Risk based decision support for new air traffic operations with reduced aircraft separation

Lennaert Speijker

Risk based decision support for new air traffic operations with reduced aircraft separation

Proefschrift

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prof. dr. R.M. Cooke

Samenstelling promotiecommissie:

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Summary

With the steady increase in air traffic, the aviation system is under continuous pressure to increase aircraft handling capacity. The introduction of Reduced Vertical Separation Minima (RVSM) during the en-route phase of flight implied that the capacity bottleneck within the air transport system has changed from en-route towards the Terminal Manoeuvring Area (TMA) around busy airports. The diversity of airport operations (departures, approaches, missed approaches) and risk events (e.g. collision risk, wake turbulence risk, third party risk, runway incursion) implies that the safety assessment of newly proposed air traffic operations in the airport environment is quite complex. New safety assessment methods are needed to assess safety. In this respect, the two most capacity limiting risk events, addressed in this Doctoral thesis, are *wake vortex encounters* and the *collision risk between aircraft*.

Various new Air Traffic Management (ATM) systems and flight procedures have been proposed to increase airport capacity while maintaining the same (required) level of safety. Newly proposed systems to cope with wake turbulence and allowing reduction of wake vortex separation minima include the ground based ATC-Wake system (for air traffic controllers) and the on-board I-Wake system (for pilots). An increase in runway capacity may also be achieved by using parallel runways more effectively or by designing new and advanced flight procedures. For all the flight procedures evaluated in this doctoral thesis, International Civil Aviation Organization (ICAO) standards and best practices do not exist and new safety assessment methodologies, incorporating the roles of the Air Traffic Controllers and pilots, are developed and applied. Introducing and/or planning changes to the air transport system cannot be done without showing that minimum safety requirements will be satisfied. This thesis therefore not only deals with the safety assessment process itself, but also with the setting of risk requirements for the newly proposed ATM systems and flight procedures.

The approach taken is to apply risk based decision making to support the introduction of new air traffic operations and systems for reduced aircraft separation in the airport environment. As worldwide quantitative risk requirements for the newly proposed air traffic operations have not yet been established, the question arises how to assess the level of risk which may be considered acceptable. Evidently, a zero incident/accident risk can not be realized and therefore risk criteria will have to be developed. There are several fundamental questions that must be resolved:

- What is the safety level of the current air traffic operations?
- Are the separation minima for the current air traffic operations overly conservative?
- Can the current separation minima safely be reduced?
- What are the requirements for the newly proposed air traffic operations and systems?

These questions require more comprehensive risk assessment models and risk criteria than currently available. Therefore, to answer these questions, several methodologies for the setting of risk criteria are developed and applied to the following safety studies:

- Collision risk analysis of the usage of parallel runways for landing;
- Collision risk analysis of simultaneous missed approaches on converging runways;
- Wake vortex safety assessment of single runway approaches;
- Safety assessment of ATC-Wake single runway departures;
- Safety assessment of the I-Wake single runway operation with reduced separation.

The developed new and innovative methods all support two common rationales for acceptance of a newly proposed air traffic operation, namely by showing that the number of risk events does not exceed some pre-defined risk requirement and furthermore also does not increase with the introduction of the new operation. The developed risk assessment models are based on risk metrics in terms of incident/accident probabilities per movement with, where possible, risk requirements derived on the basis of historical incident/accident data.

It is shown that the current wake vortex aircraft separation minima, which depend on the aircraft weight, are indeed overly conservative under certain conditions. Introduction of variable wind dependent aircraft separation rules will enable increase of airport capacity, while maintaining safety. Aircraft separation can be reduced safely, provided that new wake vortex prediction, detection and avoidance systems − such as ATC-Wake (for air traffic controllers) and I-Wake (for pilots) − are implemented for operational use. It is also shown that specific missed approach procedures, which take into account the local airport layout characteristics, may lead to an increase of airport capacity. This is shown for Amsterdam Airport Schiphol runway 22.

The safety assessments have built sufficient confidence in the operational use of the proposed new ATM systems and flight procedures for the application of reduced aircraft separation in the airport environment. The results from the collision risk analysis studies have been used by the Dutch Civil Aviation authority and Air Traffic Control Centre, and were brought forward successfully to the ICAO Obstacle Clearance Panel. The results from the wake vortex risk analysis studies have been used to support the design and also the setting of requirements for the ATC-Wake and I-Wake systems and concepts of operation. Next step will be to complete the validation process for the use of these systems through the production of the Safety Cases towards installation of these systems at airports and in aircraft respectively. Trials at European airports are foreseen as the ideal way forward for gathering the required data to complete the local Safety Cases and realize the foreseen reduction of the wake vortex separation minima.

