Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Safety assessment of ATC-Wake single runway departures

Problem area
With the steady increase in air traffic, airports are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the wake vortex separation distance between aircraft at take-off and landing without compromising safety. The European Commission Information Society Technologies project ATC-Wake has designed an integrated system for Air Traffic Control that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. Introducing and/or planning changes to the ATM system cannot be done without providing sufficiently validated evidence that minimum safety requirements will be satisfied.

Description of work
This study has quantified the possible safety implications related to installation of ATC-Wake. This includes an assessment of required crosswind values for which reduced aircraft separation can be applied. The wake vortex induced risk between a variety of leader and follower aircraft, departing under various wind conditions, has been evaluated with the Wake Vortex Induced Risk assessment (WAVIR) methodology and toolset. For the ATC-Wake departure operation with reduced separation, two more issues have been considered:

- The controller working with ATC-Wake will warn the pilot about a potential wake vortex encounter, in case an ATC-Wake alert is raised.
- If the ATC-Wake system provides wrong advice, there is a higher risk on the presence of severe wake vortices. Consequences might even be catastrophic when reduced separation is applied and a light aircraft encounters a severe wake of a heavy aircraft.

Results and conclusions
The present separation of two to three minutes between departing aircraft is designed to ensure that aircraft will not encounter wake vortices of large aircraft. For airports with ATC-Wake in use, the present study indicates that the time separation between aircraft departing at single runways might be reduced to 90 seconds for all aircraft types in the presence of sufficient crosswind. Indicative separation minima dependent on crosswind conditions have been determined. As these separation minima do not yet account for crosswind uncertainty, the setting of

Report no.
NLR-TP-2006-465

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Report classification
UNCLASSIFIED

Date
July 2007

Knowledge area(s)
Veiligheid (safety & security)

Descriptor(s)
safety
atc
wake vortex
departures

The contents of this document have been initially prepared for publication as article in Safety and Reliability for Managing Risk, Guedes Soares & Zio (editors), 2006, by Taylor and Francis Group.

requirements for the ATC-Wake system was further investigated. This was done through a qualitative analysis of the effect of failures of the ATC-Wake system. It was concluded that the Monitoring and Alerting system and Meteorological Forecast and Now-casting systems are crucial and sufficient accuracy and reliability shall be guaranteed. Additionally, it is noted that controllers shall be made very aware that a timely warning to the pilots is also crucial (safety training might help to increase awareness). During the validation activities, it was concluded that both real (measured) data and a sufficiently validated aircraft performance and dynamics model for *departures* are not yet available. 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.

Applicability
A full Safety Case for ATC-Wake departures shall also account for the local weather climatology and ATC/pilot procedures for wake vortex mitigation. In view of this, actual implementation of the ATC-Wake operation at European airports is not envisaged in the short term. It is recommended to involve airport authorities and ATC centers for gathering the required data to build the Safety Case. Follow-up research is foreseen to be performed as part of the CREDOS project, which is a logical successor of ATC-Wake.

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Safety assessment of ATC-Wake single runway departures

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The contents of this document have been initially prepared for publication as article in Safety and Reliability for Managing Risk, Guedes Soares & Zio (editors), 2006, by Taylor and Francis Group.

Customer	European Commission
Contract number	IST-2001-34729
Owner	National Aerospace Laboratory NLR and partners
Division	Air Transport
Distribution	Unlimited
Classification of title	Unclassified
	July 2007

Approved by:

Author	Reviewer	Managing department

Summary

With the steady increase in air traffic, airports are under continuous pressure to increase aircraft handling capacity. The EC IST project ATC-Wake aims to develop and build an integrated system for Air Traffic Control (ATC) that allows variable aircraft separation distances, as opposed to the fixed times presently applied at airports. Introducing and/or planning changes to the ATM system cannot be done without providing sufficiently validated evidence that minimum safety requirements will be satisfied. Therefore, this study quantifies the possible safety implications to be obtained by installation of ATC-Wake. This includes an assessment of required crosswind values for which reduced aircraft separation can be applied. The wake vortex induced risk between a variety of leader and follower aircraft, departing under various wind conditions, has been evaluated with the Wake Vortex Induced Risk assessment (WAVIR) methodology and toolset. For airports with ATC-Wake in use, the present study indicates that the time separation between aircraft departing at single runways might be reduced from two to three minutes to 90 seconds for all aircraft types in the presence of sufficient crosswind.

Indicative separation minima dependent on crosswind conditions are determined. As these separation minima do not yet account for crosswind uncertainty, the setting of requirements for the ATC-Wake system is further investigated. This is done through a qualitative analysis of the effect of failures of the ATC-Wake system, assuming that failure conditions with severe consequences must be extremely improbable and minor failure conditions may be probable. It is concluded that the ATC-Wake Monitoring and Alerting system and Meteorological Forecast and Now-casting systems are crucial and sufficient accuracy and reliability shall be guaranteed. The need for follow-up research is identified, and recommendations for improvements and validation of the safety assessment models are given.

A full Safety Case for ATC-Wake departures shall also account for the local weather climatology and ATC/pilot procedures for wake vortex mitigation. In view of this, actual implementation of the ATC-Wake operation at European airports is not envisaged in the short term. It is recommended to involve airport authorities and ATC centres for gathering the required data to build the Safety Case. Follow-up research is foreseen to be performed as part of the CREDOS project, which is a logical successor to the ATC-Wake project.

Contents

Abbreviations

AMAAI	Modelling toolset for analysis of in-trail following aircraft dynamics
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATC-WAKE	Integrated ATC Wake Vortex Safety and Capacity System (EU project)
ATFM	Air Traffic Flow Management
BADA	Eurocontrol Base of Aircraft Data
CAS	Calibrated Air Speed
CREDOS	Crosswind Reduced Separations for Departure Operations (EU project)
EC	European Commission
EDR	Eddy Dissipation Rate
ERCR	Extended Roll Control Ratio
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
FAC	Follower Aircraft
FAR	Federal Aviation Regulations
FL	Flight Level
GND	Ground Controller
HMI	Human Machine Interface
ICAO	International Civil Aviation Organization
IST	Information Society Technologies
LAC	Leader Aircraft
MTOW	Maximum Take Off Weight
NLR	Netherlands National Aerospace Laboratory
NM	Nautical Mile
QSA	Qualitative Safety Assessment methodology
RAPM	Reduced Aircraft Pilot Model
SID	Standard Instrument Departure
SRD	Single Runway Departure
S-WAKE	Assessment of Wake Vortex Safety (EU project)
TWR	Tower Controller
UK	United Kingdom
USA	United States
WAVIR	Wake Vortex Induced Risk assessment methodology
WV	Wake Vortex
WVV	Wake Vortex Vector

1 Introduction

With the steady increase in air traffic, airports are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the wake vortex separation distances between aircraft at take-off without compromising safety. The ATC-Wake project aims to develop and build an integrated system for Air Traffic Control (ATC) that would allow variable aircraft wake vortex separation distances, as opposed to the fixed times presently applied at airports. The present separation of two to three minutes between departing aircraft is designed to counter problems aircraft may encounter in the wake of large aircraft. For airports with ATC-Wake in use, the aim is to reduce the time separation between aircraft departing at single runways to 90 seconds for all aircraft types in the presence of sufficient crosswind.

The overall objective of this study is to quantify the possible safety implications of using the ATC-Wake system and to assess the required crosswind values for which the “ATC-Wake mode”, with reduced aircraft separation during departures, can be applied (for a safety analysis of the ATC-Wake single runway arrival operation, see reference 23). The wake vortex induced risk between a variety of leader and follower aircraft, departing under various wind conditions, will be evaluated. For the risk assessment of the ATC-Wake departure operation with reduced separation, three main issues have to be considered:

- The controller working with ATC-Wake will warn the pilot about a potential wake vortex encounter, in case an ATC-Wake alert is raised.
- If an ATC-Wake system component provides wrong advice, there is a higher risk on the presence of severe wake vortices. Consequences might even be catastrophic when reduced separation is applied and a light aircraft encounters a severe wake of a heavy aircraft.
- The actual (real) separation time at start of roll will usually not be exactly the same as the separation time advised by the ATC-Wake system.

Introducing and/or planning changes to the ATM system cannot be done without showing that minimum safety requirements will be satisfied. This will be supported by a quantitative safety assessment, based on the WAVIR methodology and toolset (see Speijker [9, 10, 19] and Section 3). The effect of failures of the ATC-Wake system and hazards related to the ATC-Wake operation will be investigated in a qualitative way, with the assumption that failure and/or hazard conditions with severe consequences must be extremely improbable.

Section 2 describes the ATC-Wake single runway departure operation. Section 3 describes the risk assessment methodology. Section 4 contains a description of the simulation scenarios. Risk assessment results are presented Section 5. Section 6 presents the conclusions and recommendations.

2 Single runway departure operation

2.1 Current practice regulations and recommendations

In current ATC operations, there is no exchange of information concerning wake vortices between aircrew and ATC. Control practices are based on ICAO recommendations and national regulation. ICAO separation minima between aircraft are based on Maximum Take-Off Weight (MTOW) of the involved aircraft, distinguishing categories Light, Medium, and Heavy [7]. National regulation exists in the USA and UK. ICAO non-radar separation minima for take off, as applied to aircraft operating behind larger aircraft are presented in Table 2-1. The separation is 3 minutes in case the take off is from an intermediate position on the runway. In all cases, it is up to the pilot to decide whether or not to initiate the take off (start of roll).

