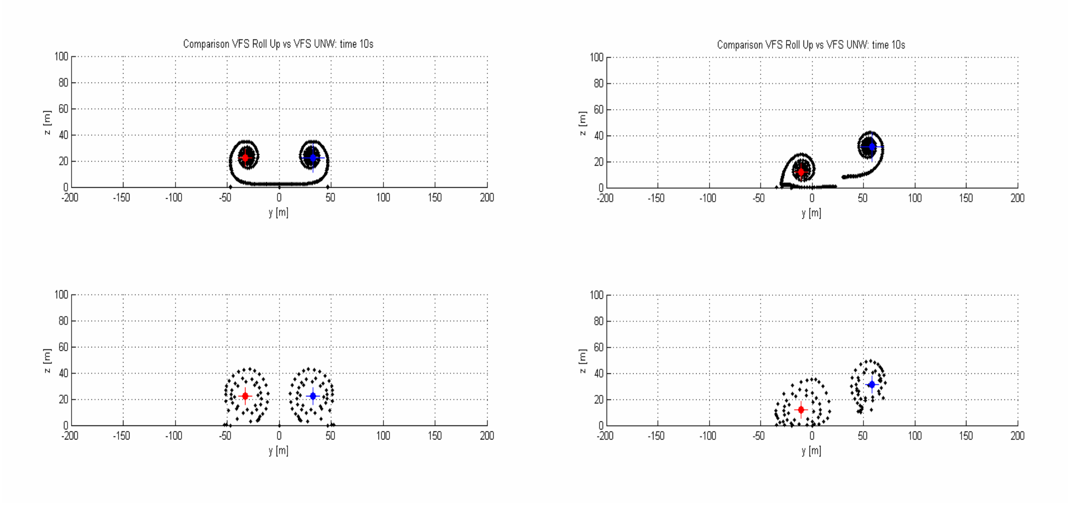
For vortices created in ground effect (say created below the height of one wingspan) the wake roll-up is influenced by the presence of the ground and the assumption of fully rolled up (point) vortices (as used in VORTEX, VFS and P2P) is perhaps no longer really appropriate. Therefore the VFS method was adapted. A comparison of results for wakes created at only 30m above ground with either the normal UNified Wake (UNW: with limited number of vortices) or the Wake Roll-Up (WRU with up to 500 vortices) method is shown in Figure 24 for t=0, t=10 and t= 50s, both for zero and 1 m/s cross-wind. The coloured dots show the vorticity centroids and the crosses show for comparison the vorticity centroid from the other initialisation method. The differences between the two results remain quite small (at least until about t=50 s). Therefore, within ATC-Wake project wake roll-up is fully neglected. However, the necessity for wake roll-up simulations close to the ground will be further investigated within the FAR-Wake project.

The work on idealized cases was followed by an application of VORTEX, VFS and P2P models against specific Dallas Forth Worth (DFW) and Memphis data as well as a comparison against some wind line data from Frankfurt airport (data supplied by DFS). This latter part of the work will not be discussed here, it has been presented during the combined WakeNet-USA and WakeNet2-Europe Workshop, New Orleans, 27-29 April 2004.

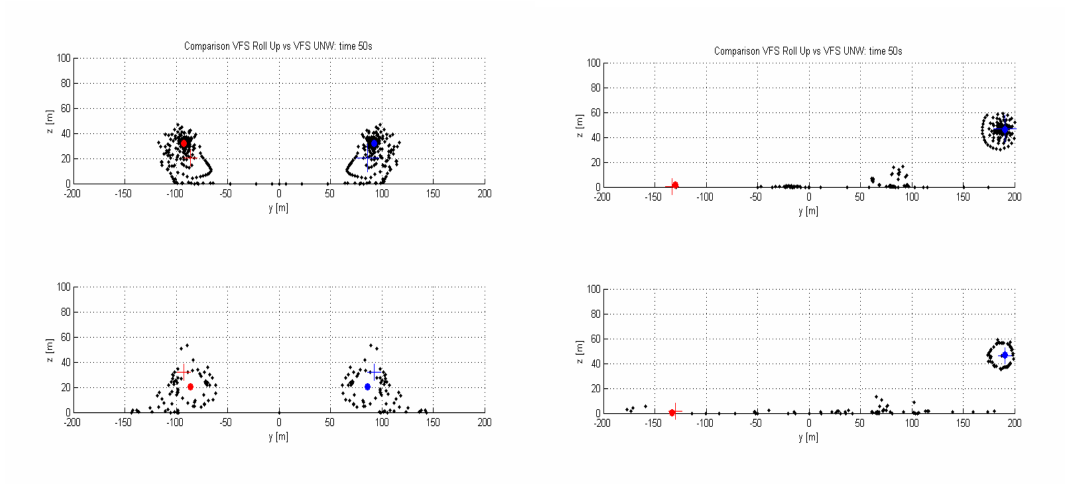
From the model verification and validation exercise it was concluded that modelling in NGE and IGE situations is still not well established and that continuous efforts are needed to improve and calibrate the models. The collection of high quality LIDAR measurements also remains of utmost importance. An in-depth analysis of wakes in ground effect is currently made in the FAR-Wake project and outcomes should be taken into account in future safety assessment studies.



a) t=0 s, no wind **b) t=0 s, cross-wind 1 m/s**



c) t=10 s, no wind **d) t=10 s, cross-wind 1 m/s**



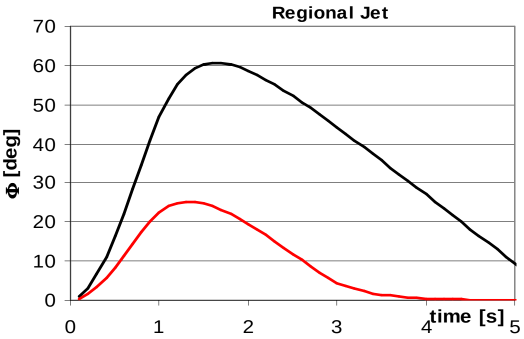
e) t=50 s, no wind **e) t=50 s, cross-wind 1 m/s**

Figure 24 – Comparison of VFS results for vortices created at 30m above the ground

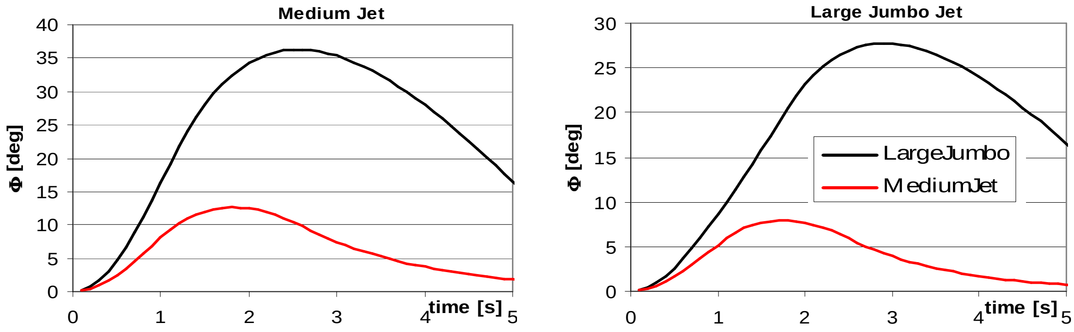
5.3.2 Wake encounter models

In WAVIR, three models of different complexity are available to compute the wake encounter upsets. The simplest model that can be used is the roll-control ratio (RCR) model, which computes the wake induced rolling moment divided by the available roll-control power for a given position of the aircraft with respect to the wake vortices. A somewhat more realistic model is the Extended Roll Control Ratio (ERCR) model, which computes for a given wake induced rolling moment (computed as with the RCR method described above) an estimate of the maximum wake induced bank angle. It is based on a one degree of freedom (1-DOF) roll model of Tatnall. The aircraft is assumed to be aligned with the wake vortices (zero wake intercept angle) and therefore does not move with respect to the wake vortices (frozen aircraft position). The duration of the encounter needs therefore to be limited in order to prevent infinite roll. Suitable (aircraft type dependent) wake encounter duration times T_v were derived by Tatnall such that the 1-DOF model predicts equal maximum roll angles as the more elaborate 3-DOF model. This wake encounter duration time T_v implicitly accounts for the dynamic aspect of the encounter. The maximum bank angle is the most important output of this model, but the roll-control ratio (RCR) is an output too which can be used to classify encounter severity. As an example the computed bank-angles for three aircraft types placed instantaneously in the vortex core of a Medium Jet or a large Jumbo Jet are shown in figure 25. A worst case condition was assumed: vortex decay was neglected, a small vortex core radius size (0.025b) and a rather conservative pilot reaction time (0.6s) were taken.

For a Large Jumbo Jet behind a Large Jumbo Jet the RCR is equal to 2.8 and for a Large Jumbo Jet behind a Medium Jet it is still equal to 1.8. So when there is no vortex decay and the vortex core remains small, according to this conservative estimate, even a Large Jumbo Jet can not fly stable in the vortex centre of a Medium Jet aircraft.



a) Regional Jet



b) Medium Jet **c) Large Jumbo Jet**

Figure 25 – Example of computed bank angles with ERCR model (worst case conditions)

A flight dynamics model based on a 5-DOF flight mechanics model (the airspeed being kept constant) is also available. This model needs more computation time and in the probabilistic framework of WAVIR it is therefore only used for the more severe wake encounter situations. The roll-control ratio (which can easily be computed with the simple RCR model) is used as a pre-selection criterion for cases that need to be considered with the RAPM model.

The RAPM model is (almost) capable to simulate the complete motion of the encountering aircraft. However, simplified aerodynamic coefficients are used: locally linearized behaviour around the given flight operation point. For given initial conditions (flight track direction and speed) it provides as a function of time:

- aircraft position (vertical, longitudinal, lateral),
- vertical and lateral speeds and accelerations,
- aircraft attitude angles,
- angular rates and accelerations (roll, pitch and yaw).

The aerodynamic effect of the wake vortices on the aircraft is taken into account through a more advanced model than in the RCR and ERCR models. A strip model is used to model the forces on wing, vertical tail and horizontal stabiliser. Just as for the Tatnall model, a “frozen” wake induced flow field is assumed. The strip model has been validated against wind-tunnel experimental data, during the WAVENC project. A recent study, employing a lifting line method, confirmed the particular (wing aspect ratio related) correction term for effective section lift coefficient used in Tatnalls and in the strip method. Application of the strip model to dynamic wake intercept flight test data from S-Wake suggests that the frozen field assumption and the empirical effective lift curve slope approximation (strictly only valid for stationary encounters) are still a reasonable approximation. A Pilot Response Model provides roll-control inputs to counteract the wake induced roll motions. A crossover model for the aileron deflection δ_t is used. This pilot model is integrated into the 5-DOF model. A comparison of computed maximum bank angles for the ERCR and the RAPM model, as a function of the initial aircraft position in the wake, is shown in Figure 26.

Computed maximum bank angles with the ERCR model were also compared with maximum bank angles observed during wake encounter flight simulations as performed within S-Wake project. A fair agreement of results was noted.

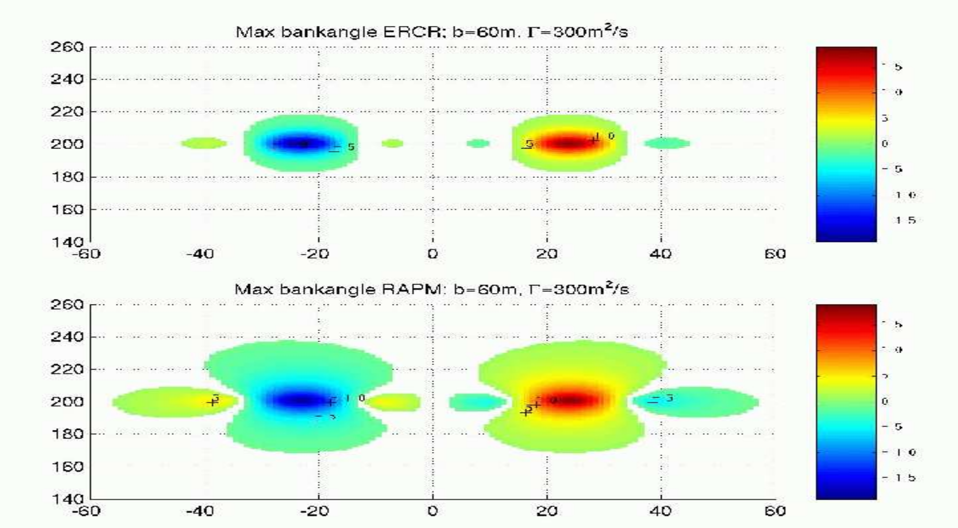


Figure 26 – Comparison between ERCR & RAPM computed maximum roll angles

5.3.3 Aircraft performance models

A new element in the WAVIR methodology is the use of a mathematical model based on Petri Nets (PN) models to determine the aircraft flight path evolution, the functioning of the ATC-Wake system and interaction with pilots and controllers during ATC-Wake arrivals. At specified distances from the runway threshold probability distributions of separation times between leader and follower aircraft is determined using the PN models. To validate this new approach, the Petri Net (PN) model has been compared with the well known AMAAI toolset developed (for EUROCONTROL) for the analysis of in-trail following aircraft. The PN-model employs a number of simplifications:

- Omission of the effect of turbulence on the flight path response of the aircraft;
- Schematic modelling of speed transition profiles, based on a given speed transition distance, in stead of modelling a realistic aircraft speed controller.

The results of a Monte Carlo simulation is visualised in Figure 27. It shows the distributions of the separation time and distances at 7 windows before the threshold (at the FAF, at the OM, and at 2000, 1000, 400, 200 and 0 m in front of the THR). It is shown that there is a good agreement between the results of the AMAAI and PN-simulations. At the FAF the results are more or less identical. The standard deviation of the calculated separation times and distances were analyzed as well, and appear to be are in very good agreement. Differences are in the order of .1 seconds (~.02 nm) between the AMAAI and PN-model. In general the separation as calculated by the PN-model is somewhat less as for the AMAAI model. Differences are in the order of 2.5 seconds (.1 nm), i.e. relatively small and are not expected to significantly affect the subsequent safety assessment results. Moreover, possible effects will be conservative, because the separations as calculated by the PN-model will be slightly smaller than those from the AMAAI model.

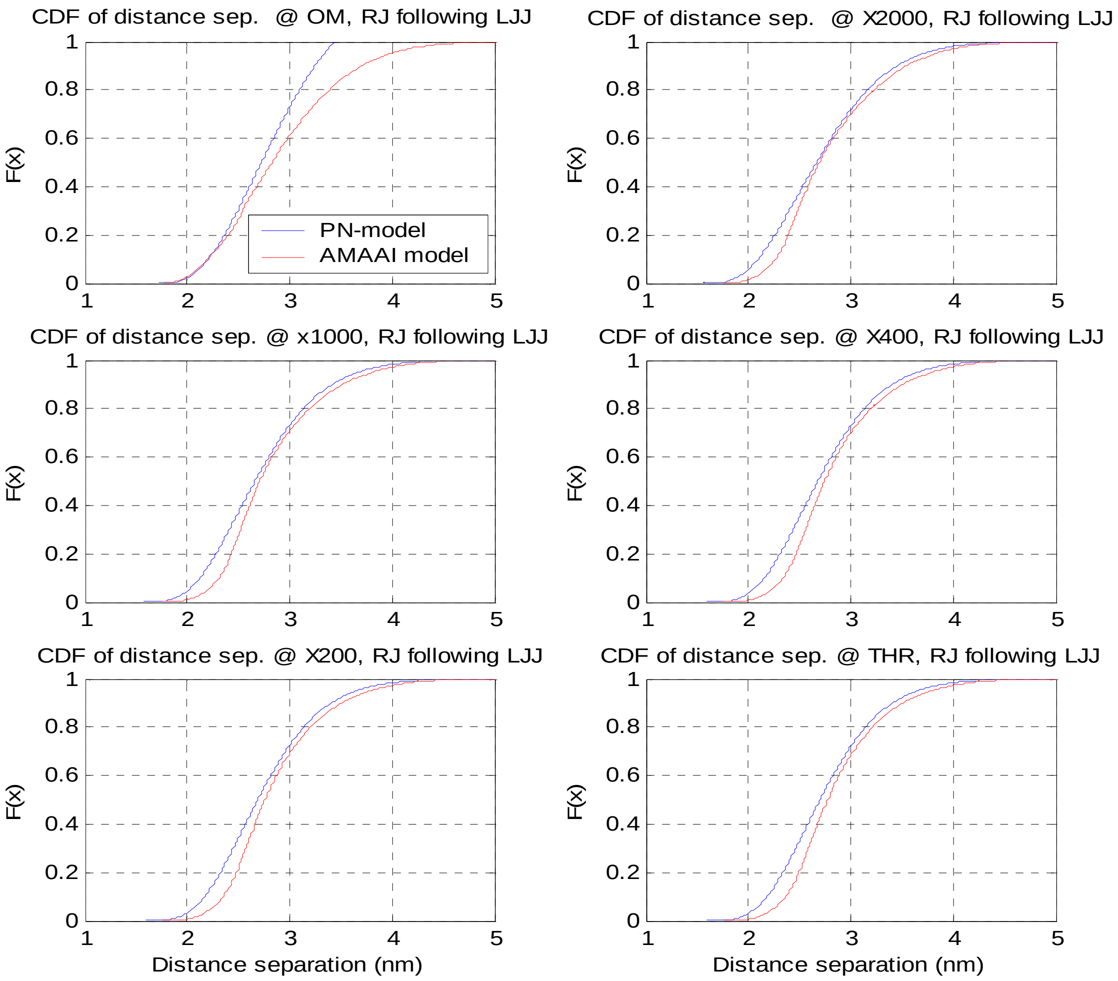


Figure 27 – Probability distribution of separation distances (with AMAAI and PN-model)

In summary, it is shown that the simplifications made in the PN model affect the flight path evolution slightly. It is also shown that this in general will lead to conservative results; i.e. the calculated separation between aircraft during a single runway approach will be slightly underestimated. In terms of risk calculation this will lead to higher risk estimates. Therefore, the model as implemented within the Petri-Net model will provide slightly conservative risk estimates. It is also found that the accuracy of the Petri-Net model is in general satisfactory. Moreover, it was verified that the implementation of the wind model, and the relations between groundspeed and airspeed (true and calibrated) have been implemented correctly within the PN-model. Based on these observations it is concluded that the PN-model provides sufficiently accurate results, such that they can be reliably (and to some extent conservatively) applied for further risk assessment calculations in WAVIR.

6 Qualitative safety assessment

6.1 Introduction

A qualitative safety assessment has been performed to get a global overview of the risks associated with the proposed ATC-Wake operation for single runway arrivals, single runway departures and closely spaced parallel runway departures. Moreover, in this way safety bottlenecks are fed back to the operation designers at an early stage, and this enables further focussing in the safety modelling activities and quantitative safety assessment that are also planned within this work package. In line with the ATC-Wake operation, the assessment is restricted to the following sub-operations:

- end of cruise to final approach;
- arrivals to single runway;
- arrivals to closely spaced parallel runways; and
- departures from single runway.

The assessment has been limited to the risks air traffic participants are running, and for which air traffic control bears responsibility. This for instance excludes risks experienced by people living on the ground, or risks not related to ATC. The assessment did not only concern wake vortex risks; also other risks (as for instance collision risk) related to ATC-Wake aspects of the operation were considered.