Samenvatting

Als gevolg van de toename van het luchtverkeer staat het luchtvaartsysteem onder druk om meer vliegtuigen af te handelen. De introductie van kleinere verticale separatieafstanden (van 2000 voet naar 1000 voet) tijdens het en route deel van de vlucht impliceerde dat het capaciteit knelpunt in het luchtverkeer verplaatst is naar de luchthavens. De verscheidenheid aan vliegprocedures (startend en landend verkeer, eventuele doorstarts) en de bijbehorende veiligheidsrisico's, impliceert dat de veiligheidsbeoordeling van nieuwe systemen en procedures in de luchthavenomgeving vrij complex is. Er is een behoefte aan nieuwe methodieken voor het beoordelen van de veiligheidsimplicaties van deze voorgestelde wijzigingen. De meeste nieuwe vliegprocedures zijn gericht op het verminderen van minimaal vereiste separatieafstanden tussen vliegtuigen, zodat meer vliegtuigen kunnen worden afgehandeld. Om het minimum vereiste veiligheidsniveau te blijven garanderen, zal voor invoering van nieuwe systemen en procedures aangetoond moeten worden dat risico’s als bijvoorbeeld botsingen tussen vliegtuigen of ongevallen als gevolg van zich achter vliegtuigen bevindende tipwervels niet vermeerderd.

Nieuwe operationele concepten en systemen als ATC-Wake (voor verkeersleiders) en I-Wake (voor piloten) richten zich op verkleinen van de minimaal vereiste tipwervel separatieafstanden. Een capaciteitstoename kan echter ook bereikt worden door het ontwerpen van nieuwe vliegprocedures voor het efficiënter gebruik van parallelle landingsbanen. Voor alle procedurele wijzigingen waarvoor de veiligheid in dit proefschrift wordt geëvalueerd, geldt dat ICAO standaarden en/of geaccepteerde veiligheidsmethodieken (nog) niet bestaan. Daarom worden nieuwe en innovatieve veiligheidsanalysemethoden ontwikkeld en toegepast. Dit proefschrift gaat, ter ondersteuning van regulerende instanties, tevens in op het vaststellen van veiligheids-normen. Waar mogelijk, wordt hierbij gebruik gemaakt van historische data over ongevallen.

De aanpak gaat uit van de toepassing van op veiligheidsrisico’s gebaseerde besluitvorming, ter ondersteuning van de (veilige) invoering van nieuwe vliegprocedures en systemen voor kleinere vliegtuigseparatieafstanden in de vliegveldomgeving. Omdat wereldwijde kwantitatieve veiligheidsnormen voor de nieuw voorgestelde vliegprocedures en systemen nog niet bestaan, doet zich de vraag voor hoe het acceptabele veiligheidsniveau bepaald dient te worden. Verschillende fundamentele vragen dienen hiertoe beantwoord te worden:

- Wat is het veiligheidsniveau van de huidige vliegprocedures in de vliegveldomgeving?
- Zijn de huidige vliegtuigseparatieafstanden mogelijk te conservatief?
- Kunnen de huidige vliegtuigseparatieafstanden veilig verkleind worden?
- Wat zijn de veiligheidseisen voor de invoering van nieuwe vliegprocedures en systemen?

Het beantwoorden van deze vragen vereist andere risicoanalysemodellen en veiligheidsnormen dan momenteel beschikbaar en gebruikelijk. Vandaar dat, om hier een antwoord op te vinden, verschillende nieuwe methoden voor het vaststellen van risico criteria zijn ontwikkeld. Deze zijn vervolgens toegepast in de volgende veiligheidsstudies:

- Analyse van het botsingsrisico bij het gebruik van parallelle banen voor landingen;
- Analyse van het botsingsrisico bij doorstarts op convergerende landingsbanen;
- Veiligheidsanalyse van het risico op ongevallen door tipwervels achter vliegtuigen;
- Veiligheidsanalyse van de ATC-Wake operatie voor startend vliegverkeer;
- Veiligheidsanalyse van de I-Wake operatie voor landend verkeer met kleinere separatie.

De nieuw ontwikkelde methoden en risicoanalysemodellen ondersteunen twee algemeen aanvaardde motivaties ter acceptatie van nieuwe vliegoperaties en systemen, namelijk door aan te tonen dat het risico op een ongeval niet hoger wordt dan een maximaal aanvaardbare norm *én* dat dit risico tevens niet hoger wordt dan momenteel het geval is. Alle ontwikkelde risico-analysemodellen zijn gebaseerd op ongevalskansen per vliegbeweging (landing of start) met, waar mogelijk, veiligheidsnormen gebaseerd op historische gegevens en data over ongevallen. Er is aangetoond dat de vliegtuigseparatieafstanden, die momenteel met name gebaseerd zijn op het gewicht van de betrokken vliegtuigen, daadwerkelijk te conservatief zijn onder bepaalde condities. Invoeren van nieuwe variabele weersafhankelijke separatieregels zal de capaciteit van vliegvelden veilig kunnen vergroten. Nieuwe operationele systemen als ATC-Wake (voor verkeersleiders) en I-Wake (voor piloten) dienen te zorgen voor betrouwbare voorspelling en detectie van tipwervels in de vliegveldomgeving. Er is ook aangetoond dat geavanceerde doorstart procedures, die rekening houden met het specifieke banenstelsel van vliegvelden, kunnen leiden tot een veilige capaciteitsvergroting van vliegvelden (zoals Schiphol).