Table 2-1 ICAO non-radar separation minima

Aircraft category		**Non-radar separation minima**
Leading aircraft	**Following aircraft**	**Departing**
HEAVY	MEDIUM	2 minutes
	LIGHT	2 minutes
MEDIUM	LIGHT	2 minutes

Separation minima of 3 minutes for departing aircraft apply in case of:

- take-off from an intermediate part of the same runway; or
- take-off from an intermediate part of a parallel runway separated by less than 760 m, see Figure 2-1 below.

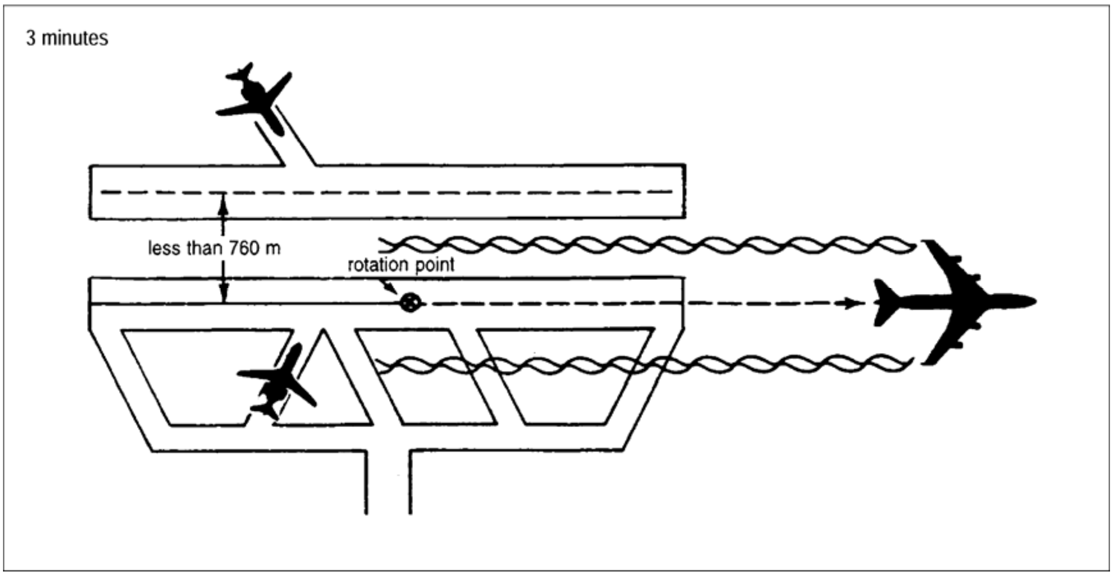

Figure 2-1 Three minutes separation for departing aircraft

2.2 The ATC-Wake departure operation

The objective of the ATC-Wake project was to develop and build an innovative platform with the aim of optimizing safety and capacity. The platform serves as a test bed to assess the interoperability of the ATC-Wake system with existing ATC systems currently used at various European airports, to assess the safety and capacity improvements that can be obtained by applying the system in airport environments, and to evaluate its operational usability and acceptability by pilots and controllers [1, 2, 11, 12, 13, 14, 17, 18]. The ATC-Wake operation consists of two phases that can be summarised as follows [1]:

- Planning Phase or Sequencing: wake vortex prediction information is used together with aircraft separation rules to establish the departure sequence;
- Tactical Phase: wake vortex detection information is used to prevent wake vortex encounter during the take-off phase (up to the end of the initial climb).

In the ATC-Wake operation for single runway departures, two separation modes are defined:

- The baseline mode with ICAO wake vortex separation minima;
- The ATC-Wake separation mode with (reduced) separation minima that depend on the weather conditions but do not depend on aircraft wake vortex category.

For departures, ATC-Wake operations will start at the beginning of the taxi phase and finish at the end of the initial climb phase, including the initiation of the first turn. Wake vortex prediction and detection will cover those areas where the risk of encountering a wake vortex is expected to be relatively high, see Table 2-2. For departures this concerns the area encompassing rotation points (second half of the runway) (Figure 2-2) and the area encompassing the first turn in the climb phase (note that noise abatement procedures might be applicable).

Table 2-2 Wake vortex prediction and detection areas

Type of Area	Description	Position and Size
Departure Area 1	Area encompassing rotation points	Position: 2nd half of the runway Length: 2000m Height: 100 ft
Departure Area 2	Area encompassing first turn in climb phase, e.g. noise abatement procedures	Position: at 10 NM from runway Length: To be determined Height: 3000 – 6000 ft

The risk of wake vortex encounters exists if the aircraft have the same rotation point or if the second aircraft takes off after the rotation point of the first aircraft. The case that a light or medium aircraft encounters a wake vortex generated by the departure of a heavy aircraft can for instance occur when an intermediate runway take-off is performed by a medium or light aircraft. Important wake vortex detection and prediction areas that are to be considered are listed in Table 2-2. The detection is performed along the extension of the runway axis and approximately up to a distance of 10 NM from the runway.

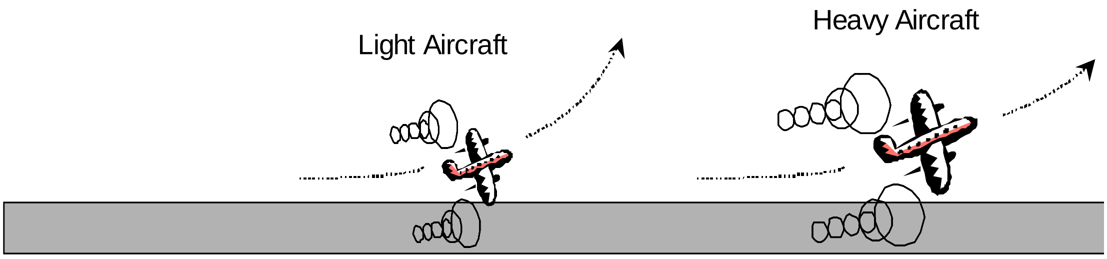

Figure 2-2 Departure rotation points and climb profiles

This initial concept assumes that the first turn takes place at about 10 NM from the runway, mainly due to noise abatement procedures. As noise abatement procedures are airport dependent, so is this location where the first turn can be initiated. Furthermore, this location may vary per Standard Instrument Departure (SID) and depend on the aircraft climb rate.

The ATC-Wake departure operation will influence the roles and responsibilities of the involved actors. Identified actors are ATC supervisor, the Ground Controller, Tower Controller and the aircrew. Table 2-3 presents an overview of these actors with their current responsibility and their specific and/or additional role in the ATC-Wake single runway departure operation.

Table 2-3 Overview of human actors in the ATC-Wake departure operation

Actor	Current Responsibility	Specific/additional Role in ATC– Wake
ATC supervisor	Monitors ATC tower and ground operations.	Decision on arrival and departure rate to be applied.
Ground Controller (GND)	Sequences departures according to landings.	Use wake vortex detection information to optimise departure sequencing.
Tower Controller (TWR)	In charge of final approach, landing and takeoff phases.	Uses wake vortex detection information (now cast) to monitor safe separations between aircraft in the departure phase (up to the first turn) using a vortex vector (display of wake vortex). On basis of wake detection information, the aircraft separation time between departures can be increased.

Actor	Current Responsibility	Specific/additional Role in ATC– Wake
Aircrew	Overall responsible for a safe and efficient flight.	Judges ATC instructions and, if considered safe, will attempt to comply, taking into consideration all factors that may influence the safe continuation of the flight. In case of incompliance, the pilot should file a report to explain his rationale.

Note that an initial climb out profile is chosen by the aircrew from various options. Noise abatement procedures do not overrule the climb out profiles as this would have a direct effect on the safe operation of the flight. It is assumed that ATC-Wake mode is only applied for departures if radar identification of aircraft is available at less than 1 NM from the runway. When the ATC-Wake separation mode is in operation, a separation of 90 seconds (wake vortex transport out of runway area confirmed by detection) between two departures is envisaged. This separation time should take into account the possibility of intersection take-offs. The following chronological order can be identified for the ATC-Wake operation for single runway departures:

1. Based on meteorological conditions and runway configuration, the ATC-Wake system will advise the ATC supervisor about applicable separation mode for a certain runway and associated validity period.
2. The ATC supervisor decides on the separation mode, also taking into account runway configuration and conditions. In case of ATC-Wake mode, the ATC supervisor decides on the separation time between two consecutive departures.
3. The Ground Controller determines the departure sequence taking into account Air Traffic Flow Management (ATFM) slots, departure routes, climb out speeds, and in addition wake vortex prediction information.
4. The Tower Controller uses wake vortex detection information (now cast) to monitor safe separations between aircraft in the departure phase (up to the first turn) using a vortex vector (display of wake vortex). On basis of wake vortex detection information separation time between departures can be increased.

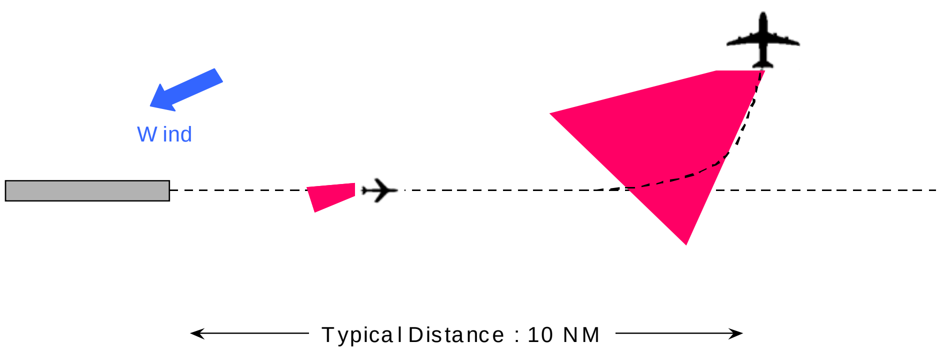

Figure 2-3 Example of vortex vectors for departures

The ATC-Wake system will include four main specific (functional) components (see Table 2-4 and Figure 2-4), which will also interface with several existing ATC system components.