6.2 Identification and evaluation of hazards and conflict scenarios

In various brainstorming sessions with operational experts, hazards have been identified that could occur in the considered operation. After the identification of hazards, these hazards have been structured into conflict scenarios, which describe all relevant ways how these hazards may lead to conflicts or worsen them. The conflict scenarios are:

I. Wake vortex encounter during departure
II. Wake vortex encounter during single runway arrival
III. Missed approach during single runway arrival
IV. Wake vortex encounter before ILS interception
V. Wake vortex encounter during arrivals on closely spaced parallel runway
VI. Missed approach during arrivals on closely spaced parallel runways
VII. Higher traffic rates in TMA, holding, sector, or on runway
VIII. Turbulence
IX. More landings in crosswind
X. Transitions between ICAO and ATC-Wake separation mode
XI. Effects on ICAO separation mode

Not all scenarios apply to each of the three operations: Single runway departure, single runway arrival, closely spaced parallel runway arrival. For single runway departures, only conflict scenario I does apply. Scenarios II, III, and IV specifically apply to the single runway arrival operation. Scenarios V and VI specifically apply to the closely spaced parallel runway operation. Each scenario is constructed from several events or clusters of events, where each event represents a set of identified hazards. The eleven conflict scenarios and the results from the analysis are presented in the following pages.

Conflict scenarios for single runway departures

I Wake vortex encounter during departure

This scenario may arise in case of the joint occurrence of a wake vortex of a leading aircraft and a separation that is too small to avoid the wake. The latter may be caused either by the combination of an aircraft taking off too early and no rejected take-off or other avoiding action taking place, or by a sudden (unpredictable) change of the wake behaviour. Three causes for an early take off have been identified:

- The pilot of the following aircraft initiates take-off without the appropriate clearance;
- The ATCo does not comply with the prescribed spacing and gives a clearance while he or she should not, and the pilot accepts this clearance; and
- The prescribed spacing is insufficient *and* the ATC-Wake Detection, Warning, and Avoidance system does not function.

For departures, it is most efficient to postpone the departure in case the wind nowcasting information timely indicates a sudden change of the wind. After initiation of the take-off, the wake representation on the ATCo’s screen may help the ATCo in informing the pilot to prepare for a potential encounter (he/she may then be able to control an encounter).

Conflict scenarios for single runway arrivals

For the conflict scenarios for single runway arrivals, distinction is made between the phase of flight before ILS interception and from interception until touchdown. Important reason for this is that there is no wake vortex detection foreseen in the phase before ILS interception, i.e. the ATC-Wake detection, warning, and avoidance system does not function here. Other differences as the height of the encounter may effect the consequences, but do not play a role in the structure of the scenario. The issue of a wake vortex encounter in the two phases is covered in conflict scenarios II and IV. In the last phase of an arrival, a missed approach may be initiated for various reasons among which a warning of the ATC-Wake detection, warning, and avoidance system. In case this occurs during ATC-Wake mode of operation, it may have different consequences than in ICAO mode and is therefore covered in a separate conflict scenario (III).

II Wake vortex encounter during single runway arrival

A wake vortex encounter may occur in case of:

- a sudden (unpredictable) change of the wake behaviour, or
- insufficient spacing *and* the ATC-Wake DWA system fails.

Reasons for insufficient spacing are:

- the ATCo does not comply with prescribed spacing, or
- the pilot does not comply with instructions, or
- the prescribed spacing is insufficient.

The ATC-Wake detection, warning, and avoidance system consists of a technical detection system that can issue a warning to the ATCo, who on his/her turn can warn and/or instruct the pilot. Then it is the pilots responsibility to initiate appropriate actions.

III Missed approach during single runway arrival

The initiation of a missed approached is considered here as a separate conflict scenario (III), as its consequences may be different in ATC-Wake mode. A missed approach can be caused by insufficient spacing in combination with the presence of a wake vortex and a successful ATC-Wake detection, warning, and avoidance system. Besides evading a wake vortex, there might be other reasons to initiate a missed approach, for example a runway that has not been vacated yet by the preceding aircraft. Both the ATCo and the pilot can initiate a missed approach in such cases. Insufficient spacing results from the same causes as in conflict scenario II. The consequences of the missed approach do depend on the initiation point of the missed approach, other traffic e.g. due to a second missed approach, and communication between ATCo and pilot or in between ATCos.

IV Wake vortex encounter before ILS interception

Obviously there is some similarity between conflict scenario IV and conflict scenario II, in which the wake vortex encounter takes place later. Most striking difference is that the separation distance is not so strictly defined for this part, and that wake vortex detection and monitoring does not take place in the piece of airspace under consideration. Additionally, consecutive aircraft do not necessarily follow the same path, and aircraft speeds are higher. Furthermore, segregation in case of closely spaced parallel runway arrivals may contribute to an increased wake vortex risk. The central event in this conflict scenario is the wake vortex encounter that is caused by the presence of a wake vortex of another aircraft and a separation that is too short to avoid a wake vortex encounter. In addition to the causes for too short separation mentioned in scenario II (ATCo applies insufficient spacing or pilot does not comply with ATC instructions and reduces spacing), vertical deviation may also be a cause here. The resolution variables playing a role are all similar to the ones considered in conflict scenario II.

Conflict scenarios for CSPR arrivals

During arrivals on closely spaced parallel runways, the same types of hazards and conflict scenarios are considered as for arrivals on a single runway. This has simplified the further analysis as only the differences of the CSPR arrivals in comparison to the single runway arrivals have to be considered. Accordingly, the conflict scenarios are:

V Wake vortex encounter during arrivals on closely spaced parallel runways

With respect to wake vortex encounters during approaches on CSPRs, three cases have been distinguished:

1. An aircraft encounters the wake vortex of the preceding aircraft on the same runway.
2. An aircraft on the downwind runway encounters the wake of the preceding aircraft on the upwind runway.
3. An aircraft on the upwind runway encounters the wake of the preceding aircraft on the downwind runway.

There are few additional hazards that specifically apply to this conflict scenario. These concern the possibility of a wake vortex that is blown to the parallel runway, erroneous segregation by the ATCO due to misidentification or confusion of aircraft types, and erroneous swing-overs, lateral deviation of the aircraft to the parallel runway.

VI Missed approach during arrivals on closely spaced parallel runways

In case the ATC-Wake operation takes place on two (closely spaced) parallel runways not only the occurrence of a single missed approach but also of two simultaneous missed approaches have to be considered. There is one major difference with single runway operations: in case of closely spaced parallel approaches, missed approaches caused by an un-vacated runway will hardly occur, since the effective separation distance between two aircraft landing on the same runway will namely be more. An issue to be considered is potential collision risk between aircraft approaching the adjacent runways.

Other conflict scenarios

The conflict scenarios defined until so far specifically treated conflicts that take place in the ATC-Wake separation mode. In the remaining conflict scenarios VII to XI this is not necessarily the case. It is noted that the hazards considered in these conflict scenarios mostly represent side-effects of the operation under consideration. Though some of these side effects may also play a role in the conflict scenarios already considered, it appears justified to take a separate look at these aspects, to make sure that the consequences of these effects are not overlooked.

VII Higher traffic rates in TMA, holding, sector, or on runway

In conflict scenario VII, the main issue is formed by the higher traffic rates. Various hazards have been identified which have in common that they treat or may lead to higher traffic rates in the TMA, a holding, a sector, or on the runway. As possible consequences have been identified: an increased workload, an increased collision risk in the air, frequency congestion, other alerts, and an increased collision risk on the runway. The conflict scenario can occur both during ATC-Wake mode and during ICAO-Wake mode.

VIII Turbulence

Conflict scenario VIII deals with the possibility that pilots may erroneously consider ‘normal’ turbulence as being wake vortex turbulence. It is unclear what the reaction will be.

IX More landings in crosswind

Reduced separation distances may be applied in crosswind conditions because of the ATC-Wake operation; this may lead to more landings taking place with larger crosswind.

X Transitions between ICAO and ATC-Wake separation mode

The transitions between the ICAO and the ATC-Wake separation mode are mentioned as a possible cause for higher traffic rates and consequently much communication may be necessary in these cases. However it is also possible that these transitions have other consequences, such as for ATFM.

XI Effects on ICAO separation mode

Even in ICAO mode, the separation applied may occasionally be too short for an ATC-Wake related cause. Relevant hazards identified are that a pilot or ATCo is confused about the active wake separation mode. Another difference with the current operations is that the controllers may use the ATC-Wake tools in the ICAO mode.

6.3 Effect of failures of the ATC-Wake System Components

Table 10 provides an assessment of the effect of the main system failures. The individual classifications are based on the assumption that other failure conditions do not occur. A simultaneous failure of two system components could aggravate the situation.

Table 10 – Effect of main ATC-Wake DWA conditions

Description	Effect	Classification	Comment
Pilot/aircraft not able to turn timely The pilot/aircraft is not able to timely perform the DWA manoeuvre, after it is requested by the controller. This could occur in case of a warning when the aircraft is still in initial take off, ie limitations in bank angle apply	An unfavourable change of weather (not enough crosswind) is passed on by the controller to the pilot. The pilot is prepared for a potential severe Wake encounter, and may be able to control the situation. Nevertheless, control problems could still occur.	MAJOR - SERIOUS INCIDENT	A Wake is stronger closer to the generating aircraft. An encounter with reduced separation will result in more severe consequence than in ICAO Mode. *The pilot is prepared for a WV.*

Description	Effect	Classification	Comment
Controller does not provide a timely warning to the pilot The controller does not provide a timely warning to the pilot, for example because he does not hear an aural warning or misses a visual warning. ATC-Wake provides an alert, but ATCo is not aware of it and does not ask the pilot to initiate a turn	An unfavourable change of weather (not enough crosswind) is not passed on to the pilot. The pilot will be unprepared for severe turbulence, i.e might experience control problems in close proximity to the ground.	SERIOUS INCIDENT	The Wake vortex is stronger closer to the generating aircraft. An encounter with reduced separation will result in more severe consequence than under ICAO separations.
Faulty or Inaccurate Separation Mode Planner Advise The advise provided by a Separation Mode Planner is wrong or inaccurate. The ATC supervisor, not being aware of it, might decide to implement ATC-Wake Mode, with reduced separation although the weather conditions are not favourable (e.g. no crosswind).	There will be an alert for (nearly) every aircraft departing or arriving, resulting in a high rate of initiated Wake vortex avoidance instructions (e.g. missed approaches during arrivals). The ATC workload increases, and Most likely a transition will be made very quickly to the ICAO Separation Mode.	SIGNIFICANT INCIDENT	It could take a few minutes before the transition to ICAO Mode is made
Loss of Wake Vortex DWA Tactical Function The ATC-Wake Monitoring and Alerting system is not operational and provides no function. The controllers, not being aware of it, are expecting the system to warn in case of a discrepancy between prediction & detection information.	The controllers will not receive an alert in case ATC-Wake separation is no longer suitable. The aircraft may encounter severe turbulence which may lead to control problems in close proximity to the ground.	SERIOUS INCIDENT	The Wake vortex is stronger closer to the generating aircraft. An encounter with reduced separation will result in more severe consequence than under ICAO separations.
Faulty or Inaccurate WV Model Estimation The predictions of Wake vortex locations and/or strengths made by the WV Model, on the basis of aircraft data and meteo data are inaccurate/wrong.	Incorrect information is passed to the ATC-Wake Predictor, causing improper functioning. The predicted Wake Vortex Vector will be wrong, and an alert might be generated on the basis of false information. There will be an increase of workload.	SIGNIFICANT - MAJOR INCIDENT	Alert is generated because there is a discrepancy between prediction and detection information. This is unlikely to occur at low altitudes if Meteo Nowcast and Predictor are working.
Faulty or Inaccurate Air Traffic Situation The air traffic situation provided by the surveillance systems is wrong or inaccurate. The controllers will most likely not be aware that the wrong leader or aircraft data is used in the ATC-Wake Predictor and on the HMI.	Incorrect information is passed to the ATC-Wake Predictor, causing improper functioning. The predicted Wake Vortex Vector will be wrong, and an alert might be generated on the basis of false information. Most likely a transition will be made to the ICAO Separation Mode. There will be an increase of workload of ATC.	SIGNIFICANT INCIDENT	The ATC-Wake separation Mode is based on a worst case combination of a Heavy leader aircraft and a Light follower aircraft.

Description	Effect	Classification	Comment
Faulty or Inaccurate Meteo Now-casting Information The nowcasted meteorological conditions are inaccurate or wrong. The controllers will most likely not be aware of a sudden unfavourable change of the wind.	Incorrect information is passed to the ATC-Wake Predictor, causing improper functioning. The predicted Wake vortex transport is wrong. An unfavourable change of weather (not enough crosswind) is not detected. The aircraft may encounter severe turbulence, which may lead to control problems in close proximity to ground	SERIOUS INCIDENT	The Wake vortex is stronger closer to the generating aircraft. An encounter with reduced separation will result in more severe consequence than under ICAO separation.
Wake Vortex outside Detection Range and/or Scanning Volume The Wake vortices generated by the leader aircraft are not detected, when they are outside the scanning volume of the ATC-Wake Detector. As the WV detection information suddenly disappears, there is an indication and ATCos will be informed of the failure.	No Wake vortex information is passed to the ATC-Wake Detector, causing improper functioning. As the ATC supervisor and the air traffic controllers will likely become aware quickly that there will not be an alert, a transition will be made to the ICAO Separation Mode. There will be an increase of workload of ATC.	SIGNIFICANT INCIDENT	It could take a few minutes before the transition to ICAO Mode is made.
Faulty or Inaccurate Detection of the Wake Vortices The Wake vortices generated by the leader aircraft are inaccurately or not detected, because of a failure of the ATC-Wake Detector.	Incorrect information is used by ATC-Wake Detector, causing improper functioning. Wake Vortices are not detected. There will be an alert if the Wake Vortex Vector generated by the ATC-Wake Predictor indicates a potential Wake encounter. There will then be an increase of workload.	SIGNICANT - MAJOR INCIDENT	Alert is generated because there is a discrepancy between prediction and detection information. This is unlikely to occur at low altitudes if Meteo Nowcast and Predictor are working.

According to ESARR4, failure conditions with severe consequences must be extremely improbable, and minor failure conditions may be probable. It is noted that a simultaneous failure of two main system components may aggravate the situation.

6.4 Risk assessment per conflict scenario

Using operational experts' judgement and knowledge from other studies, for each of the eleven conflict scenarios the severity and the frequency have been assessed. Using the risk criteria developed in Section 3, an evaluation of the acceptability of the risk of each scenario was given. Table 11 provides all identified conflict scenarios and indicates for which scenarios potential SAFETY BOTTLENECKS exist (i.e. safety objectives may need to be determined. For all conflict scenarios with potential UNACCEPTABLE risks, it could not be ruled out that the risk also potentially is TOLERABLE or NEGLIGIBLE.

Table 11 – Overview of potential SAFETY BOTTLENECKS for the conflict scenarios

Conflict scenario		Potential SAFETY BOTTLENECK in the ATC-Wake operation		
		Single runway departure	Single runway arrival	CSPR arrival
I.	Wake vortex encounter during departure	Yes	NA	NA
II.	Wake vortex encounter during single runway arrival	NA	Yes	NA
III.	Missed approach during single runway arrival	NA	No	NA
IV.	Wake vortex encounter before ILS interception	NA	No	No
V.	Wake vortex encounter during arrivals on CSPRs	NA	NA	Yes
VI.	Missed approach during arrivals on CSPRs	NA	NA	No
VII.	Higher traffic rates in TMA, holding, sector, or on runway	Yes	Yes	Yes
VIII.	Turbulence	No	No	No
IX.	More landings in crosswind	NA	Yes*	Yes*
X.	Transitions between ICAO & ATC-Wake separation mode	Yes*	Yes*	Yes*
XI.	Effects on ICAO separation mode	Yes*	Yes*	Yes*

* The risk tolerability of these conflict scenarios could not be assessed in detail.

6.5 Identification of safety bottlenecks

The possibility of UNACCEPTABLE risk could not be ruled out in the conflict scenarios I, II, V, VII, IX, X and XI. This is potentially caused by so-called safety bottlenecks: hazards which cause the conflict scenario to have a risk that might be UNACCEPTABLE. The safety bottlenecks in the concerned conflict scenarios are discussed next.

In conflict scenario I (Wake vortex encounter during departure), identified potential safety bottlenecks are:

- Supervisors may not follow the advice of the ATC-Wake Separation Mode Planner and tend to deviate to the unsafe side, for example for efficiency reasons;
- Controllers may not comply with the prescribed separation and give a take-off clearance too early, for instance due to a timing error;
- Controllers may not pay sufficient attention to the visualisation tool and react properly on an alert, because TWR controllers are used to work based on their outside view, specifically in VMC.

In the departure operation the risk is mainly expected in the area just after lift-off, though also the area around the first turn may bear a significant risk.

In conflict scenario II (Wake vortex encounter during single runway arrival), an identified potential safety bottleneck is:

- Controllers may use the wake vortex visualisation system as a separation tool (although this is not the objective of the tool), possibly leading to insufficient spacing.

It is expected that the highest risk occurs on the final approach (from 4Nm to threshold) while the area where the ILS intercept takes place is also prone to wake encounters.

Conflict scenario V (Wake vortex encounter during arrivals on closely spaced parallel runway) is expected to be less safety critical than conflict scenario II. Identified potential safety bottlenecks are:

- Controllers may use the wake vortex visualisation system as a separation tool (although this is not the objective of the tool), possibly leading to insufficient spacing;
- The use of a single controller for the two runways.

In conflict scenario VII (Higher traffic rates in TMA), holding, sector or on runway, identified potential safety bottlenecks are:

- Frequency congestion due to the expected increase in R/T load. This increase is expected firstly because of the additional information that needs to be given to the pilots, and secondly to the increase in traffic rates that is expected.
- Collision risk on the runway, because of the application of reduced separation criteria to all pairs of aircraft, irrespective of the aircraft types. If the ATC-Wake mode separation distance does not sufficiently take into account the runway occupancy time of Heavy aircraft, this is expected to lead to an increased collision risk on the runway. If the ATC-Wake mode separation distance would safely account for the runway occupancy time of Heavy aircraft, then the use of this separation distance for all aircraft types is not expected to support the capacity increase envisioned by the ATC-Wake operation.

In conflict scenario IX (More landings in crosswind) a potential safety bottleneck is:

- Adapted runway selection criteria may favour landing in crosswinds of 10 to 15 knots and higher above landing in headwind.

In conflict scenario X (Transitions between ICAO and ATC-Wake separation mode) potential safety bottlenecks are:

- Too frequent or sudden mode transitions;
- Too much information exchange in a transition.

In conflict scenario XI (Effects on ICAO separation mode) a potential safety bottleneck is:

- The possible use of the ATC-Wake visualisation system as a separation tool. This may be the case if the system is available to the controllers in the ICAO separation mode.

For the other scenarios no UNACCEPTABLE risks were identified. These scenarios are:

III. Missed approach during single runway arrival
IV. Wake vortex encounter before ILS interception
VI. Missed approach during arrivals on closely spaced parallel runways
VIII. Turbulence

6.6 Enhancements of the ATC-Wake operation

Comments and recommendations on elements related to the ATC-Wake operation were given by some operational and safety experts in the review of this study. These may be valuable for the further design and implementation of the ATC-Wake operation as they may contribute to the resolution or mitigation of the potential safety bottlenecks.