De uitgevoerde veiligheidsanalyses hebben al geleid tot een veilige vergroting van de capaciteit van het luchtverkeer. De resultaten van de botsingsrisicoanalyses zijn door de Nederlandse Luchtvaart Autoriteit en de Luchtverkeersleiding gebruikt, en zijn daarnaast ook ingebracht bij het ICAO ’Obstacle Clearance Panel’. De resultaten van de veiligheidsanalyses van het risico op ongevallen door tipwervels zijn gebruikt om de systeemeisen ten behoeve van kleinere separatieafstanden vast te stellen. Het voorgestelde ontwerp van de ATC-Wake en I-Wake systemen en de bijbehorende operationele concepten geeft een duidelijke richting aan voor de toekomstige operationele validatie voor het gebruik van deze systemen in de vliegveld omgeving. Als volgende stap wordt voorzien het produceren van de lokale ‘Safety Cases’, gebruikmakend van klimatologie data met betrekking tot de weersomstandigheden op de beoogde vliegvelden. Installatie van ATC-Wake op vliegvelden en I-Wake in vliegtuigen, en continuering van de deelname van Europese vliegvelden en luchtverkeersleidingscentra in het validatieproces is een noodzakelijke voorwaarde om te komen tot verdere capaciteitsvergroting.

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$A_R{}^i$	Aspect ratio of aircraft i
A_S	Wake vortex evolution stratification model constant
$b^j_0 = \pi / d_y{}^j$	Initial spacing between the primary vortex centres of aircraft j [in m]
C_D	Viscous drag coefficient
C_{DV}	Viscous coefficient caused by crosswind
$C_{l,\overline{p}}$	Roll damping coefficient
$C_L{}^i$	Lift coëfficient of aircraft i
$C_{L\alpha}{}^i$	Lift curve slope of aircraft i [in rad^{-1}]
$\overline{c}^i$	Mean aerodynamic chord of aircraft i [in m]
$C_{R,c,max}$	Roll control capability
$C_{R,v}$	Wake induced rolling moment
$C_{tip}{}^i$	Tip chord of aircraft i [in m]
$C_{root}{}^i$	Root chord of aircraft i [in m]
C_S	Sarpkaya atmospheric turbulence model constant
I_{xx}	Inertial rolling moment [in kg m^2]
I_{yy}	Inertial pitching moment [in kg m^2]
I_R	Inertial radius of aircraft *j*
m^j	Mass of aircraft *i* [in kg]
$M_S{}^i$	Static margin of aircraft i
n_α	Normal acceleration sensitivity
S^i	Wing area of aircraft i
$\lambda_{TR}{}^i$	Taper ratio of aircraft i
$d_x{}^i$	Length of aircraft *i* [in m]
$d_y{}^i = b_0$	Wingspan of aircraft *i* [in m]
$d_z{}^i$	Height of aircraft *i* [in m]
d^{ij}_c	c-*th* coordinate of the collision area of aircraft i and j [in m]
d_{vc}	Distance to the vortex centre [in m]
D^{ij}	Collision area of aircraft i and j (rectangular box) [in $m \times m \times m$]
x_t^i	Longitudinal component of the centre of aircraft *i* at moment t [in m]
y_t^i	Lateral component of the centre of aircraft *i* at moment t [in m]
z_t^i	Vertical component of the centre of aircraft *i* at moment t [in m]
$u_t{}^i = (x^i{}_t, y^i{}_t, z^i{}_t)$	Three dimensional location of the aircraft i at moment t [in $m \times m \times m$]
$v_t{}^i = (\dot{x}_t^i , \dot{y}_t^i , \dot{z}_t^i)$	Three dimensional velocity of the aircraft i at moment t [in $m/s \times m/s \times m/s$]
$u_t{}^{ij}$	Relative distance between aircraft i and j at moment t [in $m \times m \times m$]
$v_t{}^{ij}$	Relative position between aircraft i and j at moment t [in $m/s \times m/s \times m/s$]
$w_{x,t}^i$	Longitudinal component of wind speed acting on aircraft i at moment t [in m s^{-1}]

$w_{y,t}^{i}$	Lateral component of wind speed acting on aircraft i at moment t [in m s^{-1}]
$w_{z,t}^{i}$	Vertical component of wind speed acting on aircraft i at moment t [in m s^{-1}]
h_{t}^{i}	Height of aircraft *i* during a wake encounter [in m]
x_d	Longitudinal distance between the thresholds of two parallel runways [in m]
y_d	Lateral distance between the thresholds of two parallel runways [in m]
σ_c	Crosswind shear (at a fixed altitude of 0.5 b_0)
w_0	Crosswind magnitude at initial height [in m/s]
w_{desc}	Wake vortex descent speed [in m s^{-1}]
g	Gravitational acceleration [in m s^{-2}]
h_{CCIT}^{i}	Critical crash-into-terrain height of aircraft *i* [in m]
r_{MA}	Missed approach rate
r_{19R} , r_{22}	Missed approach rate for runway 19R (or 22)
λ_{19R} , λ_{22}	Probability that a missed approach on runway 19R (or 22) is straight ahead
λ_{DH}	Percentage of missed approaches initiated at Decision Height [in %]
p_{MA}	Shape parameter of the Beta distribution for the missed approach rate
q_{MA}	Shape parameter of the Beta distribution for the missed approach rate
ρ_{dep}	Dependency parameter in relation to the type of operations of aircraft i and j
$\bar{\rho}_{dep}$	Best estimate for the dependency parameter ρ_{dep}
$r_{core,t}^{j}$	Vortex core radius of aircraft j at moment t [in m]
$V_{\theta,t}^{j}$	Tangential velocity of a wake of aircraft j at moment t [in m s^{-1}]
t_P	Passage time of two aircraft (missed) approaching two parallel runways [in s]
τ^{ij}_{x}	Time at which aircraft *i* reaches the wake generated at position x by aircraft j [in s]
η^{ij} , η^{i}	Indicators for the type of arrival operation (landing or missed approach)
κ^{ij} , κ^{i}	Indicators for the type of aircraft combinations on two converging runways
E_{IC}	Expected number of incrossings, or collisions, between missed approaching aircraft
$\varphi^{ij}(t)$	Incrossing rate between aircraft i and j
$f_{Y_t^i}$	Probability density function of the lateral co-ordinate of aircraft i at moment t
Φ_{max}	Controlled maximum bank angle [in rad]
$\Phi_{max,inf}$	Uncontrolled maximum bank angle [in rad]
ϕ^{i}	Bank angle of aircraft i [in rad]
θ^{i}	Pitch angle of aircraft i [in rad]
ς^{i}	Yaw angle of aircraft i [in rad]
γ^{i}	Flight path angle of aircraft i [in rad]
ψ	Aileron deflection
δ_e	Elevator deflection
ξ	Roll control ratio
p_{t}^{i}	Roll rate of aircraft i at moment t [in rad s^{-1}]
q_{t}^{i}	Pitch rate of aircraft i at moment t [in rad s^{-1}]