Table 2-4 ATC-Wake System Components

ATC-Wake Separation Mode Planner	Determines applicable separation mode (ICAO or ATC-Wake mode) and advises about minimum aircraft separation distance. The advisory includes 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 departure area(s). The Wake Vortex Vector (WVV) is part of the critical area potentially affected by the wake vortex.
ATC-Wake Detector	Detects for individual aircraft WV position, extent ("vortex vector") and – if possible – also its strength in the critical area.
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

The ATC-Wake system will interface with existing ATC systems, as shown in Table 2-5.

Table 2-5 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).
Flight Data Processing System	Keeps track of flight information and updates, in particular 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)

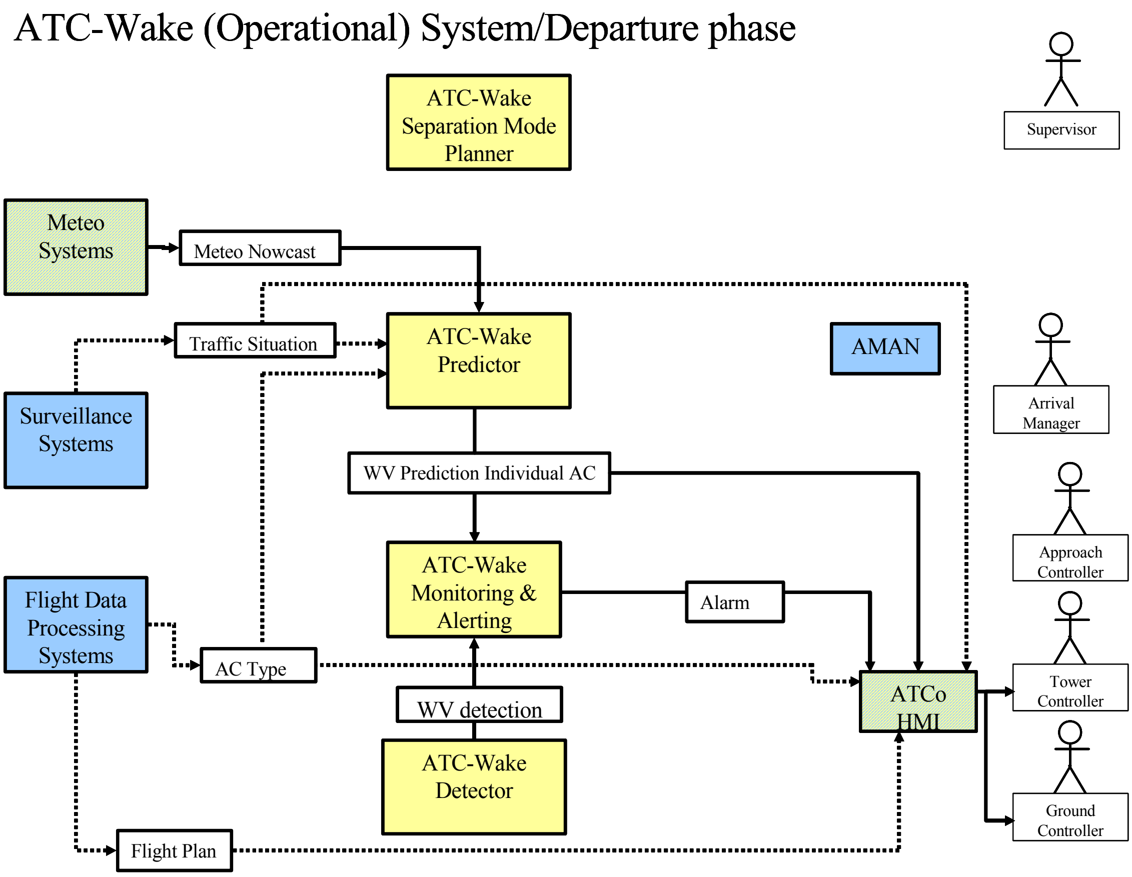

Figure 2-4 ATC-Wake Operational System and its functional flow during the departures

3 Risk assessment methodology

Evaluation of wake vortex separation distances has 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. A probabilistic safety analysis is conducted for a traffic mix of aircraft departing 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. For the risk assessment of the ATC-Wake departure operation, three main issues have to be considered:

- The controller working with ATC-Wake will warn the pilot about a potential wake vortex encounter, in case an ATC-Wake alert is raised.
- If an ATC-Wake system component provides wrong advice, there is a higher risk on the presence of severe wake vortices. Consequences might even be catastrophic when reduced separation is applied and a light aircraft encounters a severe wake of a heavy aircraft.
- The actual (real) separation time at start of roll will usually not be exactly the same as the separation time advised by the ATC-Wake system.

This study considers the first two main issues (the third issue is recommended for follow-up research). The risk assessment is performed in two (sequential) steps:

1. Assess wake vortex induced risk in the case of failure of the ATC-Wake system. The WAVIR methodology is used to determine indicative separation minima dependent on crosswind conditions. In this worst case situation, no wake vortex avoidance manoeuvre is performed by the aircraft/pilot. The uncertainty in flight path and speed of involved aircraft are modeled in the flight path evolution model. The nominal flight trajectories are based on the EUROCONTROL Base of Aircraft Data (BADA, Revision 3.6). The uncertainty about the flight trajectories is based on statistical analysis of aircraft departing at Schiphol airport. The resulting probability distributions of aircraft speed and position are used in the Monte Carlo simulations with the wake vortex evolution and wake encounter models. The resulting probabilities of an encounter in a predefined encounter severity class are used by the risk prediction model to come up with incident/accident risk probabilities. The predicted risk associated for each of four pre-defined risk events (minor incident, major incident, hazardous accident, and catastrophic accident) is the end-result of a WAVIR assessment for a specific scenario. These risk numbers can then be compared with risk requirements to judge whether or not an evaluated scenario is safe. Risk event definitions and risk requirements have been defined during the S-Wake project [9, 10]. The assessment of the wake vortex induced risk is carried out with the risk assessment model described in Speijker [19].

2. Investigate the setting of requirements for the ATC-Wake system. As the indicative separation minima determined in Step 1 do not yet account for crosswind uncertainty and the effect of failures of the ATC-Wake system, a qualitative analysis of ATC-Wake system failures is performed. Requirements can be determined under the assumption that failure conditions with severe consequences must be extremely improbable and minor failure conditions may be probable.

4 Description of scenarios

The setup of the simulation scenarios focuses on wake vortices generated during departures, such that the vortices of the leader aircraft are transported into the flight path of the follower aircraft. Basically, only the first 10 NM after take off is considered, without initiation of a turn within this area. A scenario is defined by all the parameters and variables in the WAVIR tool-set. Basically, the scenarios only differ in the so-called 'assessment parameters':

- Generator – follower aircraft combination;
- Crosswind;
- Lift off point;
- Initial aircraft separation time.

Table 4-1 Assessment parameters for the Single Runway Departure (SRD) operation

		Assessment Scenarios		
		1 through 96	97 through 192	193 through 288
Assessment parameters	Leading A/C	LAC1	LAC3	LAC7
	Follower A/C	FAC1, 4, 5, 8	FAC1, 4, 5, 8	FAC1, 4, 5, 8
	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 4-2 Aircraft characteristics (from EUROCONTROL BADA, Revision 3.6)

#	Name	ICAO CAT	High Mass Level 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 (1)	H	287000	208700	60	157	117	125
7	Wide body jet (2)	H	181400	150000	45	164	122	136
3	Medium jet	M	68000	58000	36	168	125	131
4	Regional jet	M	43090	38000	30	148	110	110
5	Med turbo prop	M	20820	18000	30	132	86	92
8	Light Business Jet	L	6025	6000	16	122	90	90
6	Light Turbo Prop	L	4700	4100	14	123	79	83

The rotation points for the different aircraft types depend on several factors, including take off weight, engines, wind, air temperature and pressure, runway characteristics, and thrust settings. A de-rated take off, using the extra available length of a runway, is often applied by the pilot to minimize the load on the engines (to increase their life time). The following is assumed (see also Table 4-3):

- The Minimum Lift Off Point is smaller than the Take Off Length, and estimated for a non de-rated take off using expert opinion.
- The Maximum Lift Off Point of an aircraft departing is estimated using expert opinion, i.e. operational expert interviews.
- The Take Off Position of leader and follower are both equal to the Runway Threshold.

Table 4-3 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	Large Jumbo Jet	H	3320	2100	3000
2	Wide Body Jet (1)	H	2925	2000	2700
7	Wide Body Jet (2)	H	2700	1900	2500
3	Medium Jet	M	2500	1500	2300
4	Regional Jet	M	1715	1200	2200
5	Medium turbo prop	M	940	700	1800
8	Light Business Jet	L	727	600	1600
6	Light Turbo Prop	L	506	400	1400

Figure 4-1 shows the vertical profile for different types of aircraft, where the longitudinal axis specifies the distance from threshold. 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. The aircraft speed profiles and climb rates are generated using the BADA, which provides Federal Aviation Regulations (FAR) Take Off Length, True Air Speed (TAS) and rate of climb for a specified flight level. Combining these numbers, one can compute height and longitudinal position as a function of time for different kinds of aircraft performing a departure.