The hazard identification and the analysis of hazards and conflict scenarios have however been performed for an operation in which these aspects were not (yet) present. Since for these aspects it was not straightforward to identify whether they would introduce any new hazards to the operation, they have not been taken into account in this assessment. These aspects are summarized below:

- In addition to the assumption that airborne equipment for wake vortex detection, such as the I-Wake system, may in future function as a safety-net to the ATC-Wake system, it is remarked that such an I-Wake system would not be considered as a potential mitigation mean in a future safety assessment but would act as a last safety resort.
- In view of the atmospheric conditions for which one of the two envisaged separation modes (ICAO Mode or ATC-Wake Mode) must be used, it is strongly recommended to focus the further elaboration of weather classes on atmospheric conditions that are relatively easy to forecast (prediction of wind climatology is relatively easy, whereas atmospheric turbulence and stratification are difficult to forecast).
- In view of the visual contact between two consecutive landing aircraft that has to be confirmed as soon as the second aircraft intercepts ILS, as proposed in the operation, it is noted that this may be more important on final approach such that the following aircraft can see if the preceding aircraft has vacated the runway or has initiated a go-around.
- It is very important that ATIS information also includes information on the ATC Wake Procedure (meteorological and visuals conditions) and the possibility that there might be an alert due to low separation.
- A-SMGCS may be required as well for the ATC-Wake operation, to provide the controller with aircraft position and identification on a radar display. Such facility may be required as higher landing rates or departure rates may be expected in the ATC-Wake operation.
- In order to safely support reduced separation, the detection information shall also have a high level of integrity and continuity of service in addition to accuracy. This substantiates the need for an ATC-wake monitoring and alerting system.

- In view of the information that "deviation from separation by the ATCo seems to be daily practice", in the training for new operations it should be explained that current practice operations were designed with large embedded safety buffers because of the uncertainties of the systems and about the raw information. Less additional buffer is expected on new operations that will be designed on more accurate raw data.
- TCAS is used to estimate distances with an accuracy of about 1 NM. However, bearing information is only relative bearing and is very uncertain. Relative bearing must not be used to estimate the track of the other aircraft. This is normally part of the TCAS training but it should be emphasized for wake vortex training. In fact, there could be a requirement to have an airborne system enabling to monitor the spacing distance with the preceding aircraft (see also http://adsb.tc.faa.gov/WG4.htm).

7 Quantitative safety assessment

7.1 Overview of the simulation scenarios

The set up and results of the quantitative risk assessment of the ATC-Wake operation are obtained using the quantitative risk assessment methodology described in Section 5.2. The assessments have been performed for the situation without the use of an ATC-Wake system, and also for the proposed ATC-Wake operation. Three studies have been carried out:

- Single runway arrivals;
- Single runway departures
- Closely spaced parallel runway arrivals.

Basically, the scenarios that have been set up differ in:

- Generator – follower aircraft combination;
- Wind velocity (direction and strength);
- Separation distance or time.

These are called ‘assessment parameters’. A simulation scenario is defined by all the parameters and variables in the WAVIR tool-set. The main deterministic parameters and stochastic variables and their values in the different scenarios are presented below.

Longitudinal positions along the flight track

Analysis of wake induced risk is done in a number of longitudinal positions up to 10 Nm from the runway thresholds. From the qualitative analysis it appears that the following areas might be the most dangerous: the area close to the ground, the area encompassing the first turn in the climb phase, and the area near ILS interception.

Wake vortex evolution model parameters

The vortex pair behind the generator aircraft is modelled as two line vortices with a vortex spacing, a vortex strength, and a core-radius. These parameters do depend on the wingspan, weight and speed of the generator aircraft. Evolution of the vortex position is modelled according to Corjon & Poinsot. This includes image vortices and secondary vortices making the vortex pair to diverge and rebound near the ground respectively. Parameters concerning secondary vortices are:

- strength of the secondary vortices as a fraction of the strength of the primary vortices; and the
- rebound height

A secondary vortex appears as soon as the primary vortex has decreased to a certain altitude: the rebound height. For the rebound height a fixed value of $0.6b_0$ will be used. The strength of the secondary vortex is a fraction of the strength of the primary vortex. This fraction is drawn from an uniform distribution between 0.3 and 0.7.

Decay model

The decay function as defined by Sarpkaya will be used. Input parameters are the Brunt-Väisälä frequency N and the Eddy Dissipation Rate (EDR).

Meteorological input parameters

- Brunt-Väisälä frequency (N)
- Eddy Dissipation Rate (EDR)

Simulations have been performed for a two-dimensional data set of Brunt-Väisälä frequencies and EDR values representing the climatology of London Heathrow at different height levels. Information on this climatology was provided by UKMO.

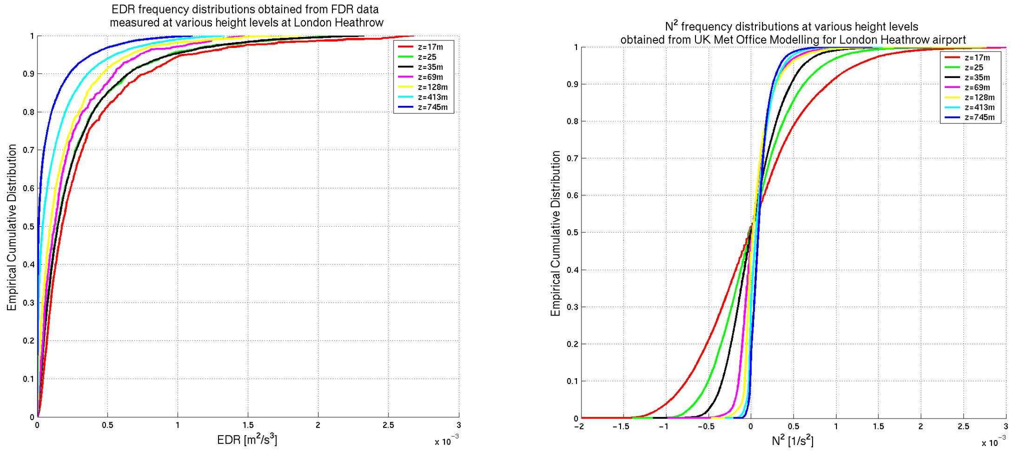


Figure 28 – Frequency distributions of EDR and N^2 for the Heathrow climatology

Wind input parameters

- Wind velocity
- Altitude of measurement
- Roughness coefficient

Wind will be simulated assuming a logarithmic wind profile up to an altitude of 1000ft. Above this altitude the wind is constant. The surface roughness is 0.03m which is representative for an airport environment. The wind value is specified at 10m altitude. For determination of the minimum crosswind value, above which the separation distance (or time) for all aircraft combinations can be reduced safely, the focus will be on varying the crosswind velocity and analysing the impact on risk accordingly. To assess the wake vortex induced risk at a generic airport, a second assessment could be performed, where the total wind vector is specified by a cumulative distribution for the probability of exceeding a given wind speed (according to JAR-AWO (ACJ AWO 131)).

Wake encounter model parameters

Two encounter models are available, the Extended Roll Control Ratio model (ERCR) and the Reduced Aircraft Pilot Model (RAPM). The aircraft dependent parameters that are required by the ERCR and RAPM model are determined for a number of generic aircraft types. In the current study, the ERCR has been applied to compute the roll control ratio and the maximum bank angle. The RAPM was used to verify and calibrate the ERCR model. An encounter severity classification scheme based on maximum bank angle and altitude of encounter is available from S-Wake.

Risk prediction model parameters

To obtain incident/accident probabilities for a given time separation between leader and follower aircraft, the risk prediction model developed within S-Wake is used. This model includes a definition of risk events (Minor Incident, Major Incident, Hazardous Accident and Catastrophic Accident), a probability transition matrix from encounter severity classes to risk events, and the associated risk requirements (Target Level of Safety).

7.2 Single runway arrivals

7.2.1 Set up of the simulation scenarios

For the analysis of the current practice situation, the generic scenario considers the final approach of a leader and follower aircraft, both descending along the ILS path from final approach point (FAP) to runway threshold (THR). The calibrated air speed of the aircraft is independent of aircraft type between FAP and the outer marker (OM), and decelerates to the final approach speed between OM and deceleration point (DP). The aircraft considered are shown in Table 12. This approach is consistent with the approach followed in S-Wake.

Table 12 – Aircraft types for single runway arrivals

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

Depending on the wind conditions, the approach operation can be performed in ATC-Wake mode, which implies that all aircraft are to be separated at a constant distance at the runway threshold. The aircraft are assumed to follow a 3 degrees glide path from ILS glide path intercept to touchdown. The lateral and vertical deviation from the nominal flight path is based on the ICAO-CRM. Nominal aircraft speed profiles are specified by:

- the airport dependent speed at the Outer Marker (OM) that is prescribed by ATC;
- from OM to the Deceleration Point (DP), the speed is linearly decreasing to the aircraft dependent Final Approach Speed (FAS);
- from DP until touchdown, aircraft dependent speed is constant and equal to the FAS.

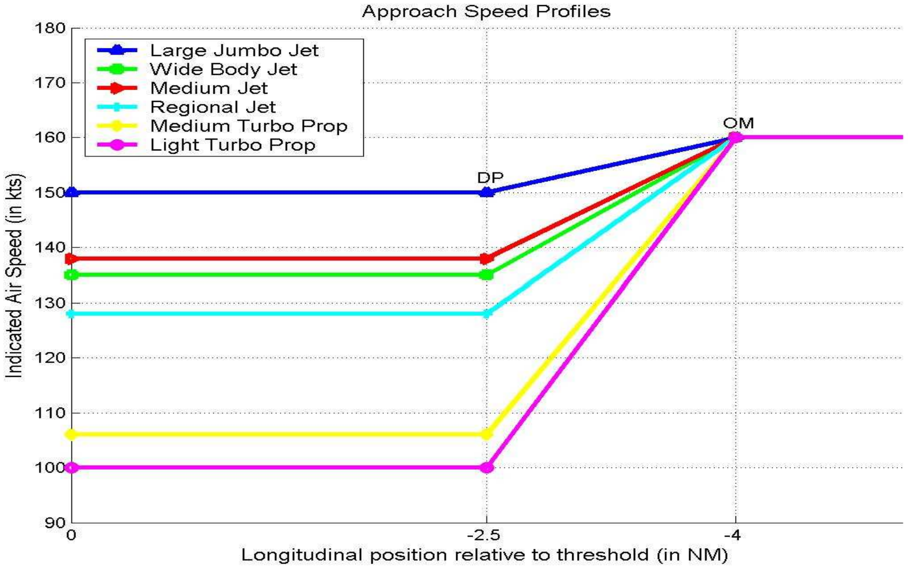


Figure 29 – Nominal approach speed profiles

For the analysis of the situation with the ATC-Wake system in use, the generic scenario follows from Monte Carlo simulations with the newly developed and validated Petri-Net approach model (see Section 5.3.3) with a large jumbo jet as leader and a medium turbo prop as follower aircraft. Here, the purpose is to determine the conditions under which reduced separation with the proposed ATC-Wake mode separation of 2.5 Nm is feasible in terms of acceptable wake vortex risk and acceptable missed approach rate.

7.2.2 Overview of main results from the current practice simulations

The detailed results of the quantitative safety assessment of the current practice are given in Appendix A, and visualized in Figure 30. A Large jumbo jet and Medium jet as Leader AirCraft (LAC) were combined with Large jumbo jet, Medium jet, Regional jet, and Light turbo prop as Follower AirCraft (FAC). Crosswind was varied between 0, 1, 2, and 4 m/s at 10m altitude, assuming a logarithmic profile with height. Evaluated separation distances, controlled at the runway threshold were 3.0, 4.0, and 5.0NM.

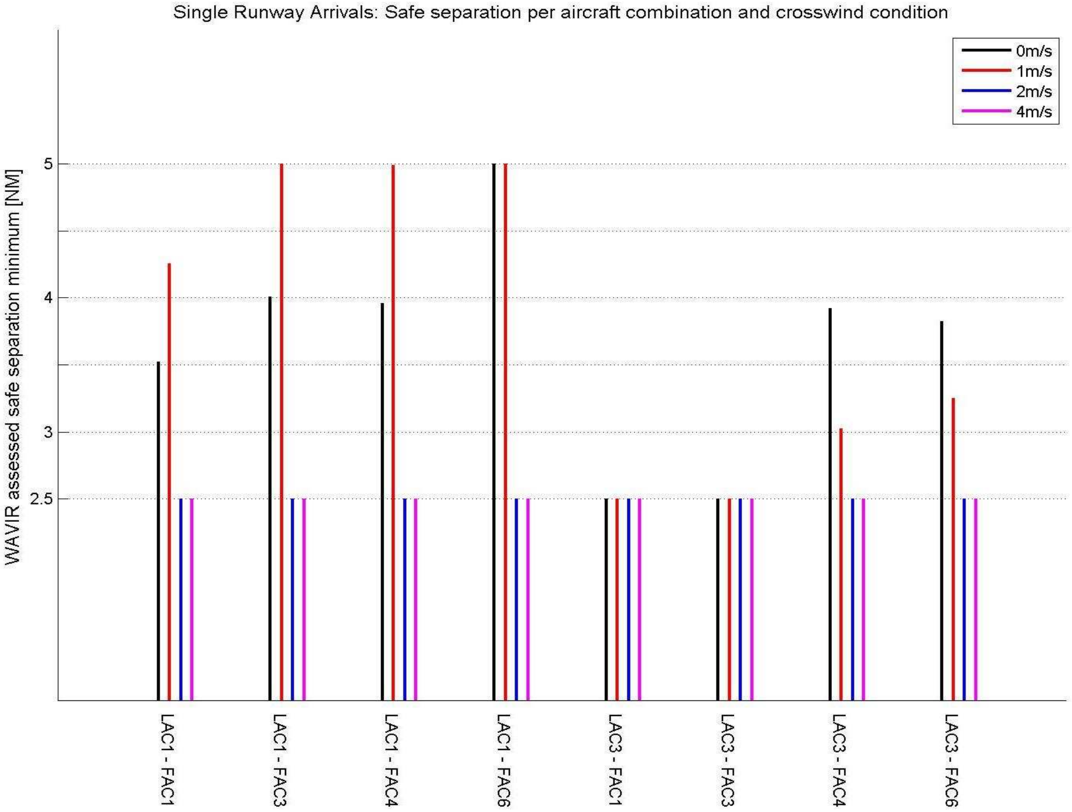


Figure 30 – Overview of WAVIR assessed safe separation minima for the SRA operation

Taking into consideration that ATC-Wake reduced separation should be applied to all aircraft combinations and that because of radar separation criteria 2.5NM is currently the minimum spacing, Table 13 indicates safe separation minima for the assessed operation for certain crosswind intervals. Please note that these are indicative numbers that do not take into account uncertainty in the crosswind conditions, safety margins and other factors that may influence safety. Also, it is assumed that these separations may only be applied in case the ATC-Wake system (and operation) is used, and the system components meet certain performance requirements which follow from Section 7.2.3.

Table 13 – Indicative separation per crosswind interval for single runway arrivals

	Proposed separation (*the largest value in a row applies*)		
Crosswind interval	Wake vortex induced separation minima	Radar separation minima	Runway Occupancy time (ROT) minima
$u_c \leq 2$ m/s	ICAO	2.5 NM	aircraft/runway dependent
$2 \leq u_c \leq 4$m/s	2.5 NM	2.5 NM	aircraft/runway dependent
4 m/s $\leq u_c$	2.0 NM	2.5 NM	aircraft/runway dependent

7.2.3 Requirements setting for ATC-Wake operation with 2.5 Nm separation

To support the identification of a set of conditions/requirements under which the ATC-Wake single runway arrival operation can fulfil the target levels of (wake vortex) safety with an acceptable rate of missed approaches, Table 14 shows the results for the proportion of approaches in the ATC-Wake mode and the missed approach rate for crosswind forecast threshold values of 2 and 4 m/s.

Table 14 – Monte Carlo simulation results for the proportion of ATC-Wake approaches and the missed approach rate for minimum crosswind forecasts of 2 and 4 m/s

Case	Explanation	Crosswind threshold (m/s)	ATC-Wake mode (%)	MA rate (%)
0	Standard case	2	76	20
		4	47	8.4
1a	Improved accuracy of wind forecast	2	62	7.8
		4	30	0.15
1b	Perfect wind forecast	2	61	2.0
		4	28	0
2a	Improved accuracy FAP separation time	2	76	20
		4	47	8.1
2b	Perfect FAP separation time	2	76	20
		4	47	8.1
3	Improved navigation & reduced WV critical area boundary box	2	76	13
		4	47	4.8
4a	Wake vortex vector divided by 2	2	76	6.3
		4	47	2.0
4b	Wake vortex vector divided by 4	2	76	1.3
		4	47	0.36

A number of observations can be made on the basis of Table 14:

- A crosswind forecast threshold value for the ATC-Wake separation mode planner of 2 m/s leads in all cases to missed approach rates of more than 0.2%. Although such a small crosswind threshold value would enable a large proportion (61 to 76%) of the approaches to be performed in the ATC-Wake mode, the small crosswinds would lead to large number of events in which the follower enters the wake vortex critical area of the leader, resulting in ATC-Wake alerts and subsequent missed approach operations.
- A crosswind forecast threshold value for the ATC-Wake separation mode planner of 4 m/s may lead to acceptable missed approach rates, depending on other operational factors. With this threshold value, about 28 to 47% of the approaches are performed in the ATC-Wake mode.

- The accuracy of the wind forecast has a strong effect on the missed approach rate. Improved accuracy (case 1a) can imply 0.15% missed approaches; a perfect wind forecast (case 1b) would imply that no missed approaches due to ATC-Wake alerts occur. The reason is that as a result of the better wind forecast the likelihood of having approaches in conditions with small crosswind values (e.g., 0 to 2 m/s) whereas the crosswind is expected to be more than 4 m/s, is strongly (or even completely) reduced.
- The uncertainty in the arrival time at the final approach point has almost no effect on the missed approach rate (cases 2a and 2b). The explanation is that the effect of the inaccuracy of the crosswind forecast by far dominates the likelihood of an ATC-Wake alert. For instance, the event in which the actual crosswind is only 1 m/s whereas it should be at least 4 m/s implies an increase in the length of the wake vortex by a factor 4. Near the final approach point this can lead to an increase in the length of the wake vortex vector of 6 km from about 2 km (with 4 m/s crosswind) to 8 km (with 1 m/s crosswind). In contrast, a significant change of 20 s in the separation time at the FAP implies a change in separation distance of less than 2 km.
- An improved navigation performance in combination with a smaller wake vortex critical boundary box (case 3) leads to halving of the missed approach rate (for a crosswind threshold of 4 m/s). This is due to the reduction of the wake vortex critical boundary box.
- Reductions in the length of the wake vortex vector (cases 4a and 4b) lead to more than proportional reductions in the missed approach rate.

Subsequently, for cases 0, 1a, 2b, 3 and 4b, the wake vortex risk is evaluated by the WAVIR toolbox (see Table 15). Details of the evaluation are gathered in ATC-Wake D3_6A.