r_t^i	Yaw rate of aircraft i at moment t [in rad s^{-1}]
α_t^i	Angle of attack at moment t [in rad]
β_t^i	Angle of side slip at moment t [in rad]
ζ	Damping coëfficient in the missed approach model
ω	Short period frequency in the missed approach model [in rad/s]
K_1, K_2	Aircraft dependent ERCR model constants
K_Q	Pilot (pitch) gain
$K_P{}^i$	Pilot (roll rate) gain
T_{ij}	Final time after which the collision probability between aircraft (i, j) is negligible [in s]
T_F	Finish time for control input [in s]
T_R	Pilot reaction time [in s]
T_S	Sarpkaya atmospheric turbulence model constant
$T_{lead}{}^i$	Pilot lead time [in s]
$T_{lag}{}^i$	Aircraft lag time [in s]
T_V	Wake encounter duration time [in s]
$\tau_e{}^i$	Equivalent time delay [in s]
ε^j	Eddy Dissipation Rate acting on the vortices of aircraft j [in m^2 s^{-3}]
$\rho^j{}_t$	Local air density acting on the vortices of aircraft j at moment t [in kg m^{-3}]
δ^{j-}	Position of left vortex generated by aircraft j at moment t
δ^{j+}	Position of right vortex generated by aircraft j at moment t
Γ^{j-}	Strength of left vortex generated by aircraft j at moment t
Γ^{j+}	Strength of right vortex generated by aircraft j at moment t
$\wp^j{}_t$	Local external influence vector acting on the vortices of aircraft j
$\varpi^j{}_t$	Local external influence vector acting on the aircraft i
$\bar{\theta}^j$	Potential temperature in the atmosphere acting on aircraft j
N^j	Brünt-Väissällä frequency acting on the vortices of aircraft j [in rad s^{-1}]
$q^j{}_{rms}$	RMS velocity of atmospheric turbulence [in m s^{-1}]
z_{FOV}	LiDAR vertical field of view [in ± degrees]
y_{FOV}	LiDAR horizontal field of view [in ± degrees]
Z_{AOR}	LiDAR angle of regard [in ± degrees]
x^{DET}	LiDAR detection distance [in [m,m]]
T_{alert}	Time of alert for potential wake vortex hazard [in s]
$T_{caution}$	Time of caution for potential wake vortex hazard [in s]
P_{FAD}	Failure probability for I-Wake inaccurate (or faulty) aircraft data
P_{FWV}	Failure probability for I-Wake inaccurate (or faulty) wake vortex model estimation
P_{FNC}	Failure probability for I-Wake inaccurate (or faulty) meteorological now-casting data
P_{FD}	Failure probability for I-Wake inaccurate (or faulty) detection of wake vortices
P_{LTF}	Failure probability for loss of the overall wake vortex DWA tactical function

χ^{j}_{t}	Wake Vortex Severity Properties (vortices generated by aircraft j at moment t)
ϑ^{ij}_{t}	Wake Encounter Severity Properties (vortices generated by aircraft j at moment t)
$\bar{\phi}_{WeakEnc}$	Weak Encounter Threshold Boundary (as function of height) [in rad]
$\bar{\phi}_{ModEnc}$	Moderate Encounter Threshold Boundary (as function of height) [in rad]
$\bar{\phi}_{SevEnc}$	Severe Encounter Threshold Boundary (as function of height) [in rad]
$\bar{\phi}_{ExtrEnc}$	Extreme Encounter Threshold Boundary (as function of height) [in rad]
$P_{collision}$	Conditional collision probability between two aircraft
p^{ij}_{MinInc}	Probability of a minor incident of aircraft *i* (induced by the vortices of aircraft *j*)
p^{ij}_{MajInc}	Probability of a major incident of aircraft *i* (induced by the vortices of aircraft *j*)
p^{ij}_{HazAcc}	Probability of a hazardous accident of aircraft *i* (induced by vortices of aircraft *j*)
p^{ij}_{CatAcc}	Probability of a catastrophic accident of aircraft *i* (induced by vortices of aircraft *j*)
$P_{T(a\rightarrow b)}$	Transition probability from encounter class a to risk event b