The vortex pair behind the generator aircraft is modeled 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 modeled according to Corjon & Poinsot [4]. This includes image vortices and secondary vortices making the vortex pair to diverge and rebound near the ground respectively. The decay function as defined by Sarpkaya [8] is used. Input parameters are Brunt-Väissällä frequency N and Eddy Dissipation Rate EDR. Simulations are 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 UK Met Office [5, 9].

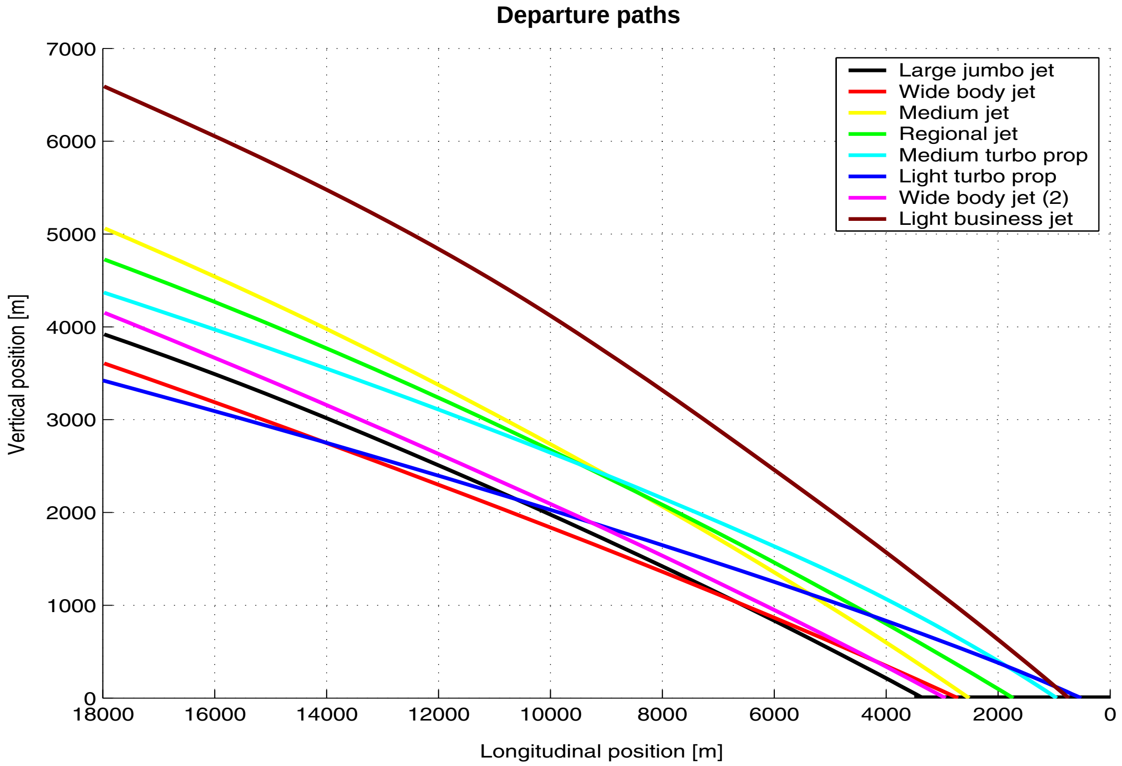

Figure 4-1 Vertical profiles of departing aircraft types based on the BADA database

Two encounter models are available, the Extended Roll Control Ratio model (ERCR) (based on [15] and the Reduced Aircraft Pilot Model (RAPM) (see Speijker [19]). The aircraft dependent parameters for the ERCR and RAPM model are determined for a number of generic aircraft types. In this 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. Wind is simulated assuming a logarithmic wind profile up to an altitude of 1000 ft. Above 1000 ft the wind is assumed to be constant (this is more or less in line with a logarithmic wind profile). The surface roughness is 0.03 m, which is representative for a generic airport environment. The wind value is specified at 10 m altitude. Analysis of wake induced risk is done in a number of longitudinal positions up to 10 NM from the runway threshold, with a focus on the critical areas: the area close to the ground and the area encompassing the first turn in the climb phase.

5 Risk assessment

5.1 Qualitative risk assessment

Table 5-1 provides an assessment of the effect of the ATC-Wake system component failures. The individual classifications are in accordance with the risk classification scheme provided in reference 6 and are based on the assumption that other failure conditions do not occur. A simultaneous failure of two system components could aggravate the situation. Failure conditions with severe consequences must be extremely improbable and minor failure conditions may be probable. A potential safety issue is that shortly after take off, at low altitudes, it will not be feasible for the pilot to turn away from the vortex of a preceding aircraft. Provision of up-to-date meteorological now-casting information to ATCOs is crucial in order to support the pilot to prepare for a potential wake encounter in case of a sudden change of wind. From the individual classifications in Table 5-1, it appears that the most severe failure conditions are related to the functioning of the Monitoring and Alerting system and the Meteorological Now-casting systems. These system components are crucial and sufficient accuracy and reliability shall be guaranteed. Additionally, it is noted that controllers should be made very aware that a timely warning to the pilots is also crucial (safety training might help to increase the awareness).

Table 5-1 Effect of main ATC-Wake system/operation failure conditions

Description	Effect	Classification	Comment
Pilot/aircraft not able to turn timely: The pilot/aircraft is not able to timely perform an avoidance maneouvre, after it is requested by the controller. This could occur in case of a warning when the aircraft is still in initial take off, i.e. limitations in bank angle will apply.	An unfavorable 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 in close proximity to ground could occur for light aircraft.	MAJOR – SERIOUS INCIDENT	The wake vortex is stronger closer to the generating aircraft. An encounter with 90 seconds separation will result in more severe consequence than in ICAO Mode. The pilot is prepared for a Wake Vortex Encounter.
Controller does not provide a timely warning to the pilot: ATCo 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 unfavorable 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 90 seconds (i.e. reduced) separation will result in more severe consequence than under ICAO separations.

Description	Effect	Classification	Comment
Loss of Monitoring and Alerting 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 and 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 90 seconds (i.e. 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 meteorological 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 (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 aircraft type (or associated 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.
Faulty or Inaccurate Meteo Now-casting Information: The now-cast meteorological conditions are inaccurate or wrong. The controllers will most likely not be aware of a sudden unfavorable change of the wind.	Incorrect information is passed to the ATC-Wake Predictor, causing improper functioning. The predicted transport of the vortices is wrong. An unfavorable change of weather (not enough crosswind) is not detected. The aircraft may encounter severe turbulence, which could lead to control problems close to ground	SERIOUS INCIDENT	The wake vortex is stronger closer to the generating aircraft. An encounter with 90 seconds (i.e. reduced) separation will result in more severe consequence than under ICAO separations.
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. The aircraft already lined up for departure will receive their take off clearance later.

Description	Effect	Classification	Comment
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 or inaccurately detected. There will be an alert if the Wake Vortex Vector generated by the ATC-Wake Predictor indicates a potential wake encounter. 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 Nowcasting and Predictor are working.

The operational hazards associated with the ATC-Wake operation have been identified in detail with the NLR Qualitative Safety Assessment (QSA) methodology. Identified potential safety bottlenecks for ATC-Wake departure operations are e.g. [13, 21]:

- 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 tower controllers are used to work based on their outside view.

A more extensive description of all the safety bottlenecks related to the ATC-Wake operation together with some further recommendations for risk mitigation is provided in reference 13.

5.2 Quantitative risk assessment

5.2.1 Wake vortex induced risk

Figure 5-5 shows the wake vortex induced risk, in terms of incident/accident probability per departure, for a separation time of 90 seconds (with no head- or tailwind). Note that LAC denotes the leader aircraft and FAC denotes the follower aircraft (the numbering is in accordance with Table 4-2). Risk assessment results for cross wind conditions of 0, 1, 2, 3, 4, and 5 m/s are provided in Figures 5-6 until 5-11 [12, 22]. Initial aircraft separation times of 60, 90, 120, 150, and 180 seconds are all evaluated. A very important departure specific and aircraft dependent parameter is the lift-off point. Therefore, it is noted once more that in the assessment a distinction has been made between early and late lift-off of the aircraft. Logically, a 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 are maximized over the variation in lift-off points of the different departing aircraft types before deriving the wake vortex induced risk results provided in this Section. The full details of the quantitative safety assessment are provided in Speijker et al. [12, 22], in which the impact of the lift off point on risk is also analysed. In this study, the aim is to derive safe separation times for departures, i.e. therefore the worst case combination of leader and follower lift off points is considered. An interesting finding is the fact that e.g. Light Business Jets behind a Large Jumbo Jet could always be separated with just 60 seconds (see e.g. Figure 5-12, in Section 5.2.2). This is explained by the fact that this aircraft usually takes off earlier, which implies that its flight path well exceeds that of the leading Large Jumbo Jet.

As an example, Figures 5-1 until 5-4 present the incident/accident risk curves for a Regional Jet departing under different crosswind conditions (no head- or tailwind) behind a Large Jumbo Jet.