Table 15 – Wake vortex encounter probabilities. Mean and maximum risk: average and maximum of instantaneous risk over trajectory from FAP to 500 m before runway threshold respectively. The crosswind threshold for use of ATC-Wake mode is 4 m/s

Case	**Risk**	**Probability per wake vortex severity class**			
		Minor	**Major**	**Hazardous**	**Catastrophic**
TLS	Mean	5.00E-04	1.00E-05	3.00E-07	9.00E-09
0	Mean	1.15E-04	9.27E-06	1.64E-06	2.05E-09
	Maximum	7.18E-04	6.55E-05	1.12E-05	1.29E-08
1a	Mean	3.65E-05	3.28E-06	6.86E-07	6.53E-10
	Maximum	2.70E-04	2.47E-05	4.80E-06	4.86E-09
2b	Mean	1.24E-04	9.27E-06	1.36E-06	2.22E-09
	Maximum	7.67E-04	6.46E-05	1.09E-05	1.38E-08
3	Mean	1.51E-04	1.10E-05	1.73E-06	2.67E-09
	Maximum	6.20E-04	5.72E-05	1.03E-05	1.12E-08
4b	Mean	1.02E-03	6.42E-05	7.59E-06	1.70E-08
	Maximum	9.00E-03	4.18E-04	4.44E-05	1.62E-07

The simulations also indicate that, provided that certain requirements are met, about 30% of the approaches might be performed with 2.5 Nm aircraft separation in case ATC-Wake is used. The model results show that a sufficiently accurate prediction of the (cross)wind is a sine qua non for the feasibility of the ATC-Wake operation. If the accuracy of the wind forecast is too low, an unacceptably large number of approaches may be initiated in ATC-Wake mode with reduced separation, since the actual crosswind might become smaller than required. The model results show that risk of wake vortex encounters can be reduced quite effectively by the ATC-Wake wake vortex prediction and detection systems and the corresponding alerts provided by the controller to the pilots. However, risk reduction is achieved at the cost of a relatively large number of missed approaches.

Based on the analysis, the bottom line for achieving a separation criterion of 2.5 NM in the ATC-Wake mode is a sufficiently accurate prediction of the crosswind during the approach. This implies that the wind forecast error may not have a bias and the standard deviation of the wind forecast error must be no more than 1.0 m/s. Stated differently, the 95% wind forecast accuracy must then be within 2.0 m/s. This means that the performance of the ATC-Wake Meteorological Forecast system, which has an error near the ground level with a bias of about 1.0 m/s and with a standard deviation of about 1.7 m/s, should be improved. In addition to the improvement of the accuracy of the wind forecast, other requirements that follow from the optimised setting of the ATC-Wake operation are:

- The lateral angle of the wake vortex critical boundary box should be 0.14 degrees. This parameter is a straightforward system setting in the ATC-Wake system.
- The (standard deviation of the) lateral deviations from the ILS during the final approach should be halved with respect to the lateral deviations in the ICAO CRM model [13]. Such an improvement in navigation performance may be supported by continuing developments in navigation systems.

7.3 Single runway departures

7.3.1 Set up of the simulation scenarios

Table 16 gives an overview of how the assessment parameters have been changed over the simulations. See section 7.1 for the leading- and follower aircraft designators. In total, 540 scenarios have been assessed. To determine the minimum crosswind value, above which the separation time for all aircraft combinations can be reduced safely to 90 s, the crosswind is varied between 0 and 5 m/s. Eight generic aircraft types have been defined. Some of their characteristic parameters have been derived from the Eurocontrol Base of Aircraft Data (see Table 17). Three different aircraft in the Heavy and Medium class will be simulated as generator aircraft: a Large jumbo jet, a Wide Body Jet and a Medium jet. Four different follower aircraft will be considered: a Large jumbo jet, a Regional jet, a Medium turbo prop, and a Light Business Jet.

Table 16 – Assessment parameters for the SRD operation

		Assessment Scenarios		
		1 through 96	97 through 192	193 through 288
Assessment parameters	Leading A/C	LAC1	LAC3	LAC4
	Follower A/C	FAC1, 5, 6, 7	FAC1, 5, 6, 7	FAC1, 5, 6, 7
	Lift Off Point LAC	Early, Late	Early, Late	Early, Late
	Lift Off Point FAC	Early, Late	Early, Late	Early, Late
	(Cross)wind [m/s]	0, 1, 2, 3, 4, 5	0, 1, 2, 3, 4, 5	0, 1, 2, 3, 4, 5
	Separation [s]	60, 90, 120, 150, 180	60, 90, 120, 150, 180	60, 90, 120, 150, 180

Table 17 – Aircraft characteristics (derived from the Eurocontrol BADA, Revision 3.6)

#	Name	ICAO CAT	High MassLevel on Take Off [kg]	Nominal Mass Level on Take off [kg]	Wingspan [m]	True Air Speed at FL=0 (kts)	V stall (CAS), at Take Off [kts]	V stall (CAS), Initial Climb [kts]
1	Large jumbo jet	H	372000	300000	60	186	140	149
2	Wide body jet	H	287000	208700	60	157	117	125
3	Wide body jet	H	181400	150000	45	164	122	136
4	Medium jet	M	68000	58000	36	168	125	131
5	Regional jet	M	43090	38000	30	148	110	110
6	Med turbo prop	M	20820	18000	30	132	86	92
7	Light Buss. Jet	L	6025	6000	16	122	90	90
8	Light Turbo Prop	L	4700	4100	14	123	79	83

Figure 31 shows the vertical profile for different types of aircraft (BADA 3.6), where the longitudinal axis specifies the distance of the climbing aircraft from lift off. It is assumed that the aircraft follow a 'nominal' climb profile, as specified in BADA 3.6, i.e. in reality the climb rate could be higher or lower than used.

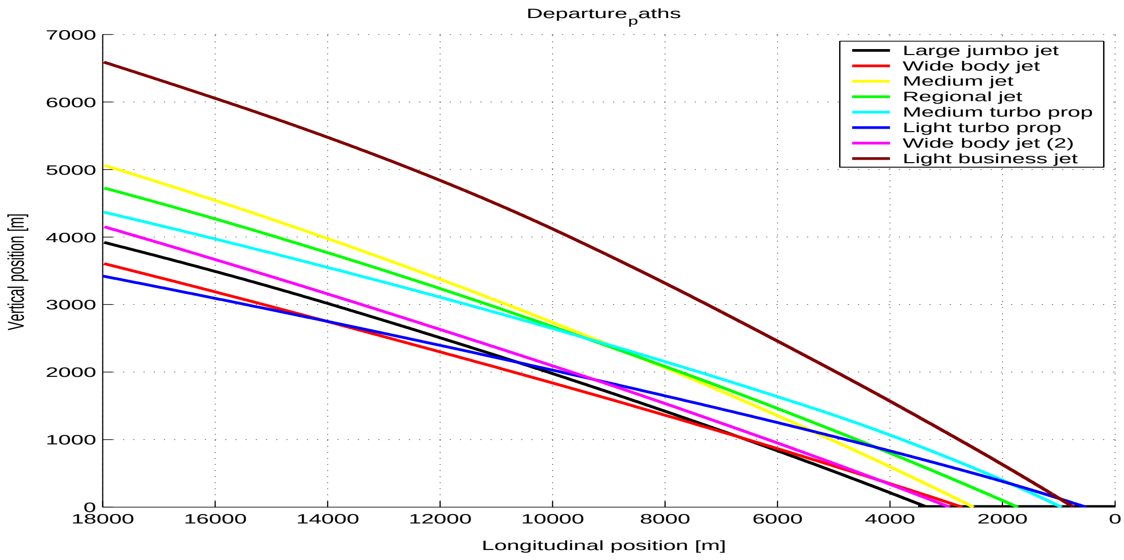


Figure 31 – Vertical profiles of departing aircraft types based on the BADA database

These aircraft speed profiles and climb rates are generated using the Eurocontrol Base of Aircraft Data (BADA), which provides FAR Take Off Length, true airspeed (TAS) and rate of climb for a specified flight level. Combining these numbers, one can compute the height, and longitudinal position as a function of time for different kinds of aircraft performing a departure.

The rotation points for the different aircraft types depend on several factors, including take off weight, engines, wind (speed and direction), air temperature and pressure, runway characteristics (length, gradient and humidity), and thrust settings. A derated take off, using the extra available length of a runway, is often applied by the pilot – at the request of airlines – to minimise the load on the engines (which increases their life time). In the simulation scenarios, the following is assumed (see also Table 18):

- The Take Off Position (TOP) of the leader and follower are both equal to the Runway Threshold (i.e. the Runway Entry Point to be specified in WAVIR is equal to 0 (zero)).
- The Minimum Lift Point of an aircraft is smaller than the Take Off Length (TOL) (from BADA, Revision 3.6) and estimated under the assumption of a non-derated take off.
- The Maximum Lift Off Point of an aircraft departing at Schiphol runway 24 (with a runway length of 3500 m) is estimated through the use of expert opinion (D3_6B).

Table 18 – Estimated lift off points of different aircraft types (at Schiphol runway 24)

#	Name	Cat	Take Off Length	Early Lift Off Point (non-derated take off)	Late Lift Off Point (e.g. using intersection take off or derated)
1	LJJ	H	3320	2100	3000
2	WBJ6	H	2925	2000	2700
3	WBJ7	H	2700	1900	2500
4	MJ	M	2500	1500	2300
5	RJ	M	1715	1200	2200
6	MTP	M	940	700	1800
7	LBJ	L	727	600	1600
8	LTP	L	506	400	1400

7.3.2 Overview of main results from the simulations

The full details of the quantitative safety assessment are provided in ATC-Wake D3_6B. An important departure specific and aircraft dependent parameter is the lift-off point. In the assessment a distinction has been made between early and late lift-off of the aircraft. The variation of lift-off points results in a variation of departure tracks. When the follower aircraft lifts off early behind a leader aircraft that lifts off late, the departure path of the follower aircraft well exceeds that of the leader aircraft, and as a consequence the associated risks are low. To stay on the conservative side, the risk results have been maximised over the variation in lift-off point before deriving the safe separation minima as presented in Figure 32.

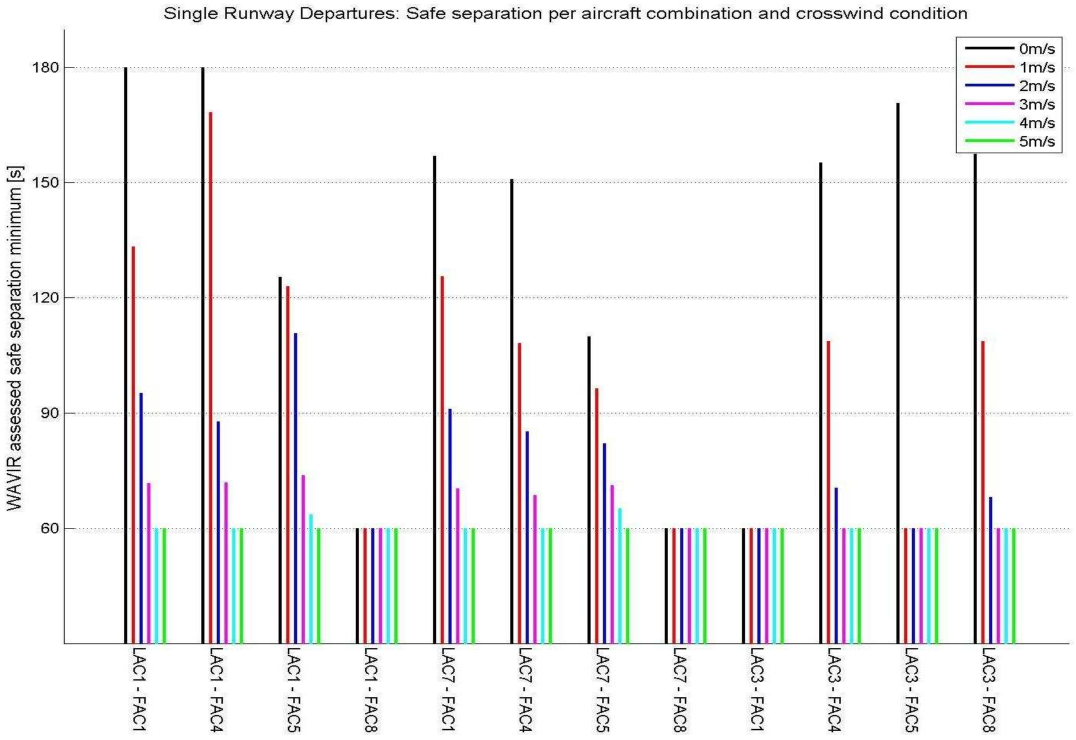


Figure 32 – Overview of WAVIR assessed safe separation minima for the SRD operation

The associated risk results are presented in Appendix B. The variety of flight tracks in the departure operation, because of differences in aircraft climb performance and lift off points, results in a number of interesting observations. For example, it appears that a Light business jet behind a Large jumbo jet might be separated with just 60s. Taking into consideration that ATC-Wake Mode should be applied to all aircraft combinations, Table 19 indicates safe separation minima for certain crosswind intervals. Please note that these are indicative numbers that do not take into account uncertainty in the crosswind conditions, safety margins and other factors that may influence safety. Also, it is assumed that these separations may only be applied in case the ATC-Wake system is used, and the system components meet certain performance requirements. Reduced separation of 90s may be applied when crosswind exceeds 3m/s, while 60s separation can be applied with crosswind above 5m/s.

Table 19 – Indicative separation per crosswind interval for the SRD operation

Crosswind interval	**Proposed wake vortex separation**
$0 \leq u_c \leq 2$m/s	ICAO
$2 \leq u_c \leq 3$m/s	120s
$3 \leq u_c \leq 5$m/s	90s
5m/s $\leq u_c$	60s

7.4 Closely spaced parallel runways

7.4.1 Set up of the simulation scenarios

The assessment of the CSPR arrival operation has been performed for a runway lay-out with 384m lateral spacing and no displaced threshold. Aircraft types that have been considered as leader are the Large jumbo jet, Wide body jet, and Medium jet while the Large jumbo jet, Wide body jet, Medium jet, Regional jet, Medium turbo prop, and Light turbo prop all have been evaluated as follower aircraft. In case of parallel runways, particularly dangerous wake vortex encounters may occur if the vortex is transported by the crosswind from the upwind to the downwind runway. To investigate those crosswind values that could be hazardous and those that safely allow reduced separation, crosswinds of 1, 3, 5, 7, and 9m/s have been evaluated. This relates to a crosswind speed at 10m altitude. A logarithmic profile with altitude is assumed. To analyse the wake vortex induced risk as a function of the reference separation distance, controlled at the runway threshold, separation has been varied between 2.0, 2.5, 3.0, and 4.0NM. Table 20 summarises the assessment parameters.

Table 20 – Assessment parameters for the CSPRA operation

		Assessment scenarios		
Assessment parameters	Leading Aircraft	LAC1	LAC2	LAC3
	Follower Aircraft	FAC1, 2, 3, 4, 5, 6	FAC1, 2, 3, 4, 5, 6	FAC1, 2, 3, 4, 5, 6
	Crosswind [m/s]	1, 3, 5, 7, 9	1, 3, 5, 7, 9	1, 3, 5, 7, 9
	Separation [NM]	2.0, 2.5, 3.0, 4.0	2.0, 2.5, 3.0, 4.0	2.0, 2.5, 3.0, 4.0

The assessment of various aircraft combinations provides information for both the segregated CSPRA operation as proposed in the ATC-Wake concept and the more generic non-segregated operation.

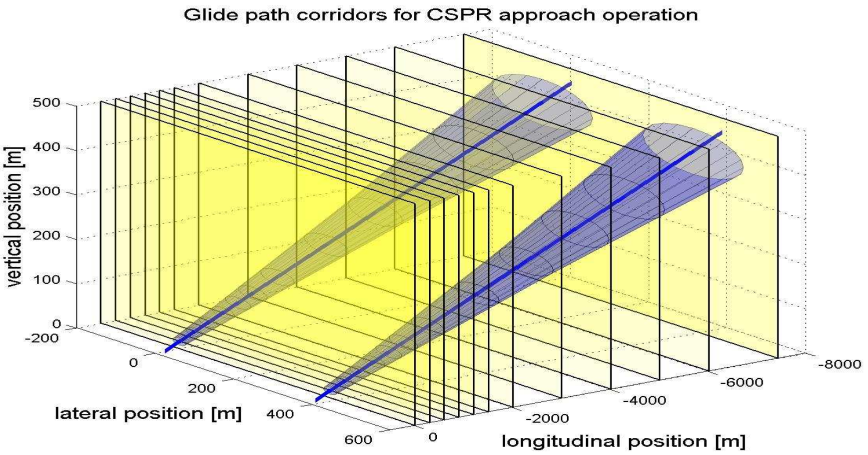


Figure 33 – Flight path corridors based on ICAO-CRM used in the CSPR assessment

7.4.2 Summary of main results from the simulations

For each of the evaluated scenarios the risk results are provided in Appendix C. An overview of the safe separation distances is shown in Figure 34. Considering non-segregated traffic, i.e. both Heavy and Medium aircraft may land on either runway, it appears that a crosswind of 1m/s is too weak to transport the vortices to the adjacent runway. A crosswind of 3 m/s is most critical and for most aircraft combinations the risk at all considered separation distances was too high compared to the risk criteria. Only for combinations of a Medium jet leader aircraft followed by a Large jumbo or Wide body jet the risk appears to be such low that reduced separation is considered safe. In case of 5m/s crosswind, WAVIR assessed separation varies between 2.7NM behind a Medium jet and 3.6NM behind a Large jumbo jet. Crosswind of more than 7m/s does enable separation reduction to 3.0NM or even lower.

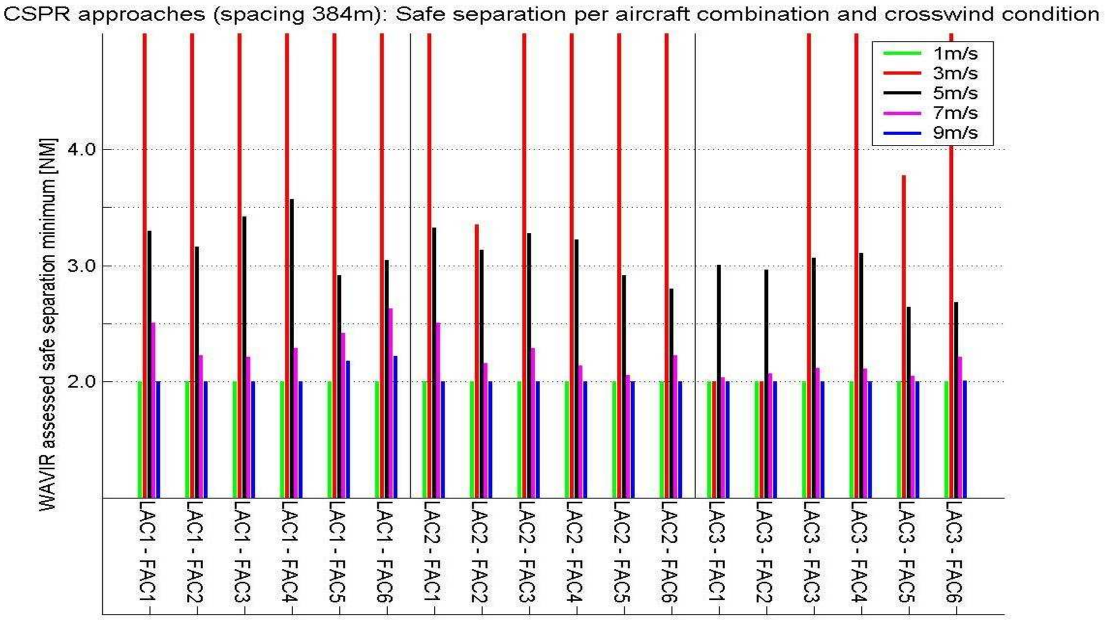


Figure 34 – Overview of safe separation distances for the CSPR arrival operation

Taking into consideration that ATC-Wake reduced separation should be applied to all aircraft combinations and that because of radar separation criteria 2.5NM is minimum spacing, Table 21 indicates safe separation minima for the assessed configuration for certain crosswind intervals (second column). Please note that these are indicative numbers that do not take into account uncertainty in the crosswind conditions, safety margins and other factors that may influence safety.