1 Introduction

1.1 Scope

With the steady increase in air traffic, airports are under pressure to increase aircraft handling capacity. The introduction of Reduced Vertical Separation Minima during the en-route phase of flight implied that the capacity bottleneck within the aviation and air transport system will change from en-route towards Terminal Manoeuvring Areas (TMA) around busy airports. The diversity of airport operations (departures, approaches, missed approaches) and risk events (e.g. collision risk, wake turbulence risk, third party risk, runway incursion) implies that the safety assessment of newly proposed flight procedures in the airport environment is quite complex. New safety assessment methodologies are needed to assess the safety. The newly proposed flight procedures aim to reduce the separation distances between aircraft at take-off and landing without compromising safety. In this respect, the two most capacity limiting risk events are wake vortex encounters and the collision risk between aircraft.

Figure 1-1 Wake vortex generated behind a heavy aircraft

Aircraft create wake vortices when flying, restricting runway capacity (Figure 1-1). 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 in time.

The ATC-Wake project aims to develop and build a ground based wake vortex prediction, monitoring, and alerting system for Air Traffic Controllers that will allow variable wind dependent aircraft reduced separation distances, as opposed to the fixed distances presently applied. Similarly, the I-Wake project aims to develop an aircraft on-board wake vortex detection, warning and avoidance system. A combination of both is foreseen as the ideal way to cope with the risk related to wake turbulence in the airport environment.

An increase in runway capacity may also be achieved by using existing parallel runways more effectively or by building additional parallel runways. A reduction of the minimum parallel runway spacing for independent parallel approaches was proposed by the Federal Aviation Administration (FAA), provided usage of the Precision Runway Monitor (PRM) system [27, 39]. For the safety assessment of the associated flight procedure, evaluation of the collision risk between aircraft is required. A recent study focusing on improvement of the capacity at Schiphol airport addresses the risk related to simultaneous missed approaches on runways 19R and 22, where a reduction of the Obstacle Clearance Altitude (OCA) would allow the use of runway 22 in actual Cat I weather conditions.

For the newly proposed flight procedures, ICAO standards and best practices do not exist and therefore new safety assessment methodologies and toolsets, preferably incorporating the roles of the Air Traffic Controllers and pilots, will need to be developed and applied.

1.2 Objectives

The overall objective of this thesis is to develop and apply safety assessment methodologies to support the safe introduction of newly proposed aviation systems and flight procedures. A variety of mathematical techniques, based on statistical analysis and expert judgment, will be developed for assessment of incident/accident risk. The aim is to reduce the separation distances between aircraft at take-off and landing without compromising safety. Evaluation of separation distances - imposed by wake turbulence and collision risk - has historically been conducted using three approaches:

1. Experimental flight test data,
2. Historic operational data, and
3. Analytical models.

As the newly proposed flight procedures and systems are not yet in operation, this thesis follows the third approach. The aim is to build sufficient safety confidence, enabling the decision makers to decide on operational testing and/or even direct implementation.

Introducing and/or planning changes to the air transport system cannot be done without showing that minimum safety requirements will be satisfied. In this respect, the risk requirements intend to be compliant with the Eurocontrol Safety Regulatory Requirements (ESARR 4) posed by EUROCONTROL's Safety Regulation Commission (SRC). This means that the setting of risk requirements for risk based decision making is an important issue within this doctoral thesis. Historical incident/accident data will be used to support the risk based decision making process.

1.3 Approach: risk based decision making

The approach taken is to apply risk based decision making to support the introduction of new air traffic operations and systems for reduced aircraft separation in the airport environment. As worldwide quantitative risk requirements for the newly proposed air traffic operations have not yet been established, the question arises how to assess the level of risk which may be considered acceptable. Evidently, a zero incident/accident risk can not be realized and therefore risk criteria will have to be developed. There are several fundamental questions that must be resolved:

1. What is the safety level of the current air traffic operations?
2. Are the separation minima for the current air traffic operations overly conservative?
3. Can the current separation minima safely be reduced?
4. What are the requirements for the newly proposed air traffic operations and systems?

These questions require more comprehensive risk assessment models and risk criteria than available. Historically, safety assessments are often based on experimental flight tests and operational data analysis. This doctoral thesis will contribute with new methods based on mathematical modelling and risk based decision support, where the risk criteria for the risk events will be expressed in suitable incident/accident risk metrics based on historical data. To increase airport capacity, the FAA has proposed use of the Precision Runway Monitor (PRM) system during independent parallel approaches. Although safety analyses of the PRM system have provided operational recommendations and requirements, collision risk during a simultaneous missed approach was not previously quantified or assessed. To fill this gap, this doctoral thesis will develop and apply new collision risk assessment models. Wake vortex research has generally focused on analysis of wake vortex behaviour in different weather conditions and on analysis of the impact on wake encountering aircraft. Wake vortex safety related to newly proposed operations for reduced aircraft separation was not previously quantified or assessed in terms of incident/accident risk probabilities. To fill this gap, a new Wake Vortex Induced Risk assessment (WAVIR) methodology will be developed and applied.

Several methodologies for the setting of risk criteria have been proposed up to now. Some methods worth mentioning for air traffic operations are:

1. Air transport as safe as surface public transport (e.g. railway or bus);
2. Expected passenger fatality rate in air traffic comparable with population fatality rate due to all causes;
3. Air crew risk of accidental death comparable with other occupations;
4. Current air traffic accident rates with a factor of improvement;
5. Maintaining current air traffic accident statistics;
6. Fitting in with present safety requirements for air traffic operations.