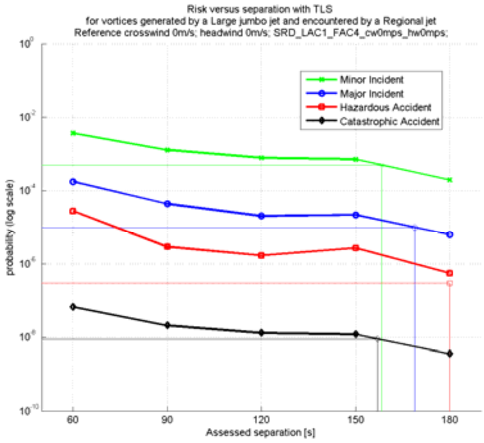

Figure 5-1 Risk with crosswind 0 m/s

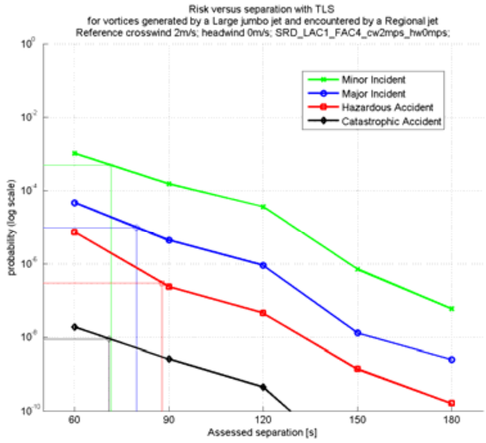

Figure 5-3 Risk with crosswind 2 m/s

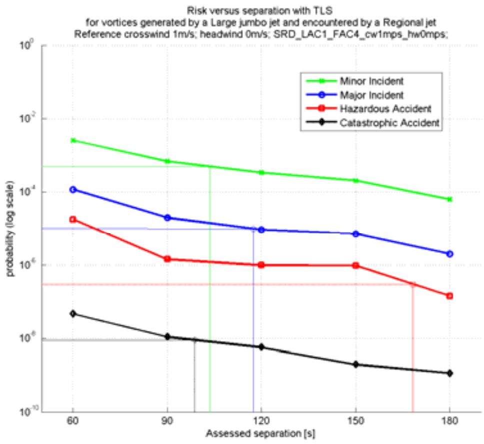

Figure 5-2 Risk with crosswind 1 m/s

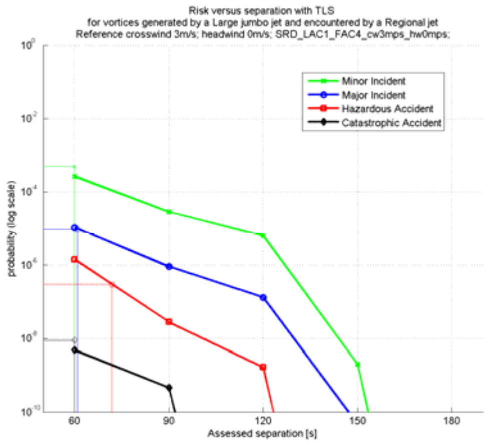

Figure 5-4 Risk with crosswind 3 m/s

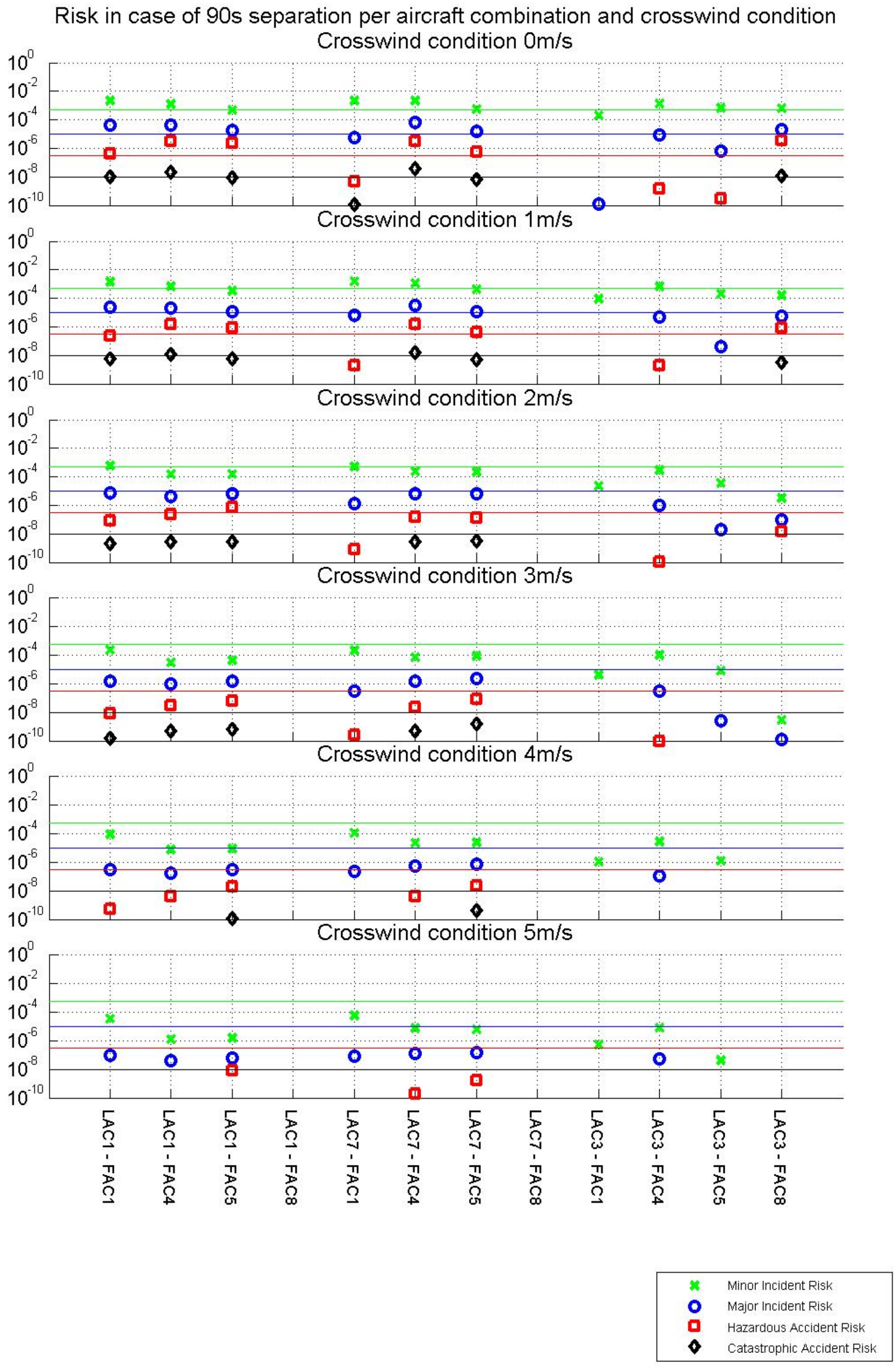

Figure 5-5 Overview of risk results in case of 90 seconds separation

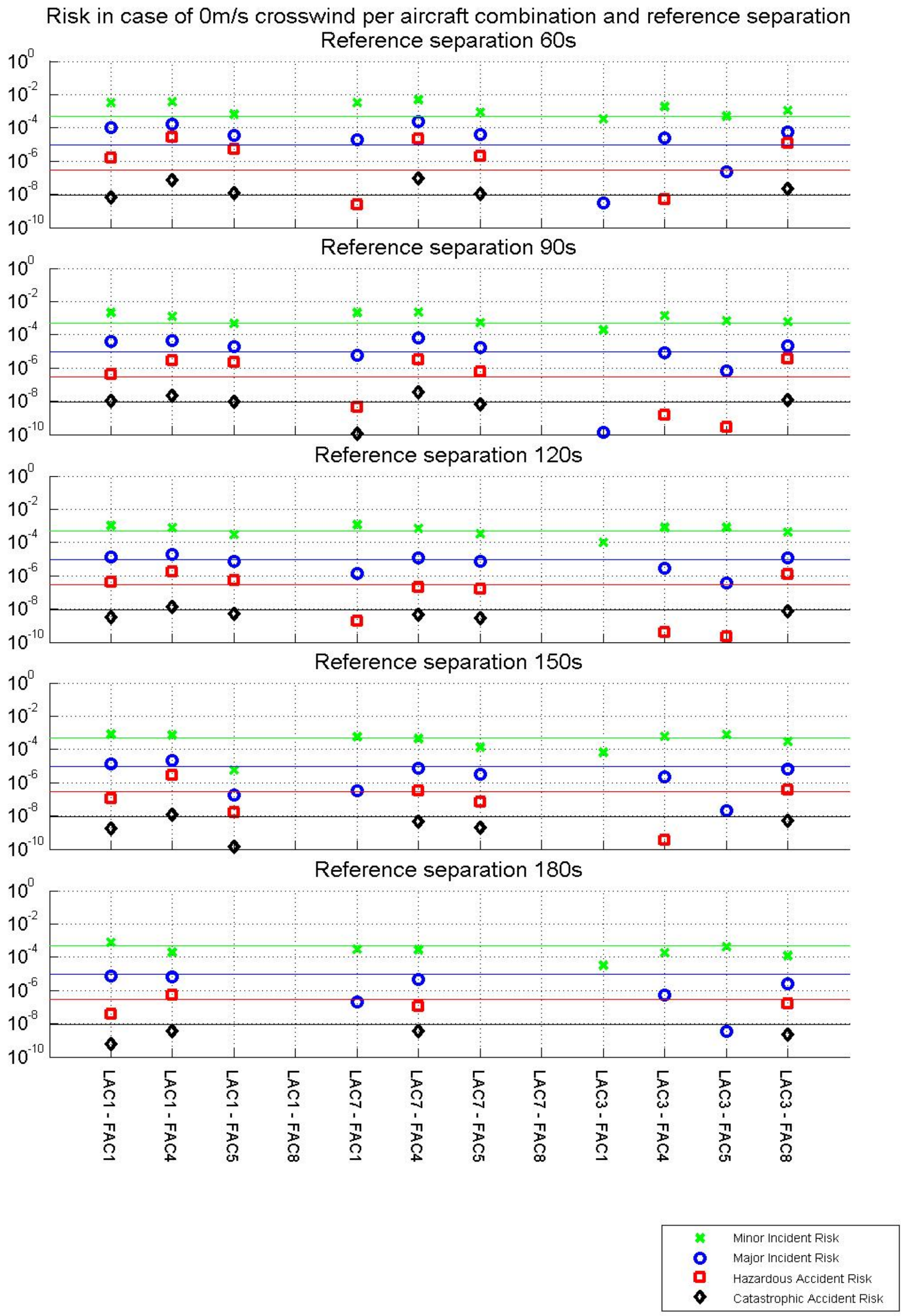

Figure 5-6 Overview of risk results in case of 0 m/s crosswind

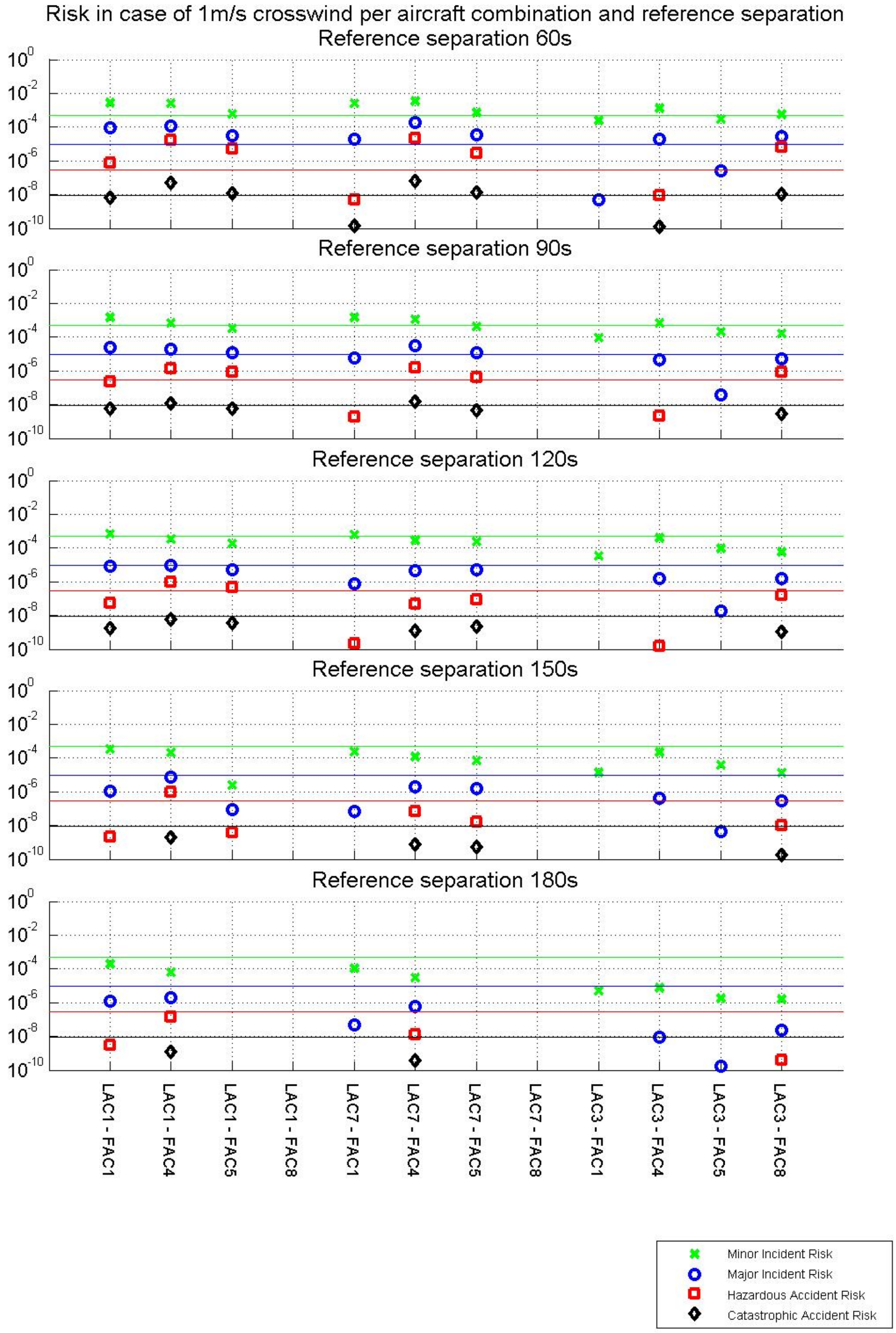

Figure 5-7 Overview of risk results in case of 1 m/s crosswind

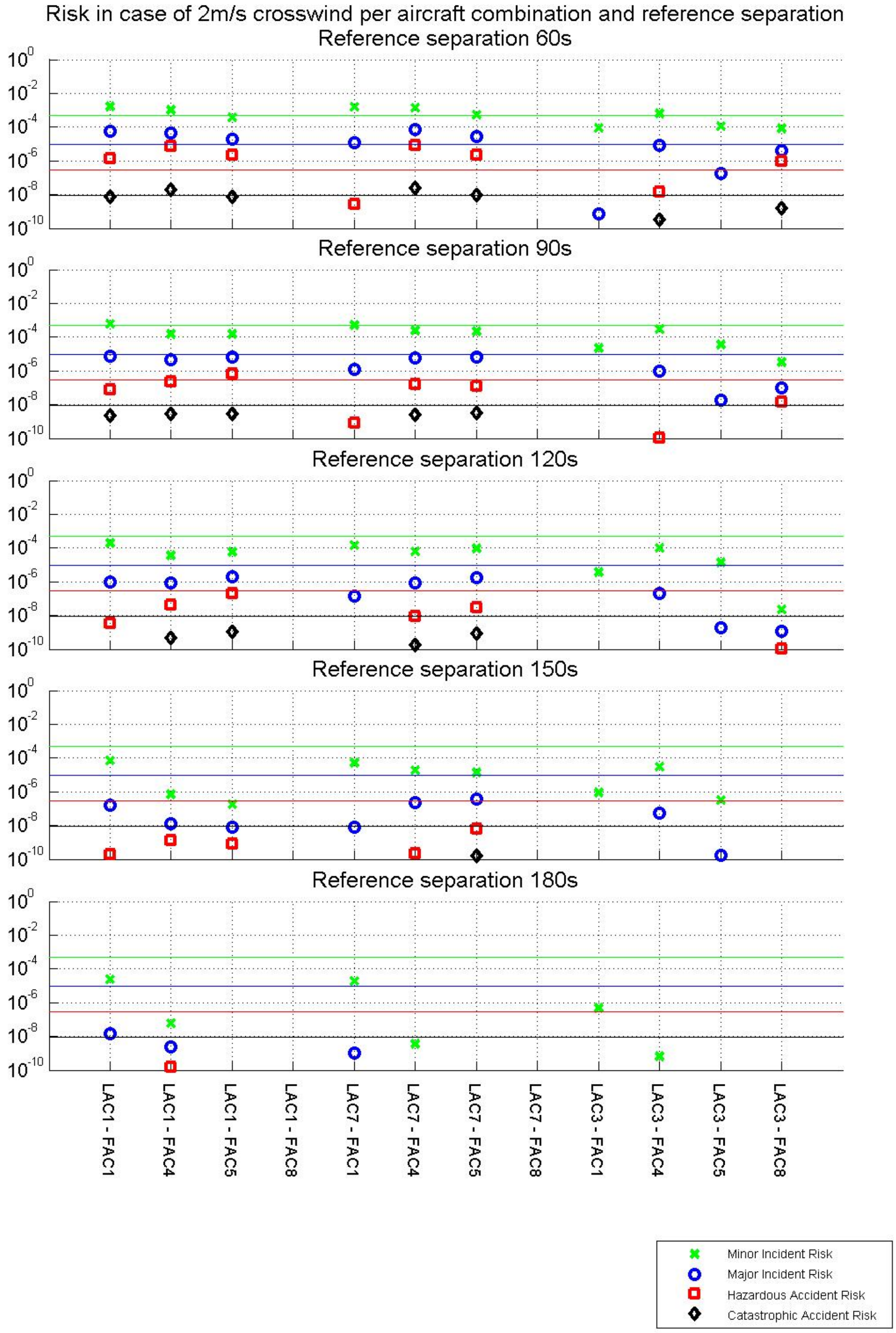

Figure 5-8 Overview of risk results in case of 2 m/s crosswind

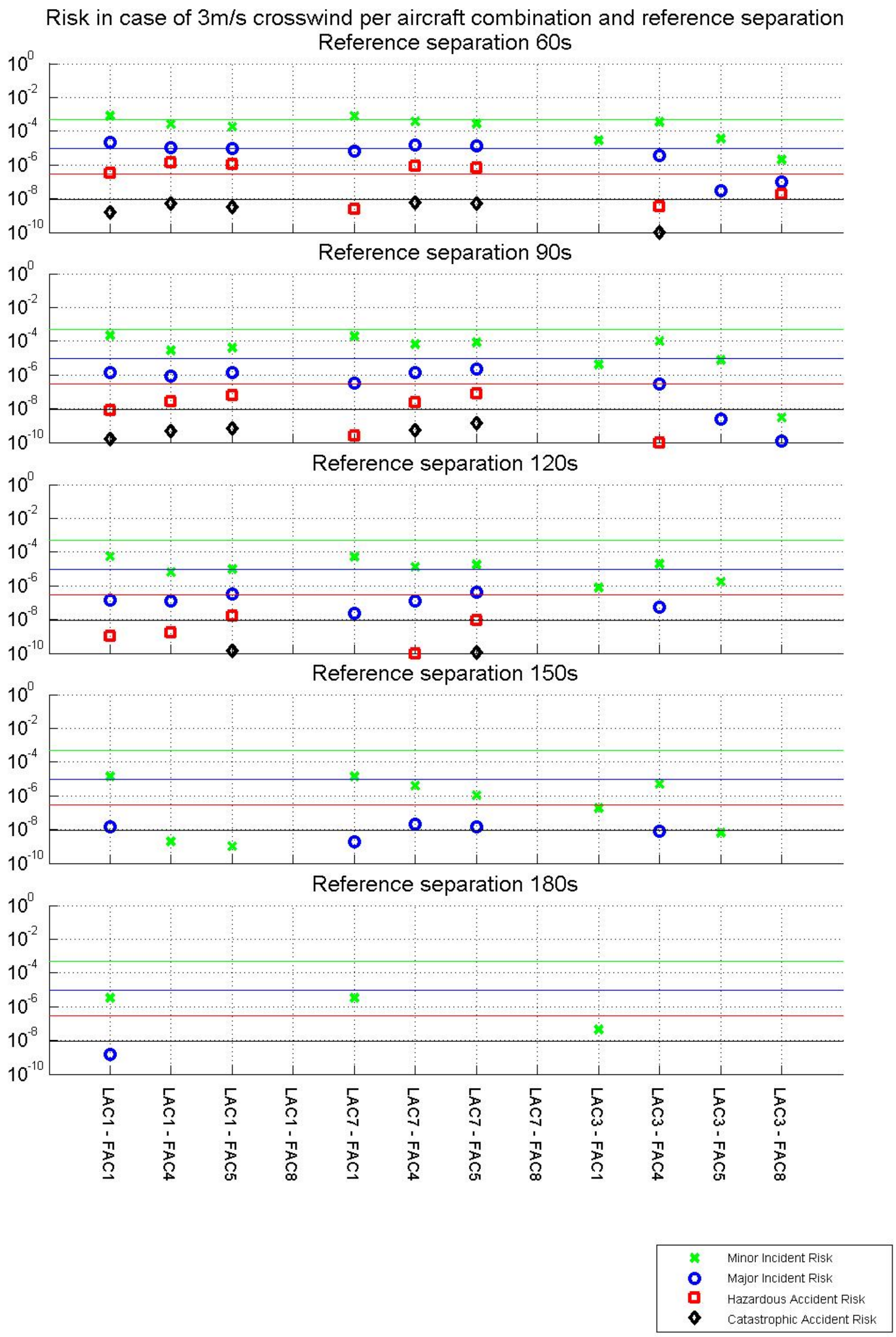

Figure 5-9 Overview of risk results in case of 3 m/s crosswind

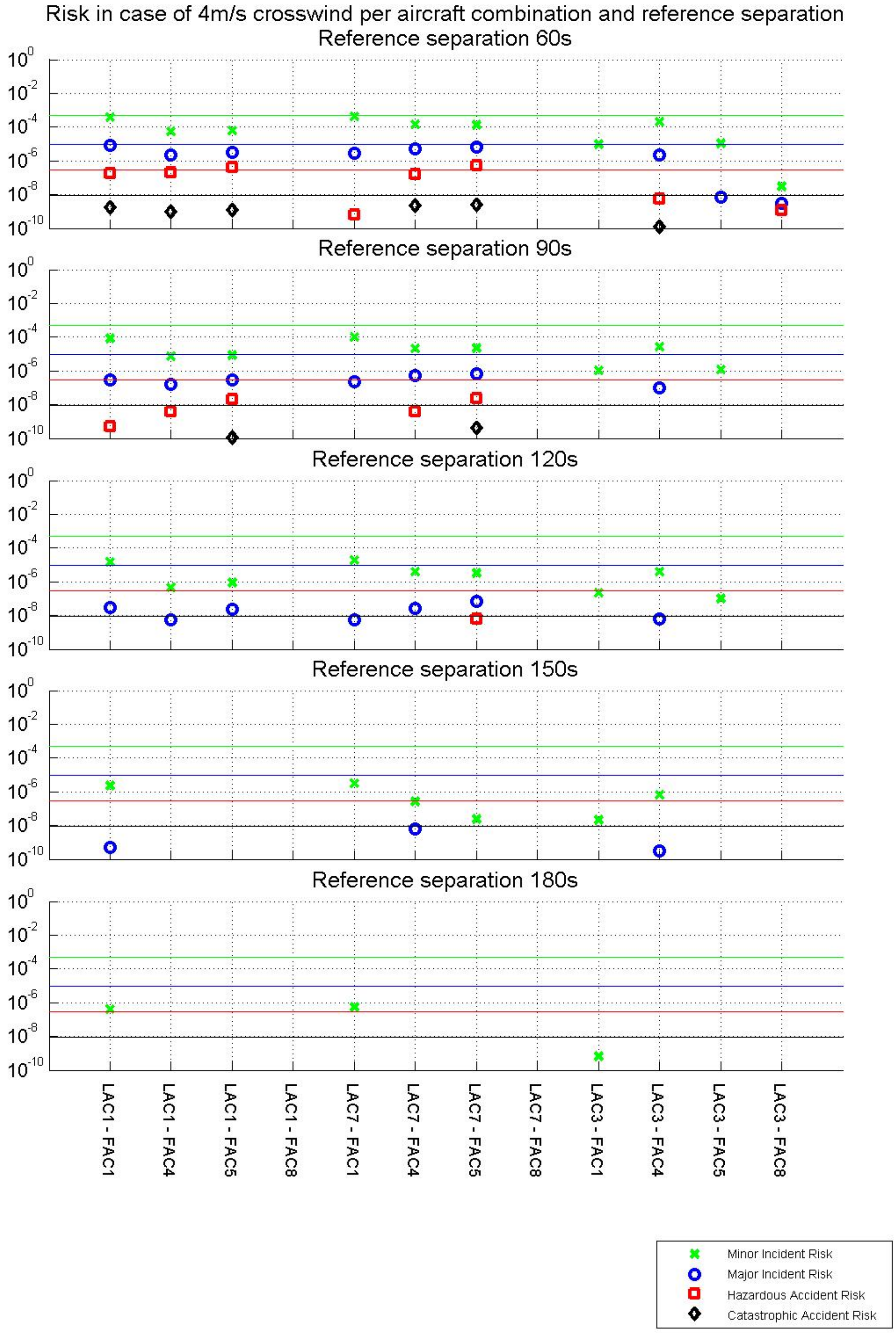

Figure 5-10 Overview of risk results in case of 4 m/s crosswind

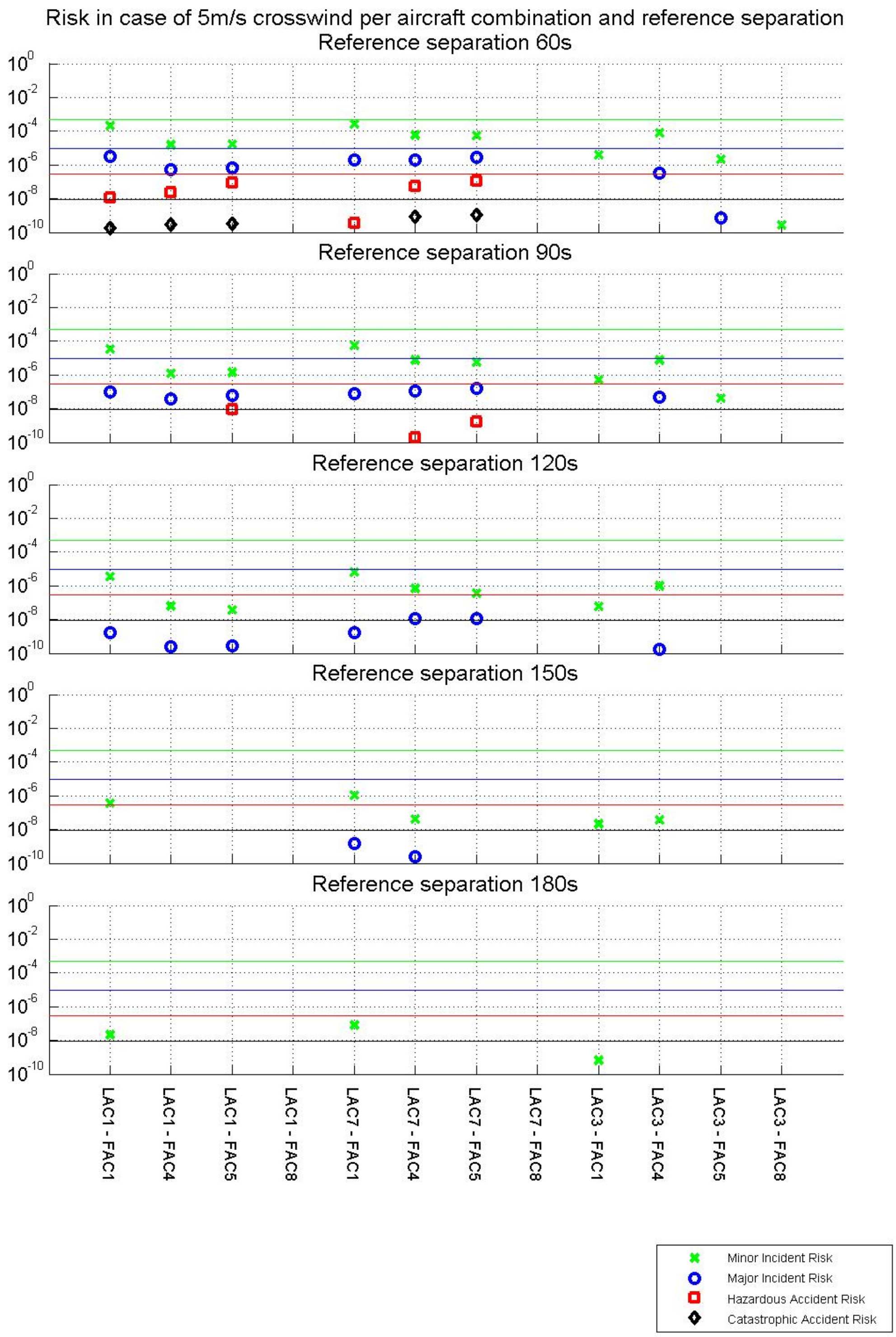

Figure 5-11 Overview of risk results in case of 5 m/s crosswind

5.2.2 Initial estimate of the minimum required aircraft separation time

An initial estimate of the minimum required separation times for various leader and follower aircraft combinations and for various crosswind conditions is provided in Figure 5-12 on the basis of the quantitative risk assessment results sketched in Section 5.2.1.

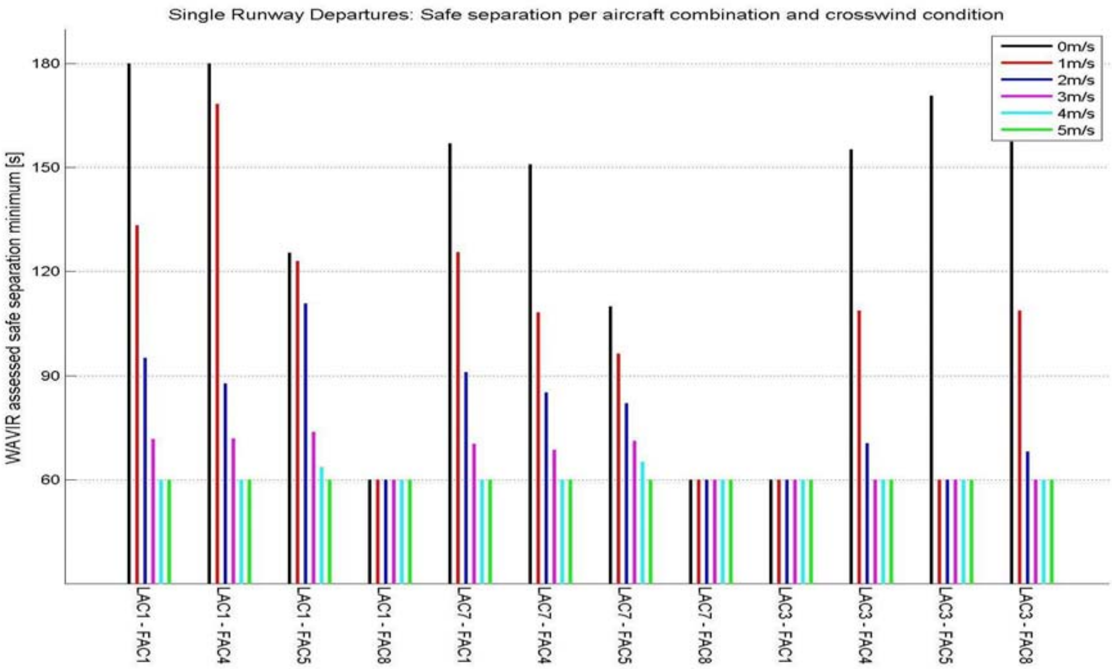

Figure 5-12 Overview of WAVIR assessed safe separation minima for the SRD operation

Taking into consideration that ATC-Wake Mode should be applied to all aircraft combinations, Table 5-2 indicates safe separation minima for certain crosswind intervals (these are indicative numbers that do not take into account uncertainty in the crosswind conditions, safety margins and other factors that may influence safety). These separations may only be applied in case ATC-Wake is used, and the system meets performance requirements that follow from Table 5-1. Reduced separation of 90 seconds may be applied when crosswind exceeds 3 m/s, while 60 seconds separation can be applied with crosswind above 5 m/s.