When considering segregated traffic, i.e. Heavy aircraft (like Large jumbo jet and Wide body jet) are only allowed on the downwind runway, the worst case situation is when the vortices of a Medium aircraft (like Medium jet) on the upwind runway are encountered by a Heavy aircraft (like Wide body jet) on the downwind runway. Following the results as presented in Figure 34, indicative separation minima then become as listed in the third column of Table 21. A less strict segregation of traffic, indicated as 'semi-segregated', may allow Medium aircraft also on the downwind runway. Then, the worst case situation is when the vortices of a Medium aircraft (like Medium jet) on the upwind runway are encountered by a Medium aircraft (like Medium turbo prop) on the downwind runway and indicative separation minima become as listed in the fourth column of Table 21.

Table 21 – Indicative separation per crosswind interval for the CSPRA operation

	Proposed separation		
Crosswind interval	Non-segregated traffic	Segregated traffic (Heavy only on downwind runway)	Semi-segregated traffic (Heavy and Medium on downwind runway)
$0 \leq u_c \leq 1$m/s	2.5NM	2.5NM	2.5NM
$1 \leq u_c \leq 4$m/s	ICAO	2.5NM	ICAO
$4 \leq u_c \leq 6$m/s	4.0NM	3.0NM	3.5NM
$6 \leq u_c \leq 8$m/s	3.0NM	2.5NM	2.5NM
8m/s $\leq u_c$	2.5NM	2.5NM	2.5NM

In all three considered cases, reduced separation may be applied for especially weak crosswinds (in between 0 and 1 m/s) and strong crosswinds (above 8m/s). Segregation of traffic enables reduced separation for all crosswinds while for semi-segregated traffic ICAO separation should be applied when the crosswind is in between 1 and 4m/s. Note that such calculated crosswind intervals strongly depend on the runway spacing.

7.5 Overview of proposed ATC-Wake Mode separations

Indicative separation minima have been derived for each of the 3 ATC-Wake operations, and indicative tables have been derived that link the prevailing crosswind speed to the separation to be applied in ATC-Wake Mode. The results are summarised in Table 22. The crosswind intervals have now been split up to bins of 1m/s width. A crosswind climatology based on 400,000 observations at about 10 European airports has been used to determine the probabilities of occurrence of the crosswind interval. The data source itself is confidential. Crosswind from left and right appeared to be equally likely. The resulting crosswind probabilities listed in Table 22 give an indication about the likelihood of certain (wind) conditions.

Table 22 – Indicative separation per crosswind interval for the ATC-Wake operation

	Proposed separation					**Crosswind probability**
Crosswind interval	SRD operation	SRA operation	CSPRA operation (non-segregated)	CSPRA operation (segregated)	CSPRA operation (semi-segregated)	Crosswind probability per interval
0 ≤ u_c ≤ 1m/s	ICAO	ICAO	2.5NM	2.5NM	2.5NM	0.080
1 ≤ u_c ≤ 2m/s	ICAO	ICAO	ICAO	2.5NM	ICAO	0.208
2 ≤ u_c ≤ 3m/s	120s	2.5NM	ICAO	2.5NM	ICAO	0.206
3 ≤ u_c ≤ 4m/s	90s	2.5NM	ICAO	2.5NM	ICAO	0.164
4 ≤ u_c ≤ 5m/s	90s	2.5NM	*ICAO*	3.0NM	3.5NM	0.118
5 ≤ u_c ≤ 6m/s	60s	2.5NM	*ICAO*	3.0NM	3.5NM	0.081
6 ≤ u_c ≤ 8m/s	60s	2.5NM	3.0NM	2.5NM	2.5NM	0.053
8m/s ≤ u_c	60s	2.5NM	2.5NM	2.5NM	2.5NM	0.090

8 Evaluation of capacity improvements

8.1 Introduction

The potential for the sustainable growth of air transport is inherently linked to the extent to which the ATM network is able to support capacity increases whilst maintaining necessary safety levels. An increase of capacity can be achieved via the implementation of ATC-Wake allowing to reduce the standard ICAO separations. Nevertheless, this may be expensive and a cost-benefit analysis has to figure out what is the balance between an acceptable level of delay and some feasible airport equipment improvements.

8.2 Runway throughput and delay in full ICAO and ATC-Wake Mode

A first estimation of the potential capacity improvements has been established through the use of analytical models based on aircraft spacing, queuing models, and sequencing approximation methods for the arrival and departure flows (D4_5). Table 23, 24, and 25 respectively show departure throughput, arrival throughput, and arrival delay characteristic numbers in case of ICAO separation and in case of ATC-Wake separation.

Table 23 – Departure throughput in case of ICAO or reduced separation (from D4_5)

Configuration	Departure Capacity (ac/h)	% Change
ICAO	37.8	0 % (reference)
ATC-Wake mode (60s)	40.0	6.3 %

Table 24 – Arrival throughput in case of ICAO or reduced separation (from D4_5)

Configuration	Arrival Capacity (ac/h)	% Change
ICAO (2.5 Nm radar separation)	35.2	0 % (reference)
ATC-Wake mode (3.0 Nm)	37.4	6.3 %
ATC-Wake mode (2.5 Nm)	37.7	7.1 %

Table 25 – Arrival delay in case of ICAO or reduced separation (from D4_5)

Configuration	Arrival delay (min)	% Change
ICAO (2.5 Nm radar separation)	3.0	0 % (reference)
ATC-Wake mode (3.0 Nm)	2.0	-33 %
ATC-Wake mode (2.5 Nm)	1.8	-40 %

The comparison of ATC-Wake mode with ICAO operations has shown that (D4_5):

- The arrival capacity increases significantly when changing from standard ICAO wake vortex separations to ATC-Wake mode separations.
- The departure capacity increases significantly when changing from standard ICAO wake vortex separations to ATC-Wake mode separations.
- The average arrival delay decreases significantly when changing from standard ICAO operations to ATC-Wake mode for the same demand level.

8.3 Runway throughput and delay of the ATC-Wake SRA operation

To derive the potential benefits of the ATC-Wake SRA operation at an airport with average (wind) conditions, the statistical data on the occurrence of crosswind at an airport, the ATC-Wake SRA separation schemes as function of crosswind, and the results from the analytical study reported in D4_5 have been combined. The results are provided in Table 26 (throughput) and Table 26 (expected delay).

Table 26 – Expected throughput for the SRA operation

	SRA operation			
Crosswind interval	Separation	Throughput [ac/hr]	Crosswind probability per interval	Weighed throughput
$0 \le u_c \le 1m/s$	ICAO	35.2	0.080	2.8
$1 \le u_c \le 2m/s$	ICAO	35.2	0.208	7.3
$2 \le u_c \le 3m/s$	2.5NM	37.7	0.206	7.8
$3 \le u_c \le 4m/s$	2.5NM	37.7	0.164	6.2
$4 \le u_c \le 5m/s$	2.5NM	37.7	0.118	4.4
$5 \le u_c \le 6m/s$	2.5NM	37.7	0.081	3.1
$6 \le u_c \le 8m/s$	2.5NM	37.7	0.053	2.0
$8m/s \le u_c$	2.5NM	37.7	0.090	3.4
Expected throughput [ac/hr]				37.0
Change compared to reference situation (ICAO)				5.0%

Table 27 – Expected delay for the SRA operation

	SRA operation			
Crosswind interval	Separation	Delay [min]	Crosswind probability per interval	Weighed delay
$0 \le u_c \le 1m/s$	ICAO	3.0	0.080	0.24
$1 \le u_c \le 2m/s$	ICAO	3.0	0.208	0.62
$2 \le u_c \le 3m/s$	2.5NM	1.8	0.206	0.37

3 ≤ u_c ≤ 4m/s	2.5NM	1.8	0.164	0.30
4 ≤ u_c ≤ 5m/s	2.5NM	1.8	0.118	0.21
5 ≤ u_c ≤ 6m/s	2.5NM	1.8	0.081	0.15
6 ≤ u_c ≤ 8m/s	2.5NM	1.8	0.053	0.10
8m/s ≤ u_c	2.5NM	1.8	0.090	0.16
Expected delay [min]				2.15
Change compared to reference situation (ICAO)				-28.5%

8.4 Runway throughput and delay of the ATC-Wake SRD operation

To derive the potential benefits of the ATC-Wake SRD operation at an airport with average (wind) conditions, the statistical data on the occurrence of crosswind at an airport, the ATC-Wake SRD separation schemes as function of crosswind, and the results from the analytical study reported in D4_5 have been combined. Expected throughput is provided in Table 28.

Table 28 – Expected throughput for the SRD operation

	SRD operation			
Crosswind interval	Separation	Throughput [ac/hr]	Crosswind probability per interval	Weighed throughput
0 ≤ u_c ≤ 1m/s	ICAO	37.8	0.080	3.0
1 ≤ u_c ≤ 2m/s	ICAO	37.8	0.208	7.9
2 ≤ u_c ≤ 3m/s	*ICAO*	37.8	0.206	7.8
3 ≤ u_c ≤ 4m/s	90s	38.9	0.164	6.4
4 ≤ u_c ≤ 5m/s	90s	38.9	0.118	4.6
5 ≤ u_c ≤ 6m/s	60s	40.0	0.081	3.2
6 ≤ u_c ≤ 8m/s	60s	40.0	0.053	2.1
8m/s ≤ u_c	60s	40.0	0.090	3.6
Expected throughput [ac/hr]				38.6
Change compared to reference situation (ICAO)				2.1%

8.5 Summary of the runway throughput and delay characteristics

Table 29 provides a summary of the runway throughput and delay characteristics of the SRA, SRD, and CSPRA operations (note that for the latter a distinction is made between non-segregated, segregated, and semi-segregated traffic).

Table 29 – Summary of runway throughput and delay characteristics

	Runway throughput [ac/hr]			**Delay [min]**		
Operation	ICAO	ATC-Wake	Change	ICAO	ATC-Wake	Change
SRD	37.8	38.6	+2.1%	N/A	N/A	N/A
SRA	35.2	37.0	+5.0%	3.0	2.15	-29%
CSPRA (non-segr.)	35.2	35.7	+1.5%	3.0	2.74	-8.6%
CSPRA (segregated)	35.2	37.6	+6.9%	3.0	1.84	-38.7%
CSPRA (semi-segr.)	35.2	35.8	+1.6%	3.0	2.73	-8.9%

All results are promising as already a 1 or 2% increase in runway throughput may lead to substantial economic benefits. The current study focused on crosswind only. Strong headwind conditions (as studied in Time Based Separation) is known to be beneficial as well. It is therefore recommended for future work to focus on elaboration of the current approach towards an evaluation of individual airports with their local weather conditions.

9 Conclusions and recommendations

9.1 Conclusions

With the steady increase in air traffic, civil aviation authorities are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the separation distance between aircraft at take-off and landing without compromising safety. One major limiting factor is that aircraft always give each other a wide berth to avoid eachother wake turbulence. With the aid of smart planning techniques, however these distances can be safely reduced, significantly increasing airport capacity. The IST project ATC-Wake aims to develop and build an integrated system for ATC (Air Traffic Control) that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. As motivation for the use of ATC-Wake, the potential safety and capacity improvements have been analyzed. It has been shown that **runway throughput and delay improves noticeably when the ATC-Wake system is used**. Depending on the occurrence of favourable crosswind conditions, the increase in runway throughput is about 2% for the ATC-Wake SRD operation and 5% for the ATC-Wake SRA operation (at a generic airport with average wind conditions). Introduction of a new ATC system cannot be done without **showing that minimum safety requirements are met**. ATC-Wake risk assessments intend to be compliant with ESARR4 requirements posed by the Safety Regulation Unit (SRU) of EUROCONTROL. Guidelines for development of new wake vortex safety regulation have been given (using a Wake Vortex risk management framework developed in S-Wake).

The safety assessment of the ATC-Wake operation has been performed in three steps. First, as part of the qualitative safety assessment, potential hazards and conflict scenarios related to use of ATC-Wake have been evaluated. Second, through use of the ‘classical’ WAVIR tool, indicative separation minima dependent on crosswind conditions have been determined. As these indicative separation minima do not yet account for crosswind uncertainty, as part of the third step, the setting of requirements for the ATC-Wake system components was further investigated. It appears that the especially the Monitoring and Alerting system and Meteorological Forecast and Now-casting systems are crucial and sufficient accuracy and reliability shall be guaranteed.

WAVIR simulations for the SRA operation indicate that reduced separation of 2.5 Nm might be applied safely in ATC-Wake Mode provided that crosswind is forecasted to be above a certain limit. During ATC-Wake arrivals, the Monitoring and Alerting component will anticipate potential wake encounters in time (and generate an alert); nevertheless if the meteorological forecast information is not accurate and stable enough, this might be achieved at the cost of a relatively large number of missed approaches. The simulations indicate that, provided that certain requirements are met, about 30% of the approaches might be performed with 2.5 Nm aircraft separation in case ATC-Wake is used.

WAVIR simulations for the SRD operation also indicate that reduced separation of 90 seconds can be applied safely in ATC-Wake Mode, provided that crosswind is forecasted to be above a certain limit. If the accuracy of the wind forecast information is too low, the Monitoring and Alerting component could provide a relatively large number of alerts. A potential issue is that immediately after take off, i.e. at relatively low altitude, it will not be feasible for the pilot to turn away from the wake vortex of a preceding aircraft. Provision and use of meteorological now-casting information by the controller will be very beneficial during the second departure phase, in order to support the pilot to prepare for a potential encounter in case of a sudden change of the wind conditions.

Qualitative safety assessment of the ATC-Wake operation

For the operations outlined in the ATC-Wake operational concept, a qualitative safety assessment was performed for single runway departures, single runway arrivals and closely spaced parallel runway arrivals. It was concluded that for these operations there exist some conflict scenarios that may bear potential SAFETY BOTTLENECKS, i.e., the risk may be above a maximum tolerable probability. No definitive answers on the acceptability of the risks were attained in the qualitative safety assessment, as the results included extensive uncertainty bands. Therefore, the analysis was supported with a subsequent quantitative safety assessment with support of mathematical models for aspects of the ATC-Wake operations. Some safety bottlenecks have been identified, enabling adaptation and enhancements of the ATC-Wake operation. The scenarios are:

- Wake vortex encounter during departure;
- Wake vortex encounter during single runway arrival;
- Missed approach during single runway arrival;
- Wake vortex encounter during arrivals on CSPRs;
- Missed approach during arrivals on CSPRs;
- Higher traffic rates in TMA, holding, sector, or on runway;
- Turbulence;
- More landings in crosswind;
- Transitions between ICAO and ATC-Wake Separation Mode;
- Effects on ICAO Separation Mode.

For some of these scenarios, potential enhancements have been proposed, which have been addressed by ATC-Wake operational experts in *WP4 Operational Feasibility* (D4_7).

Development of human operator models

Models for the performance of human operators during single runway arrivals have been developed (in particular for the ATC supervisor, arrival sequence manager, initial approach controller, intermediate approach controller, tower controller and aircraft crews). The models describe monitoring, interaction with ATC-Wake systems and decision making of the controllers and aircraft crews. The human operator performance models have been developed and included in an integrated model, representing the performance of human operators, related aircraft movements, meteorological influences and technical systems (surveillance systems, communications systems and ATC-Wake systems).

Validation of the quantitative safety assessment

To validate the safety assessment method, a number of activities have been carried out:

- A comparison between two wake vortex evolution models (VFS and VORTEX) was made, taking into consideration conditions far and close from the ground. The models seem to predict different behaviour of vortices even for cases without crosswind, i.e. further investigation might be needed in order to better understand this phenomena.
- A comparison between available wake encounter models with different complexity was made, including validation against computed maximum bank angles observed during wake encounter flight simulations. A fair agreement of the results was noted.
- A newly developed Petri-Net (PN) aircraft flight path evolution model was validated against the AMAAI toolset developed for the analysis of in-trail following aircraft. It was concluded that the PN model provides sufficiently accurate results for use in WAVIR.

Quantitative safety assessment methodology

For the quantitative assessment of the wake vortex induced risk related to the ATC-Wake operation with reduced separation, there are three main issues to consider:

- The controller working with the ATC-Wake system has to instruct the pilot to initiate a wake vortex avoidance manoeuvre, in case an ATC-Wake warning/alert is raised.
- If one or more ATC-Wake system components provide wrong or erroneous advice, there will be a higher risk on the presence of (severe) wake vortices. The consequences might be CATASTROPHIC, because reduced separation is applied.
- The separation distance/time will vary along the flight track, and will usually not be exactly the same as the separation minima advised by the Separation Mode Planner.

The 'classical' WAVIR methodology, which originates from S-Wake, has been used to assess wake vortex induced risk. To cope with all the above issues, WAVIR has been extended with a graph and decision theory based structure. A variety of mathematical models and techniques (including fault trees, discrete and continuous Bayesian Belief Nets and vines, and Petri Nets) are introduced to incorporate the role of humans working with ATC-Wake. The details of the model are described in ATC-Wake D3_5b.

Evaluation of safe separation distances and capacity

To determine the crosswind threshold values, above which reduced separation for all aircraft combinations may be applied, three simulation studies have been carried out:

- Single runway arrivals;
- Single runway departures;
- Closely spaced parallel runway arrivals.

Indicative separation minima have been determined for all three operations, and an initial assessment of throughput improvements has been made using analytical models based on aircraft spacing, queuing models and sequencing approximation methods. These indicative separation minima for the three operations are given in the Table below. A crosswind climatology based on 400000 observations at 10 European airports has been used.

Indicative separation minima per crosswind interval for the ATC-Wake operations

	Proposed separation					**Crosswind**
Crosswind interval	SRD operation	SRA operation	CSPRA operation (non-segregated)	CSPRA operation (segregated)	CSPRA operation (semi-segregated)	Crosswind probability per interval
0 ≤ u_c ≤ 1m/s	ICAO	ICAO	2.5NM	2.5NM	2.5NM	0.080
1 ≤ u_c ≤ 2m/s	ICAO	ICAO	ICAO	2.5NM	ICAO	0.208
2 ≤ u_c ≤ 3m/s	120s	2.5NM	ICAO	2.5NM	ICAO	0.206
3 ≤ u_c ≤ 4m/s	90s	2.5NM	ICAO	2.5NM	ICAO	0.164
4 ≤ u_c ≤ 5m/s	90s	2.5NM	*ICAO*	3.0NM	3.5NM	0.118
5 ≤ u_c ≤ 6m/s	60s	2.5NM	*ICAO*	3.0NM	3.5NM	0.081
6 ≤ u_c ≤ 8m/s	60s	2.5NM	3.0NM	2.5NM	2.5NM	0.053
8m/s ≤ u_c	60s	2.5NM	2.5NM	2.5NM	2.5NM	0.090

9.2 Recommendations

Since 2005, application of the European Operational Concept Validation Methodology (E-OCVM) and the use of the Validation Data Repository (VDR) is required by all new EC/EUROCONTROL ATM related projects. E-OCVM provides a common approach to validation of operational concepts as a pre-requisite for industrialisation and operational introduction. *A Safety Case, Human Factors Case, Benefits Case and Technology Case will need to be produced before the ATC-Wake system can be used at European airports.* In this respect, a full Safety Case shall take into account the local airport weather climatology and specific local ATC/pilot procedures for wake vortex mitigation.