These methods all support two commonly accepted rationales for acceptance of a newly proposed air traffic operation / system by involved interest groups (i.e. pilots, controllers, regulators), namely by showing that the number of risk events:

- does not exceed some pre-defined, and agreed upon, risk requirement;
- does not increase with the introduction of a new air traffic operation.

Various novel and innovative safety assessment methodologies to derive risk criteria and to set the appropriate requirements for the introduction of new air traffic operations in the airport environment are introduced in this thesis. The proposed methods will be based on:

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

The mathematical risk assessment models and toolsets will be developed and implemented into the NLR Information System for Safety and Risk analysis (ISTaR). Where possible, models will be validated with historical data or statistical data from simulation experiments.

1.4 Thesis outline

This Section 1 provides an introduction to the newly proposed air traffic operations for which the safety will need to be assessed. Section 2 deals with a reduction of the minimum required parallel runway spacing for independent parallel approaches. In Section 3, an assessment of collision risk between aircraft conducting a simultaneous missed approach on converging runways is given. Section 4 describes the development and application of the Wake Vortex Induced Risk assessment (WAVIR) methodology. An assessment of the risk of a wake vortex induced incident/accident during current practice single runway arrivals and under different weather conditions is given. Section 5 presents an assessment of wake vortex safety related to single runway departures. The WAVIR methodology is extended with a graph based model structure, in order to evaluate the impact of hazards and system failures when ATC-Wake is used. Section 6 presents an assessment of the risk of a wake vortex induced incident/accident related to the I-Wake single runway arrival operation under reduced separation (2.0 and 2.5 NM between landing aircraft). Conclusions and recommendations are given in Section 7. References are contained in Section 8. The Appendix A contains a description of the mathematical models used for the assessment of wake vortex induced incident/accident risk.

1.4.1 Collision risk related to independent parallel approaches

An increase in runway capacity may be achieved by using existing parallel runways more effectively or by building additional parallel runways. An important factor for both is the reduction of the minimum required distance between parallel runways used for independent parallel approaches. The minimum required runway spacing for independent parallel approaches has already been reduced several times, thereby trying to maintain the same required level of safety. These reductions were induced by improved operational procedures and technological improvements. The latest reduction to 1035 m (3400 ft), approved by ICAO as from November 9th 1995, was initiated by an airport capacity programme developed by the Federal Aviation Administration (FAA), and based on use of the Precision Runway Monitor (PRM) system. Reducing the minimum required runway spacing without taking other measures generally brings along an enlargement of risks which must be avoided. The main risk is the risk of collision between aircraft. In order to evaluate the risks related to independent parallel approaches, insight into the collision risk during all approach flight phases, including intermediate approach, final approach, and missed approach, is necessary.

Section 2 describes a probabilistic risk analysis of the collision risk between aircraft conducting independent parallel approaches under Instrument Meteorological Conditions (IMC), thereby using Instrument Landing System (ILS) procedures. First, ICAO standards and recommended practices for simultaneous ILS approaches are described. The risk model, developed for determination of the collision risk during identified hazardous flight phases is presented. In order to assess the minimum required runway spacing, a suitable risk metric is selected and a Target Level of Safety is adopted. A number of scenarios with varying runway spacing and different operational conditions are numerically evaluated. The worst case scenario is identified, risk reducing measures are examined, and recommendations for a safe operation are given.

1.4.2 Simultaneous missed approaches on converging runways

The increase in air traffic implies that for busy airports, such as Schiphol, new flight procedures are being developed. For some proposed procedures, ICAO regulations do not exist and a safety assessment incorporating the role of Air Traffic Control (ATC) and pilots is required. The Dutch Civil Aviation Authorities (CAA) and the Luchtverkeersleiding Nederland (LVNL) propose to reduce the Obstacle Clearance Altitude[1] of runway 22 from 350 ft to values less than 200 ft. This would allow the use of runway 22 in actual Cat I weather conditions, which will support the optimization of arrival scheduling.

[1] The Obstacle Clearance Altitude (OCA) is the lowest altitude above the elevation of the relevant runway threshold or above the aerodrome elevation, as applicable, used in establishing compliance with appropriate obstacle clearance criteria.

As a consequence, the point where a missed approach is initiated, when the missed approach is based on visibility conditions or un-stabilized approach, moves to a point further down the approach for runway 22. Section 4 describes a risk analysis performed to quantify and evaluate the risk of simultaneous missed approach procedures on runways 19R and 22, up to and including ILS Cat I circumstances. Runway 19R is one of the primary runways for arriving aircraft [2], and is favourable because of noise restrictions and the minimum impact on the other runways. Arrivals on runway 22 are not favourable with respect to noise as the approach is right across the centre of Amsterdam. Combined use of 19R and 22 is therefore in principle limited to inbound peak time periods and in general not allowed during the night. The missed approach procedure for runway 19R is straight ahead on runway track, whereas the procedure for runway 22 prescribes a left turn with required track change of 63°. For safety reasons, the turn may only be initiated after completion of the initial missed approach phase. As a consequence, in case of a simultaneous missed approach on the runways 19R and 22, the two aircraft missed approach tracks might be close under certain non-favourable conditions. Therefore, although the procedure for runway 19R does not prescribe a turn, in reality ATC often instructs aircraft conducting a missed approach to initiate a turn away from the nominal trajectory for runway 22.