Table 5-2 Indicative separation per crosswind interval

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
5 m/s $\leq u_c$	60s

6 Capacity improvements

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 an analytical study [20] are combined. Expected throughput is provided in Table 6-1.

Table 6-1 Expected throughput for the ATC-Wake SRD operation

	ATC-Wake Single Runway Departure operation			
Crosswind interval	Separation	Throughput [aircraft/hour]	Probability of crosswind in interval [1)]	Throughput per crosswind interval
$0 \leq u_c \leq 1$	ICAO	37.8	0.080	3.0
$1 \leq u_c \leq 2$	ICAO	37.8	0.208	7.9
$2 \leq u_c \leq 3$	ICAO	37.8	0.206	7.8
$3 \leq u_c \leq 4$	90s	38.9	0.164	6.4
$4 \leq u_c \leq 5$	90s	38.9	0.118	4.6
$5 \leq u_c \leq 6$	60s	40.0	0.081	3.2
$6 \leq u_c \leq 8$	60s	40.0	0.053	2.1
$8\text{m/s} \leq u_c$	60s	40.0	0.090	3.6
Expected throughput [aircraft/hour]				38.6
Change compared to ICAO reference situation				2.1%

Runway throughput improves when the ATC-Wake system/operation is used. Depending on the occurrence of favorable crosswind conditions, the increase in runway throughput is estimated at about 2% for the ATC-Wake SRD operation at a generic airport with average wind conditions.

1) A crosswind climatology based on about 400,000 observations at about 10 m altitude at 3 large European airports is used.

7 Conclusions and recommendations