During the validation activities, it appeared that both real (measured) data as well as a sufficiently validated aircraft performance and dynamics model for *departures* are not yet available. Sufficient validation of the ATC-Wake single runway departure safety assessment results was therefore not possible. It is therefore recommended to extend the well known AMAAI toolset (developed for EUROCONTROL) for the analysis of in trail following aircraft during arrivals with a module dedicated to departure operations. Wake vortex evolution models and wake encounter models for departures also appeared not sufficiently validated.

In view of the above, actual implementation of the ATC-Wake operation at European airports is envisaged around 2010 at the earliest. It is recommended to involve airport authorities and ATC centres for gathering the required data to build the Safety Case.

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Appendix A Single runway arrivals

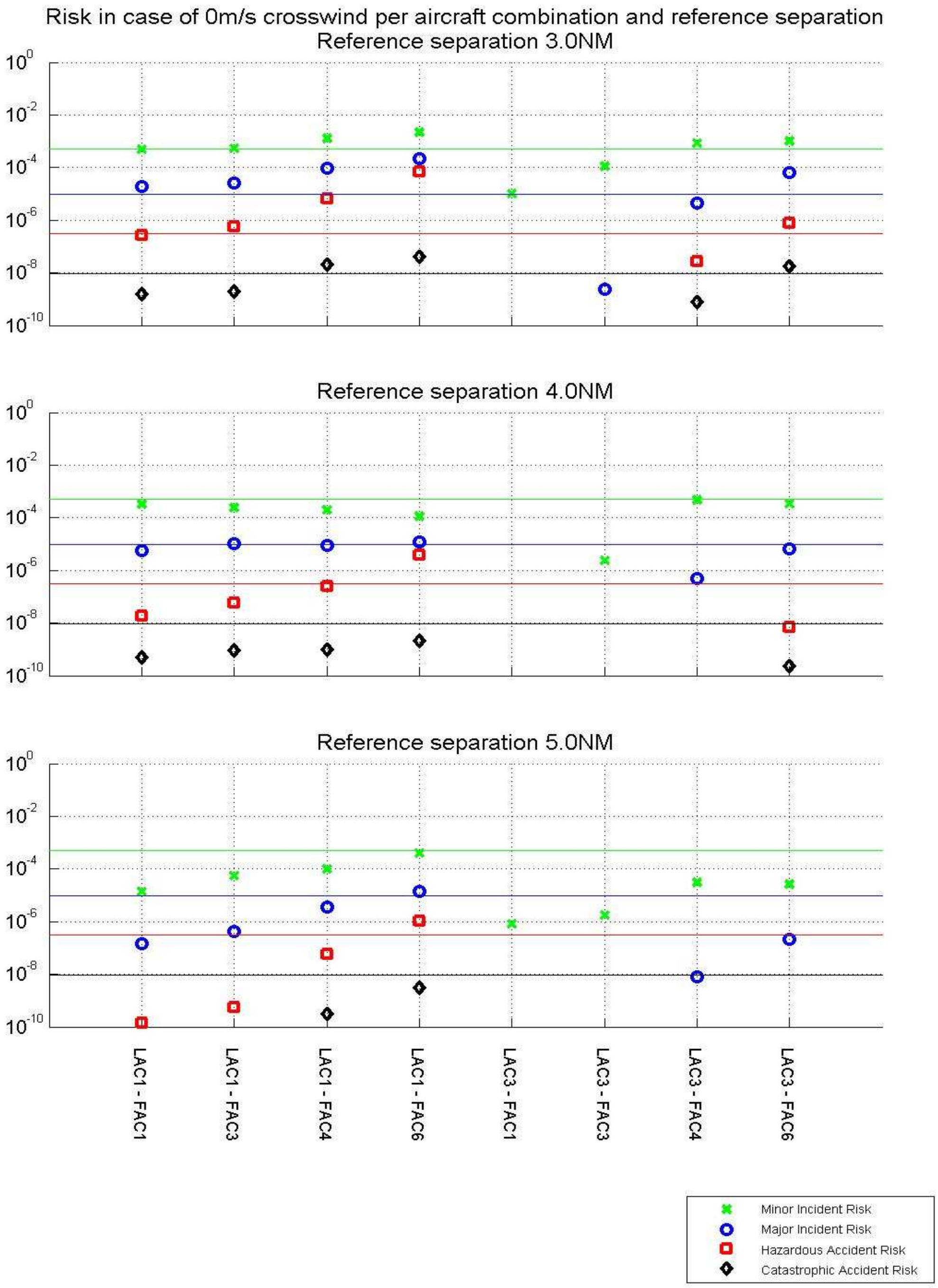

Figure A-1 – Overview of risk results in case of 0 m/s crosswind

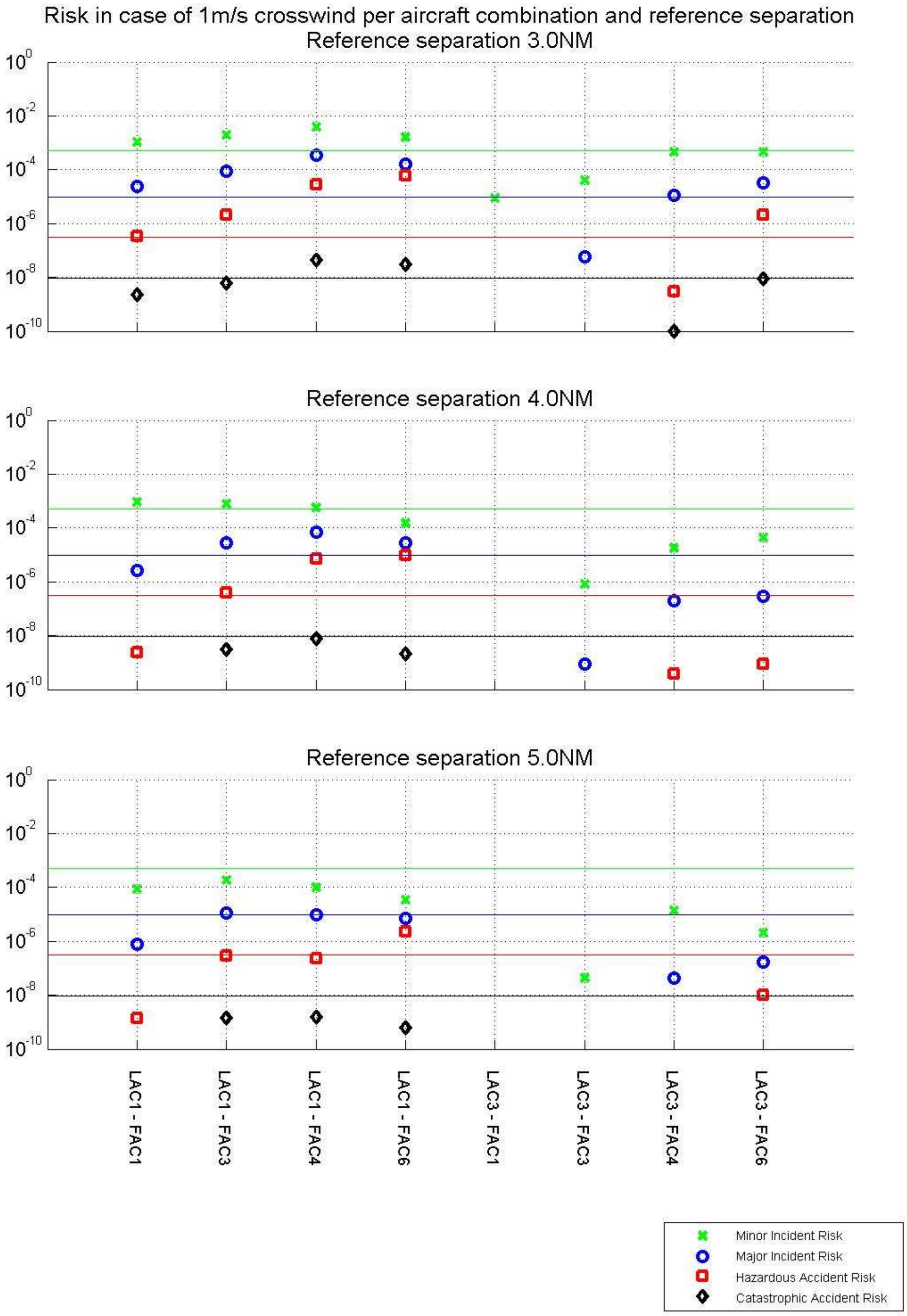

Figure A-2 – Overview of risk results in case of 1 m/s crosswind

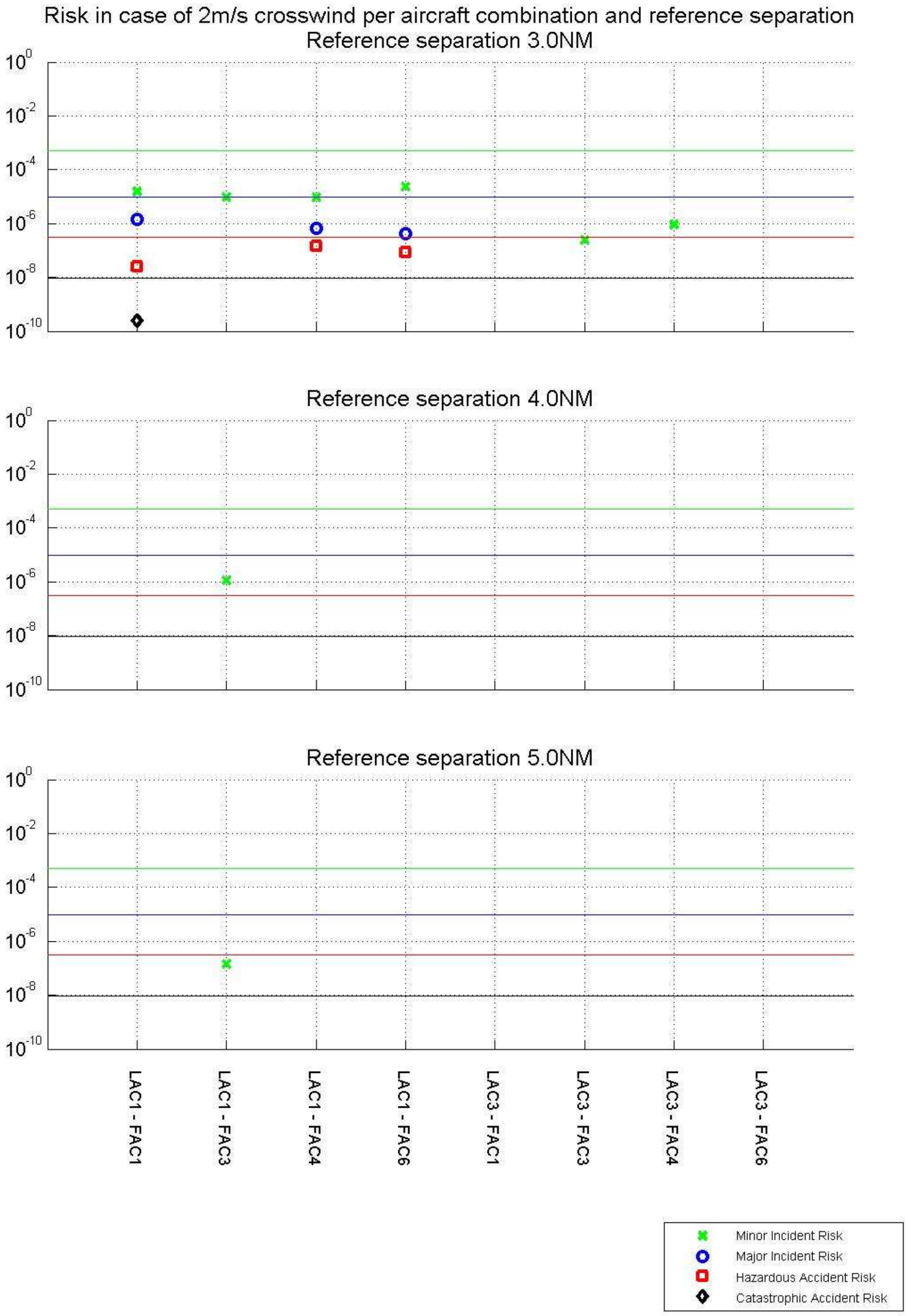

Figure A-3 – Overview of risk results in case of 2 m/s crosswind

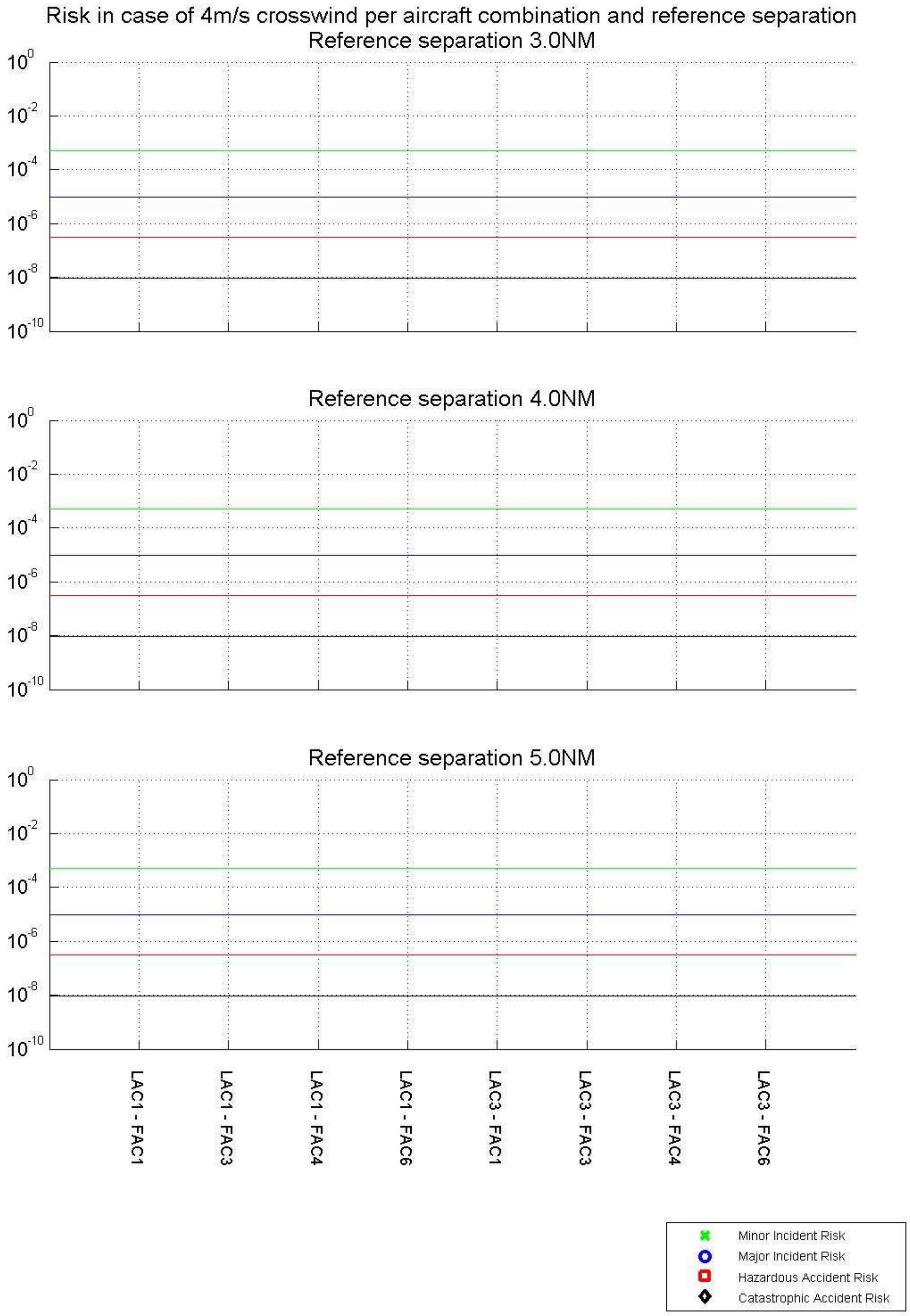

Figure A-4 – Overview of risk results in case of 4 m/s crosswind

Appendix B Single runway departures

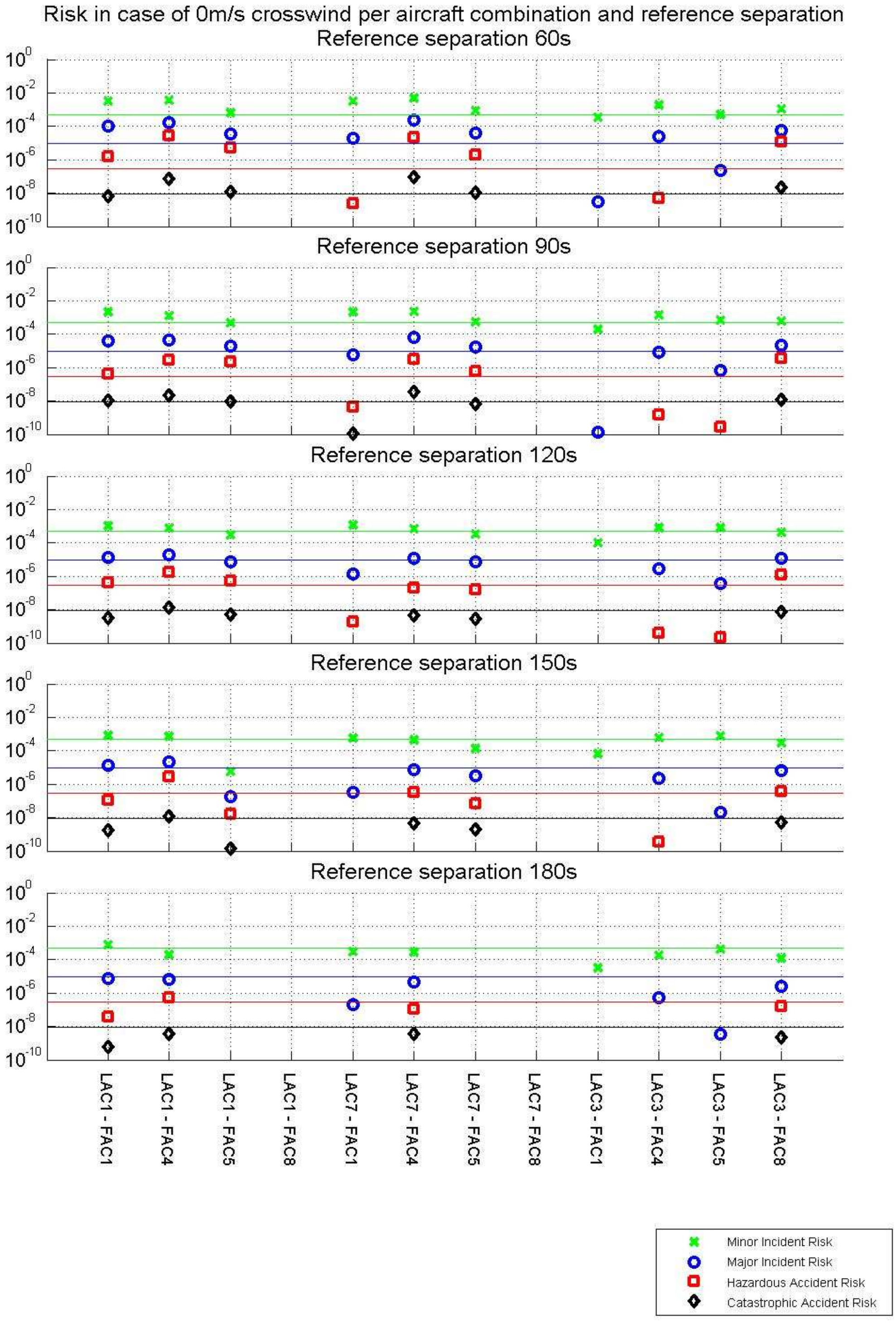

Figure B-1 – Overview of risk results in case of 0 m/s crosswind

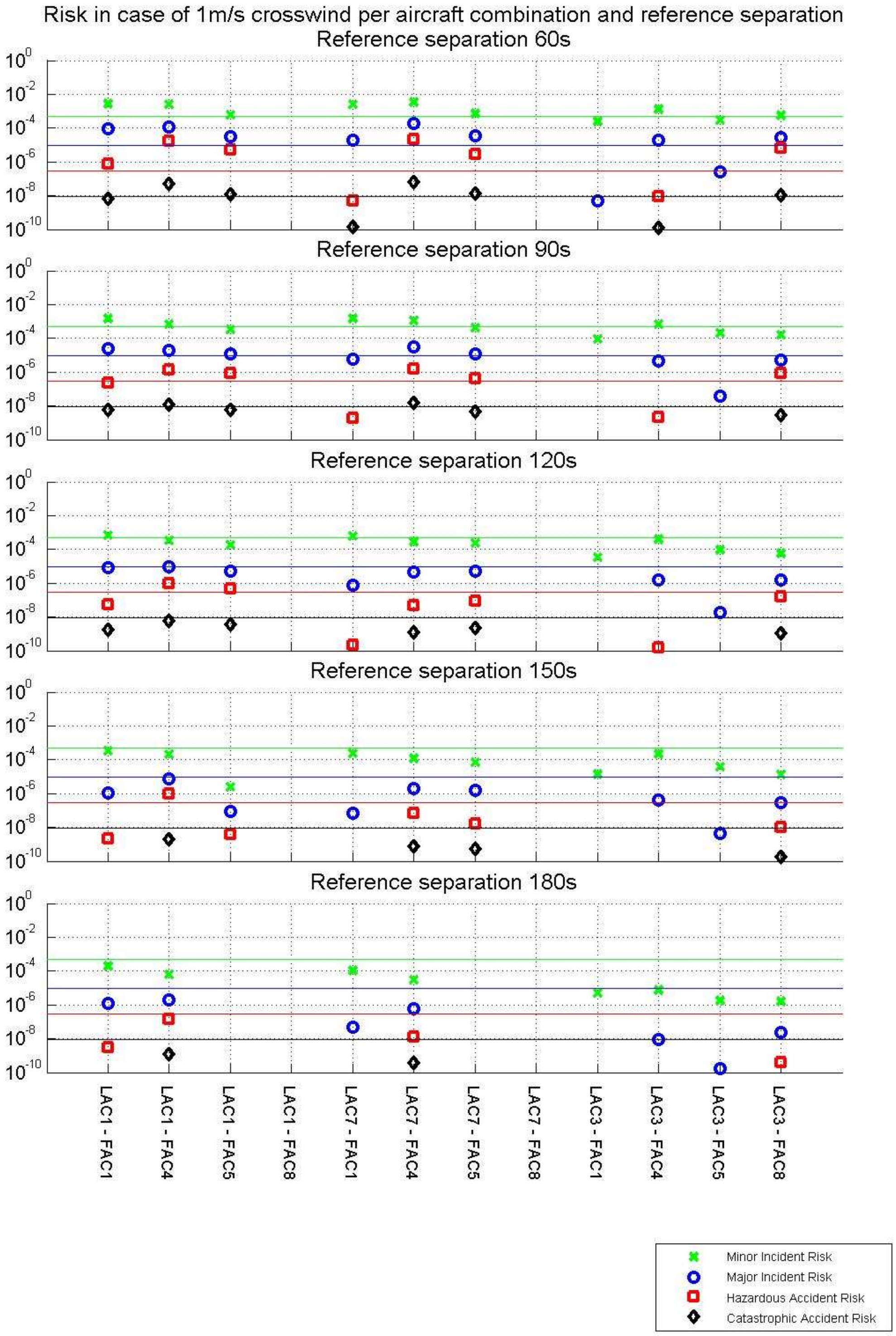

Figure B-2 – Overview of risk results in case of 1 m/s crosswind

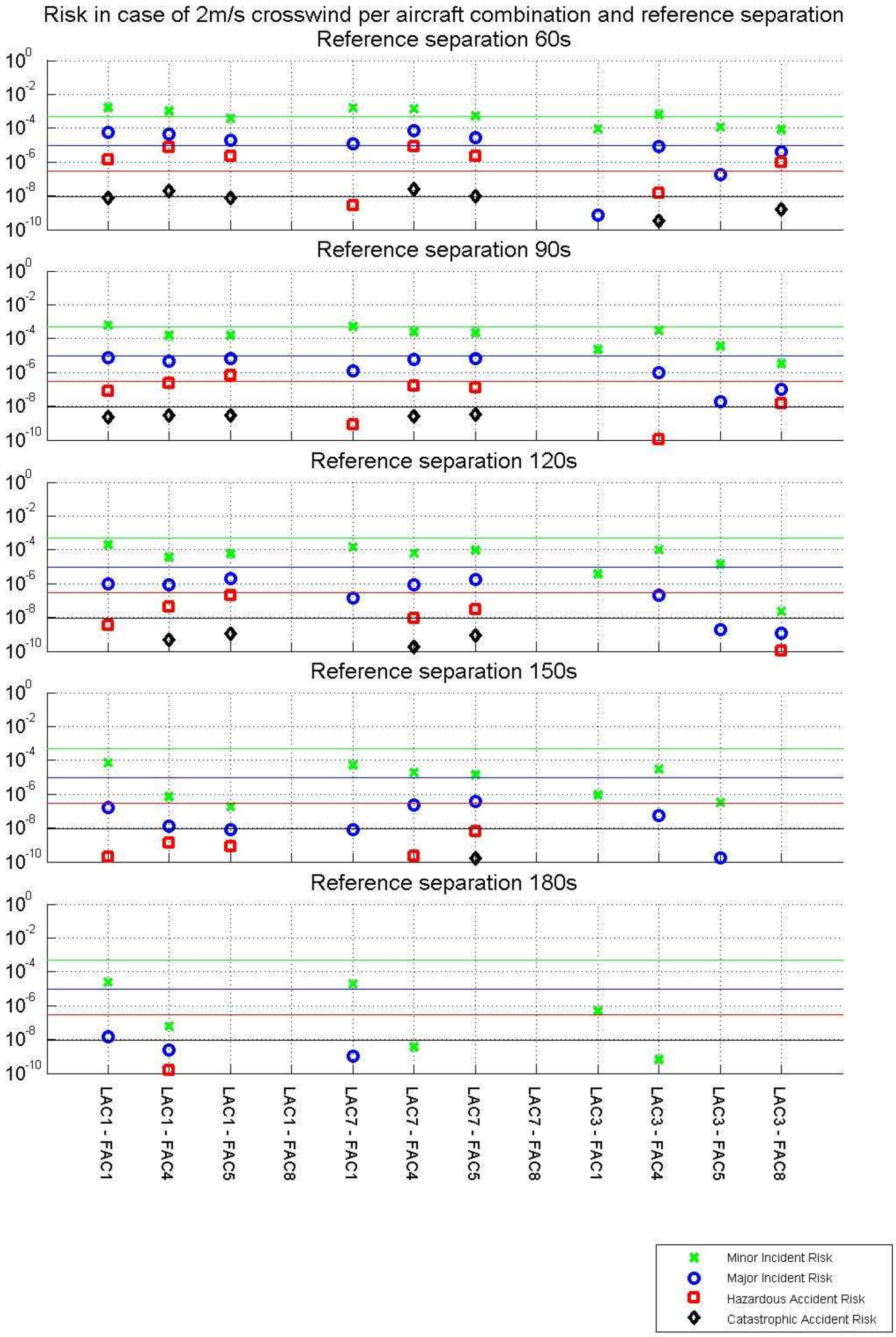

Figure B-3 – Overview of risk results in case of 2 m/s crosswind