Section 3 outlines the methodology to determine the collision between aircraft, and describes its application to assess the safety of the independent usage of runway 22 as a Cat I ILS runway. The new methodology uses 3 NLR tools ((Information System for Safety and Risk Analysis (ISTaR), Traffic Organizer and Perturbation AnalyZer (TOPAZ), and Flight track and Aircraft Noise Monitoring System (FANOMOS)) in order to assess the collision risk between aircraft conducting a simultaneous missed approach to Schiphol runways 19R (now 18C) and 22.

1.4.3 Wake vortex safety assessment of single runway approaches

With the increasing air-traffic congestion problems around major airports, the problem of wake turbulence has gained a lot of interest, both in the United States of America (USA) and in Europe. Research in the US by the National Aeronautics and Space Administration (NASA) was mainly focused on the development of an Aircraft wake VOrtex Spacing System (AVOSS) and wake vortex advisory systems. In Europe, airport operators such as Frankfurt Airport are spending large efforts in introducing new airport approach procedures (e.g. the High Approach Landing System/Dual Threshold Operation (HALS/DTOP) [108]) in order to enable separation distances between aircraft to be reduced while retaining safety. The current separation minima based on aircraft maximum take-off weight, basically stem from the 70's.

[2] In this doctoral thesis, the numbering of the Amsterdam Schiphol runways is in accordance with the runway numbering in use before the opening of the Polderbaan (in 2003). Note that Schiphol runway 19R (the Zwanenburgbaan) is now indicated as 18C.

Although experience obtained over the past 30 years indicates that the wake vortex separation minima are ‘sufficiently safe’, the current safety level is unclear. Also there is a deficiency of tools and methods for bringing into account new developments in operational usage at busy airports and the introduction of new bigger aircraft in the air transport system.

Therefore, in Section 4, the new Wake Vortex Induced Risk assessment (WAVIR) methodology is presented, and applied to assess wake vortex safety for single runway approaches under current practice flight regulations. In view of the uncertainties and the difficulties in understanding the wake vortex phenomena, a probabilistic approach will be followed to evaluate the safety related to different separation distances between landing aircraft on a single runway. The probabilistic approach is based on a stochastic framework that incorporates sub models for wake vortex evolution, wake encounter, and flight path evolution, and relates the severity of encounters to possible risk events (i.e. incidents/accidents). The impact of weather conditions on wake vortex induced risk will be studied, so as to show that a reduction of the current separation minima – and consequently an increase of capacity – might be possible under certain wind conditions (in particular crosswind and/or strong headwind).

New wake vortex detection, warning, and avoidance systems (as being developed in ATC-Wake and I-Wake) require actions from air traffic controllers and pilots in case there is a discrepancy between wake vortex prediction and detection information. The 'classical' WAVIR approach, which originates from the S-Wake project, is not able to account for human and system performance. Therefore, the next Sections will introduce additional ways of dealing with wake vortex risks, taking into account operational hazards and system failures that can occur.

1.4.4 Safety assessment of ATC-Wake single runway departures

One potential approach to increase airport capacity is to reduce the separation time between aircraft at take-off without compromising safety. Accurate meteorological forecasts and precise measurements of wake turbulence enable more efficient intervals to be set, particularly when weather conditions are stable in time. With the aid of smart planning techniques, these adjustments can generate capacity gains of up to 10%, which has major commercial benefits. ATC-Wake aims to develop and build an integrated system for ATC that would allow variable aircraft 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 improvements when using the ATC-Wake system and to assess the required crosswind values for which the “ATC-Wake mode”, with reduced aircraft separation, can be applied. The wake vortex induced risk between a variety of leader and follower aircraft, departing under various wind conditions, will be evaluated. The ATC-Wake decision-support system will help air traffic controllers decide how long the intervals should be. In the operation for single runway departures, two separation modes are defined:

- The Baseline Separation 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.

Section 5 outlines the methodology to assess wake vortex induced risk during ATC-Wake single runway departures. The methodology makes use of WAVIR in combination with a qualitative analysis of the impact of failure and/or hazards conditions related to the use of ATC-Wake.

1.4.5 Safety assessment of I-Wake single runway arrivals

A potential improvement of wake vortex safety in the airport environment is through installation and use of a wake vortex detection, warning, and avoidance system on-board aircraft. The fundamental part is a pulsed Light Detection and Ranging (LiDAR) sensor system that measures disturbances in the atmosphere and enables real-time forewarning of turbulent conditions. Fifteen seconds or less prior to encountering a severe wake, the flight crew will receive a visual and an aural WARNING alert. A CAUTION alert will be provided between 15 and 30 seconds before encountering a wake vortex that stronger than the caution threshold. This I-Wake system consists of a tactical and a strategic function. The tactical function measures atmospheric disturbances, and alerts the flight crew when a potentially severe wake vortex encounter is expected. The strategic function predicts wake locations and estimates wake behaviour based on information of generating aircraft and meteorological data. The strategic information is presented to the crew in order to raise the flight crew’s wake awareness. Information about possible wake hazards is displayed on the navigation display in the cockpit.