With the steady increase in air traffic, airports are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the wake vortex separation distance between aircraft at take-off and landing without compromising safety. The EC project ATC-Wake has designed an integrated system for Air Traffic Control that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. Introducing and/or planning changes to the ATM system cannot be done without providing sufficiently validated evidence that minimum safety requirements will be satisfied. Therefore, this study has quantified the possible safety implications related to installation of ATC-Wake. This includes an assessment of required crosswind values for which reduced aircraft separation can be applied. The wake vortex induced risk between a variety of leader and follower aircraft, departing under various wind conditions, has been evaluated with the Wake Vortex Induced Risk assessment (WAVIR) methodology and toolset. For the ATC-Wake departure operation with reduced separation, two main issues have been considered:

- The controller working with ATC-Wake will warn the pilot about a potential wake vortex encounter, in case an ATC-Wake alert is raised.
- If an ATC-Wake system provides wrong advice, there is a higher risk on the presence of severe wake vortices. Consequences might even be catastrophic when reduced separation is applied and a light aircraft encounters a severe wake of a heavy aircraft.

The present separation of two to three minutes between departing aircraft is designed to ensure that aircraft will not encounter wake vortices of large aircraft. For airports with ATC-Wake in use, the present study indicates that the time separation between aircraft departing at single runways might be reduced to 90 seconds for all aircraft types in the presence of sufficient crosswind. Indicative separation minima dependent on crosswind conditions have been determined. As these separation minima do not yet account for crosswind uncertainty, the setting of requirements for the ATC-Wake system was further investigated. This