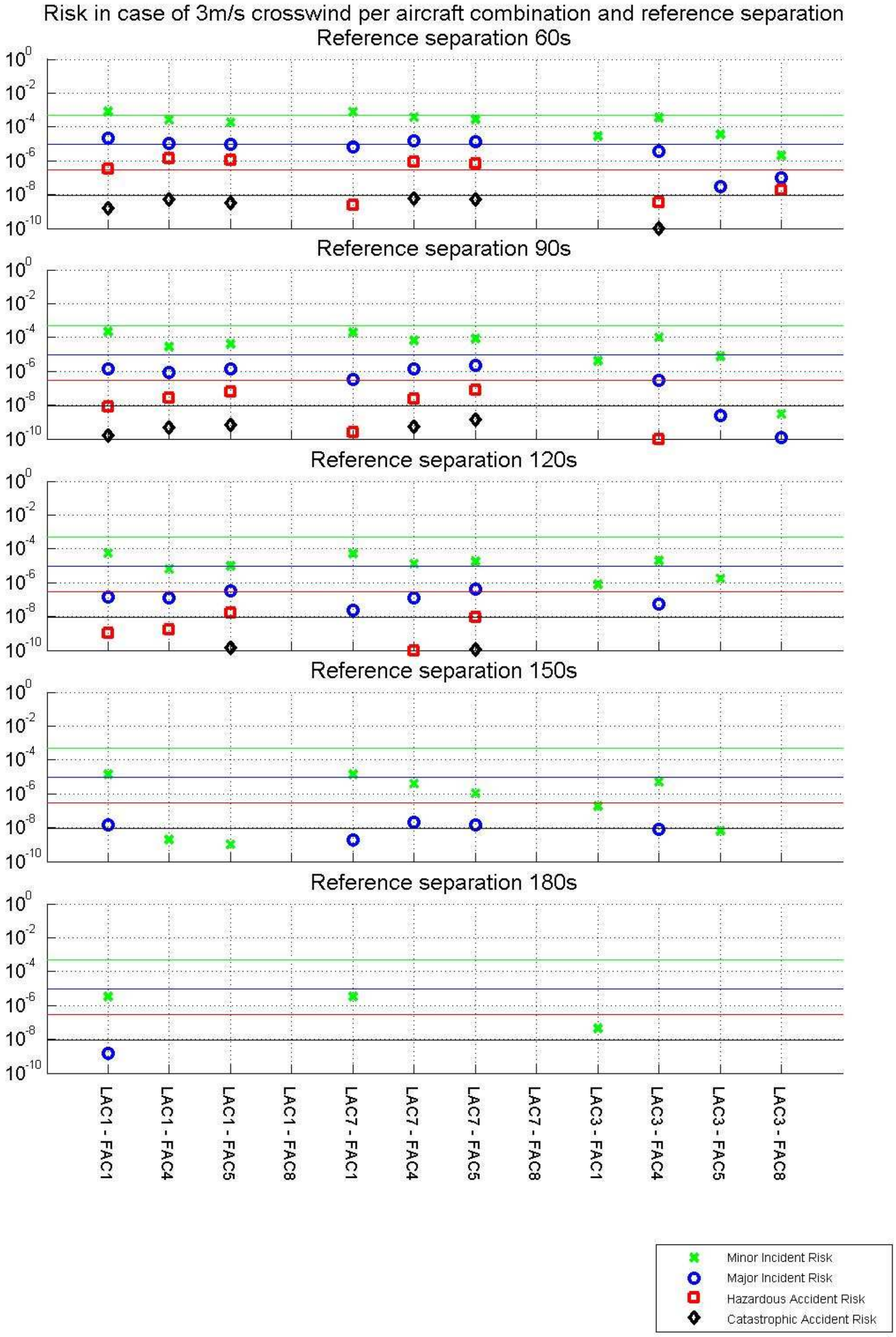

Figure B-4 – Overview of risk results in case of 3 m/s crosswind

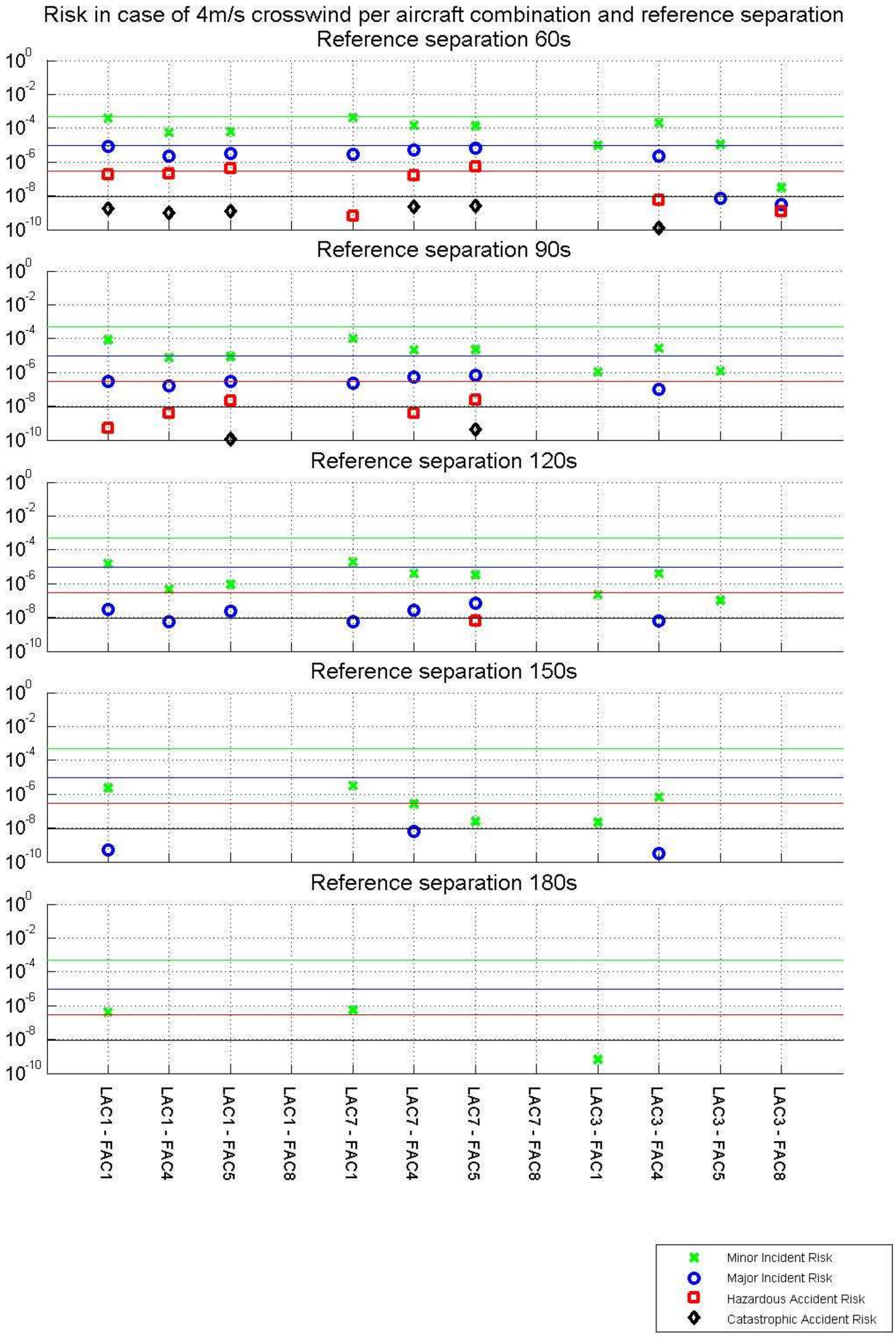

Figure B-5 – Overview of risk results in case of 4 m/s crosswind

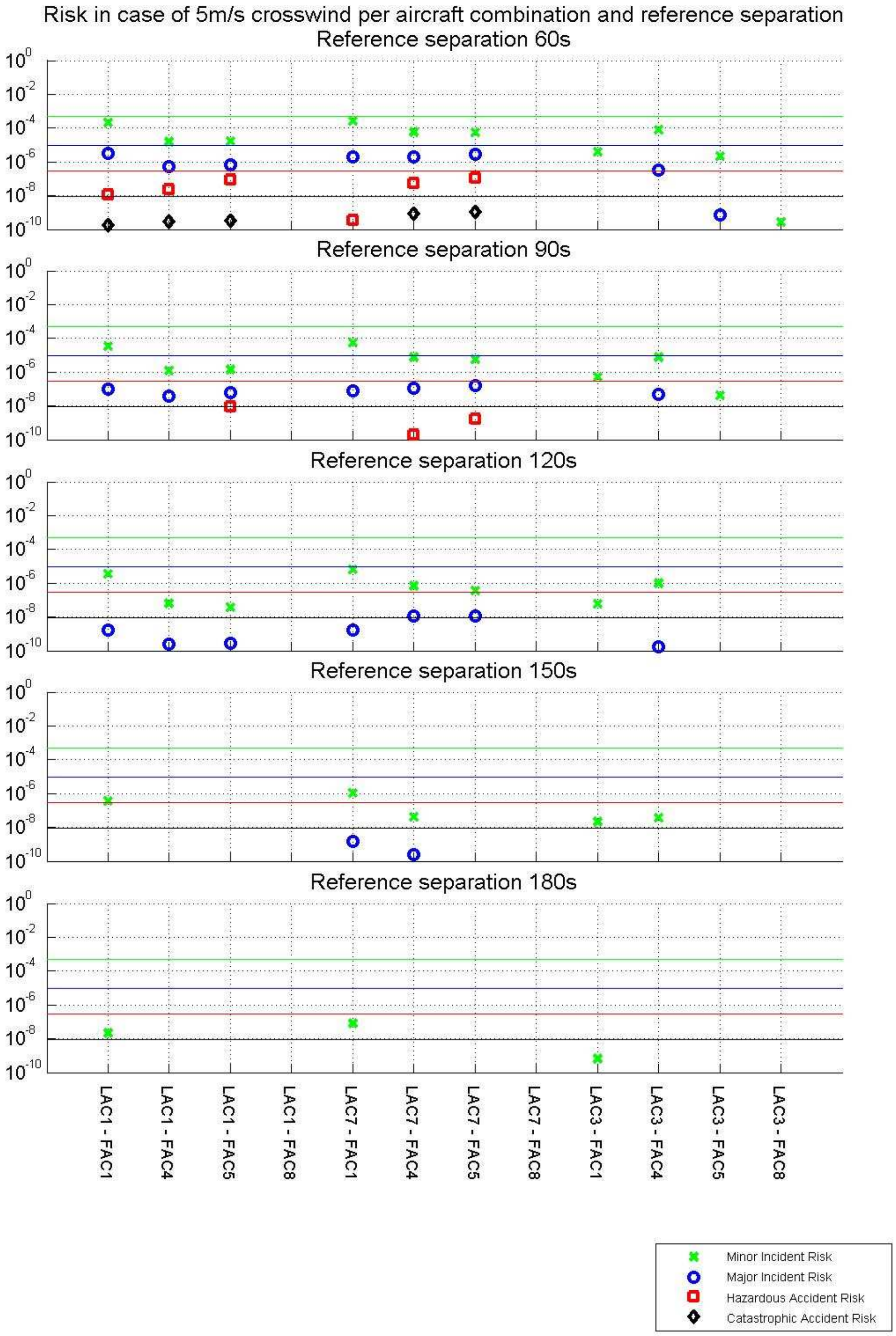

Figure B-6 – Overview of risk results in case of 5 m/s crosswind

Appendix C Closely spaced parallel runways

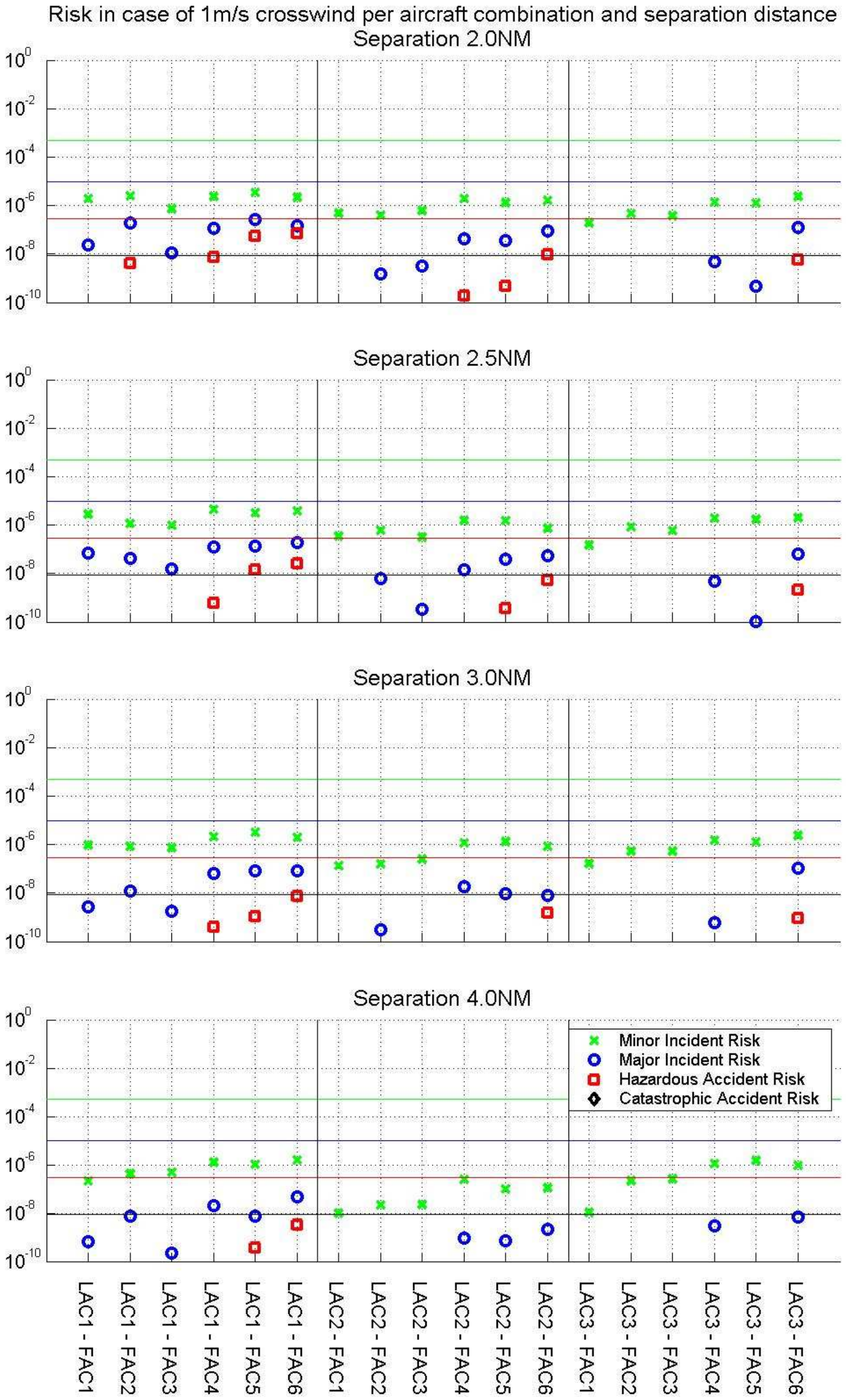

Figure C-1 – Overview of risk results in case of 1m/s crosswind

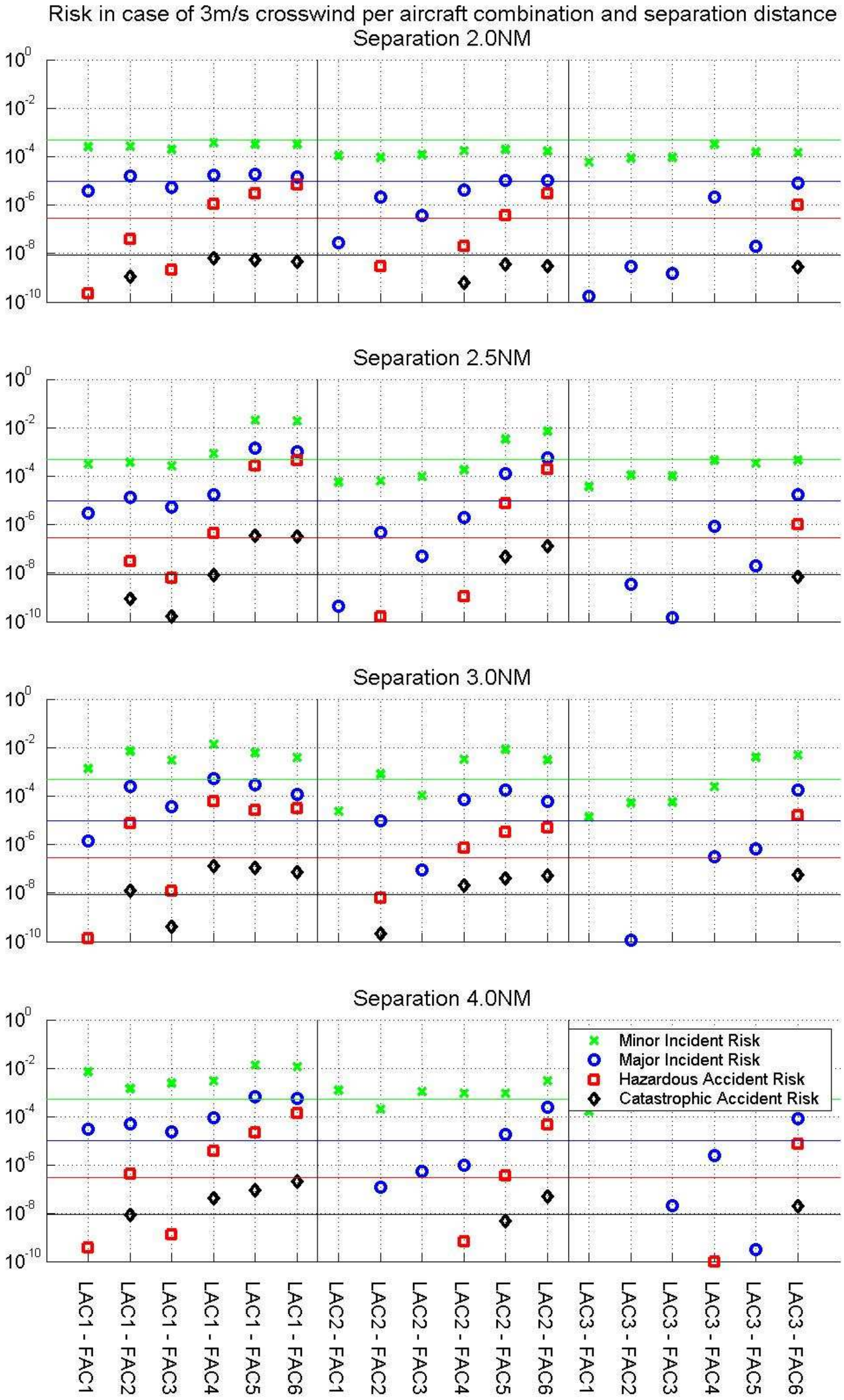

Figure C-2 – Overview of risk results in case of 3m/s crosswind

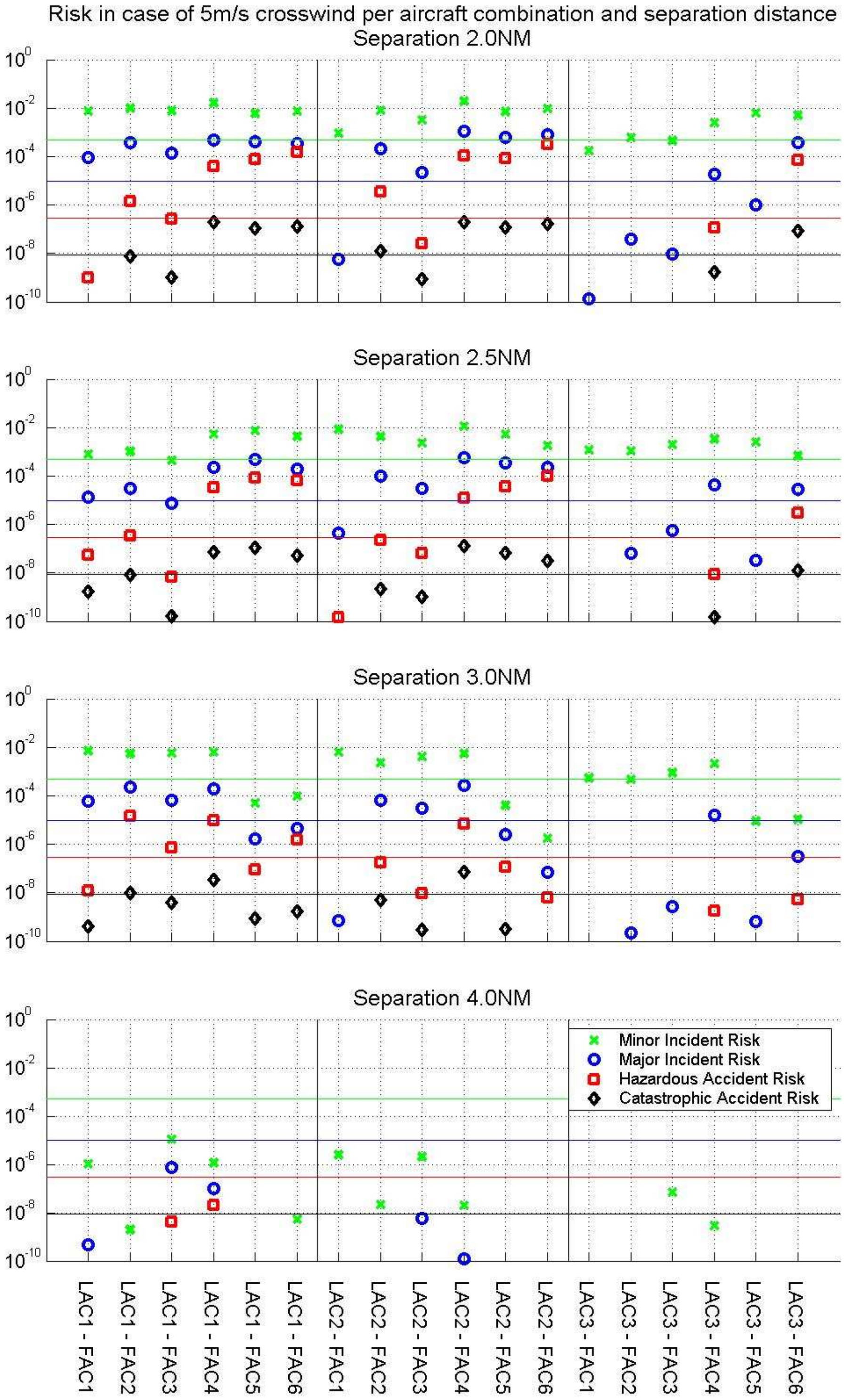

Figure C-3 – Overview of risk results in case of 5m/s crosswind

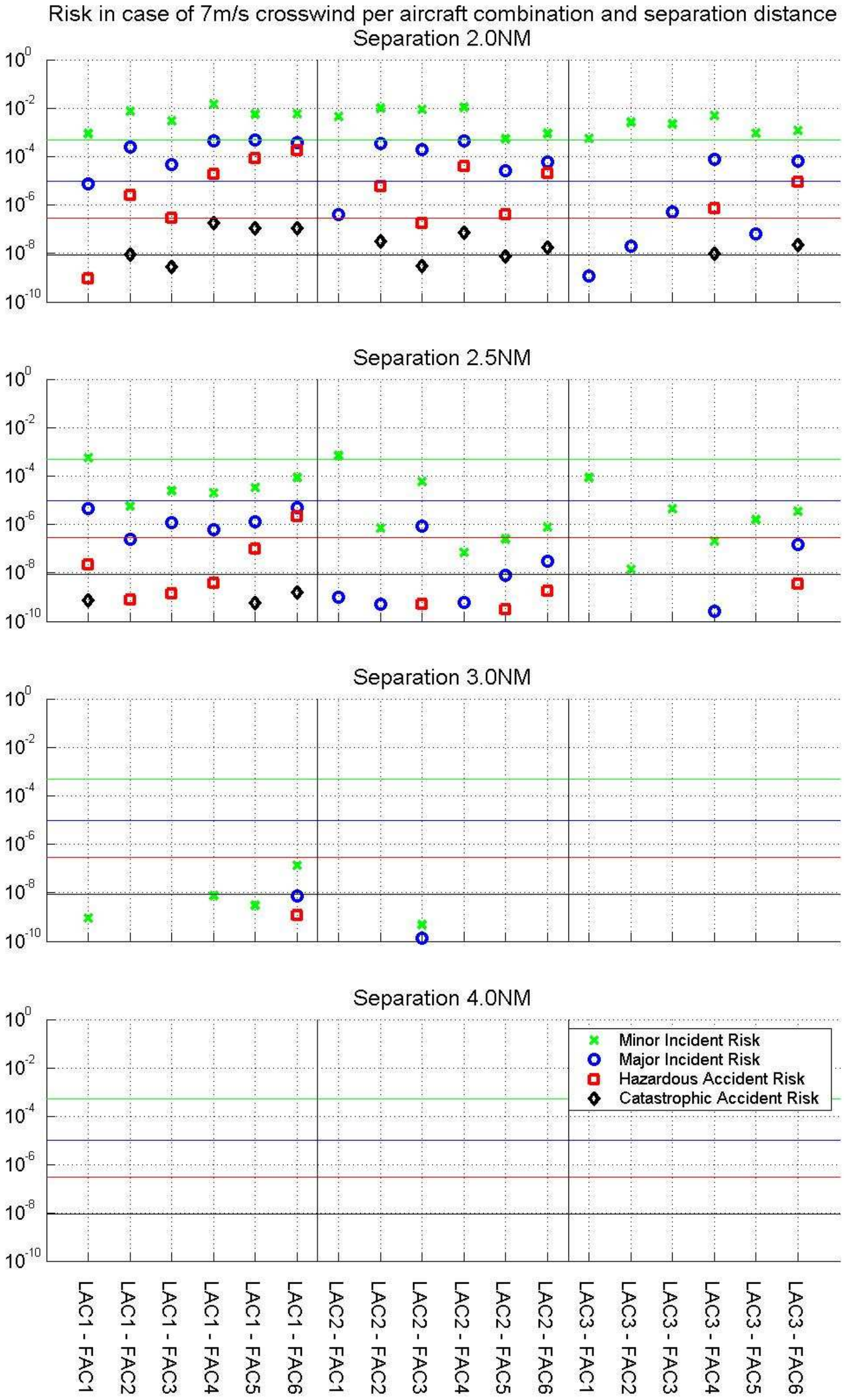

Figure C-4 – Overview of risk results in case of 7m/s crosswind

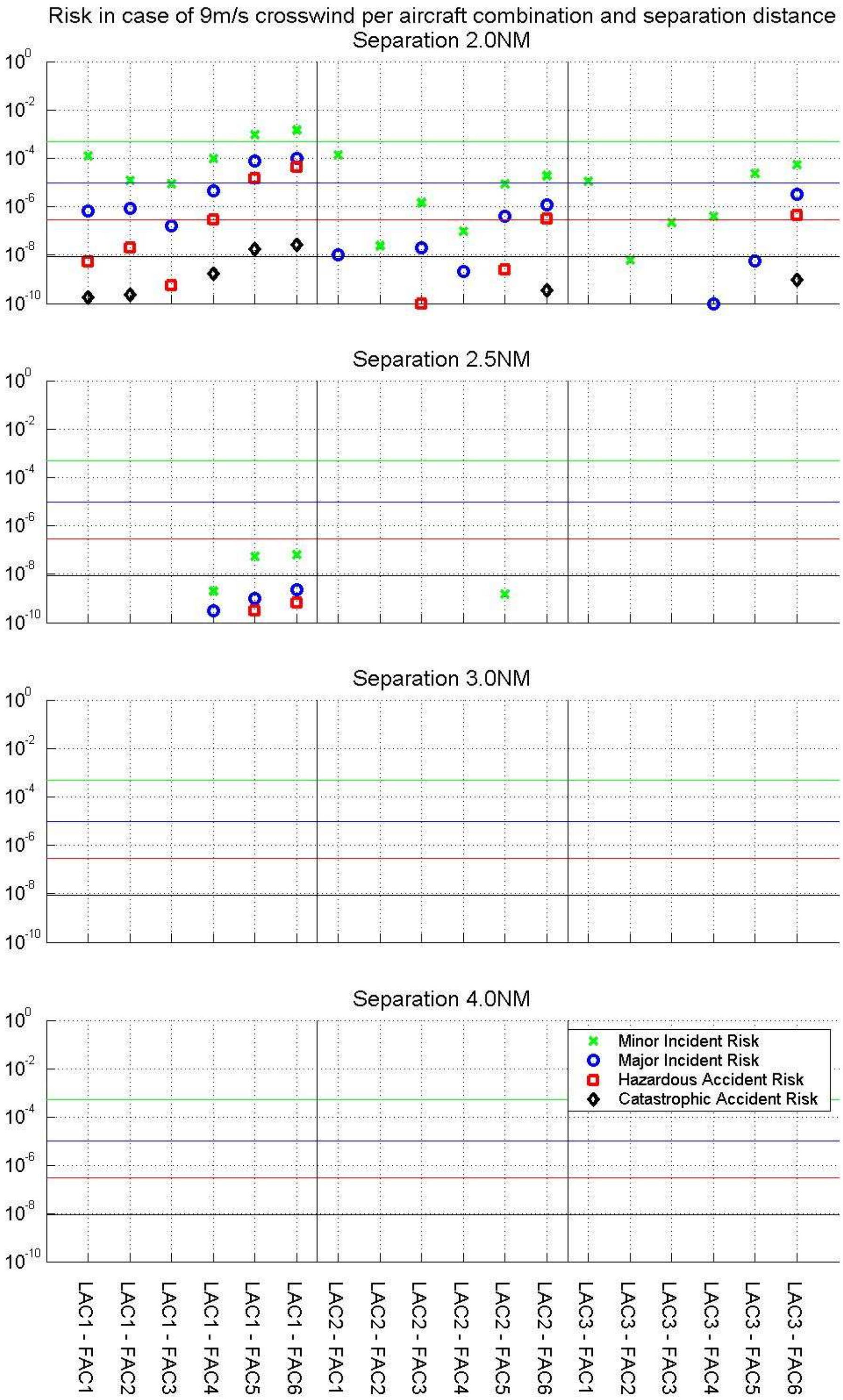

Figure C-5 – Overview of risk results in case of 9m/s crosswind