was done through a qualitative analysis of the effect of failures of the ATC-Wake system. It appears that the most severe failure conditions are related to the functioning of the Monitoring and Alerting system and the Meteorological Now-casting systems. These system components are crucial and sufficient accuracy and reliability shall be guaranteed. Additionally, it is noted that controllers should be made very aware that a timely warning to the pilots is also crucial (safety training might help to increase the awareness). A sufficiently validated aircraft performance and dynamics model for *departures* is not yet available. 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 [16]. A further issue to be investigated is the fact that the actual (real) separation time at the start of roll of the aircraft will usually not be exactly the same as the advised separation time.

A full Safety Case for ATC-Wake departures shall also account for the local weather climatology and ATC/pilot procedures for wake vortex mitigation. In view of this, actual implementation of the ATC-Wake operation at European airports is not envisaged in the short term. It is recommended to involve airport authorities and ATC centers for gathering the required data to build the Safety Case. Follow-up research is foreseen to be performed as part of the CREDOS project, which is a logical successor to the ATC-Wake project.

Acknowledgements

The authors acknowledge the EC IST Programme for providing part of the funding for this study, which was carried out under the ATC-wake contract, with project number IST-2001-34729. The authors are especially grateful to the technical comments and suggestions from Peter van der Geest and Marijn Giesberts (NLR), Dorota Kurowicka and Veronica Angeles Morales (University Technology of Delft).

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