Section 6 presents an investigation of wake vortex safety under reduced separation (2.0 or 2.5 NM between all aircraft) during the approach and landing phases of flight when using such an I-Wake system on-board aircraft. It is assumed that the ATC-Wake system provides predictions for the prevalence of circumstances under which operations with reduced separation can take place. Wake vortex induced risk related to this type of operation has first been assessed qualitatively through a Functional Hazard Assessment [88]. Section 6 now presents a quantitative risk assessment based on a combination of the WAVIR methodology with a variety of mathematical models for aircraft/pilot performance and I-Wake system performance.

2 Collision risk related to the usage of parallel runways for landing

2.1 Introduction

The steady increase in air traffic imposes a need for enhanced airport capacity. An increase in runway capacity may be achieved by using existing parallel runways more effectively or by building additional parallel runways. An important factor for both is the reduction of the minimum required distance between parallel runways used for independent parallel approaches [35, 38]. The minimum required runway spacing for independent parallel approaches has already been reduced several times, thereby trying to maintain the same required level of safety. These reductions were induced by improved operational procedures and technological improvements. The latest reduction to 3400 ft (approved by the International Civil Aviation Organisation (ICAO) as from November 9th 1995) was initiated by an airport capacity programme developed by the Federal Aviation Administration (FAA), and based on use of the Precision Runway Monitor (PRM) system [27, 28, 39].

Reducing the minimum required runway spacing without taking other measures generally brings along an enlargement of risks which must be avoided. Main risk is the risk of collision between aircraft. Accident data regarding collisions between aircraft during parallel runway approaches is not available. In order to properly evaluate the risks related to independent parallel approaches, insight into the collision risk during all approach flight phases, including intermediate approach, final approach, and missed approach, is necessary. This enables the identification of hazardous situations, and the derivation of collision risk reducing measures. A thorough collision risk analysis strongly supports the decision taking about building (additional) parallel runways or defining specific approach and/or missed approach procedures.

This study describes a probabilistic risk analysis of the collision risk between aircraft conducting independent parallel approaches under Instrument Meteorological Conditions (IMC), thereby using Instrument Landing System (ILS) procedures. The next Section 2.2 gives the prescribed procedures and requirements for simultaneous ILS approaches to parallel runways. Section 2.3 contains the identification of hazardous flight phases, identification of suitable risk measures, and adoption of the Target Level of Safety (TLS). Section 2.4 describes the risk model, developed for determination of the collision risk. In section 2.5, a number of scenarios, with varying runway spacing and under different operational conditions, are numerically evaluated. The worst case scenario is identified, and risk reducing measures are examined. The conclusions are given in Section 2.6.

2.2 Requirements and procedures for parallel approaches

2.2.1 Required runway spacing for parallel approaches

In general, parallel runways can be used for four different modes of operations: independent parallel approaches, dependent parallel approaches, independent parallel departures, and segregated parallel operations [30]. The first two operations are illustrated in Figure 2-1 (note that nmi denotes Nautical Miles). With segregated operations, one runway is used for departures, while the other runway is used for arrivals. According to mode of operation and weather condition, different runway spacings are required to obtain the same level of safety. Under IMC, dependent parallel approaches may now be conducted at runways spaced from 2500 ft to 3400 ft, whereas independent parallel approaches are only permitted at runways spaced more than 3400 ft. Over the last 30 years, the minimum required runway spacing for independent parallel approaches has been reduced several times. An overview of these reductions is given in Table 2-1.

Table 2-1 Minimum required runway spacing for independent parallel approaches

Year	Required runway spacing
1962	6200 ft
1963	5000 ft
1974	4300 ft
1995	3400 ft

These reductions were induced by improved operational procedures and technological improvements, such as new navigation and landing systems, and surveillance radar of higher update rate and resolution. ICAO has approved the latest reduction to 3400 ft as from November 9th 1995, provided that certain conditions and requirements are satisfied. One of these requirements is usage of the PRM system, which is a radar monitoring system intended to increase utilization of multiple, closely spaced, parallel runways under IMC [27, 28, 39].

2.2.2 Required operational procedures for parallel approaches

According to available facilities (e.g. ground and onboard equipment), a variety of instrument approach procedures have been developed to guide aircraft safely to the runways during IMC. In general, an instrument procedure may have five segments: arrival, initial, intermediate, final, and missed approach. This study only considers usage of ILS, the presently most used procedure. A detailed description of ILS procedures can be found in the PANS-OPS [32]. For now, only the additional requirements for simultaneous ILS approaches to parallel runways are described.

For independent parallel approaches radar separation minima between aircraft on adjacent localizers are not prescribed [30]. The approaches must be flown straight in, with turn on to the localizer separated vertically by at least 1000 ft. This vertical separation has to be maintained until the aircraft intercept their glide path at the Final Approach Point (FAP). Separate radar controllers have to monitor the approaches once the 1000 ft vertical separation is lost during ILS procedures, and must intervene if any aircraft is observed to penetrate the No Transgression Zone (NTZ). The latter is a corridor of airspace located centrally between the two extended runway centre lines, with width depending on, among other aspects, the surveillance system, responding time of controllers, pilots and aircraft, and lateral track separation [30]. If one aircraft enters the NTZ, the aircraft on the adjacent localizer must be issued appropriate instructions to avoid collision, such as turns or the initiation of a missed approach.

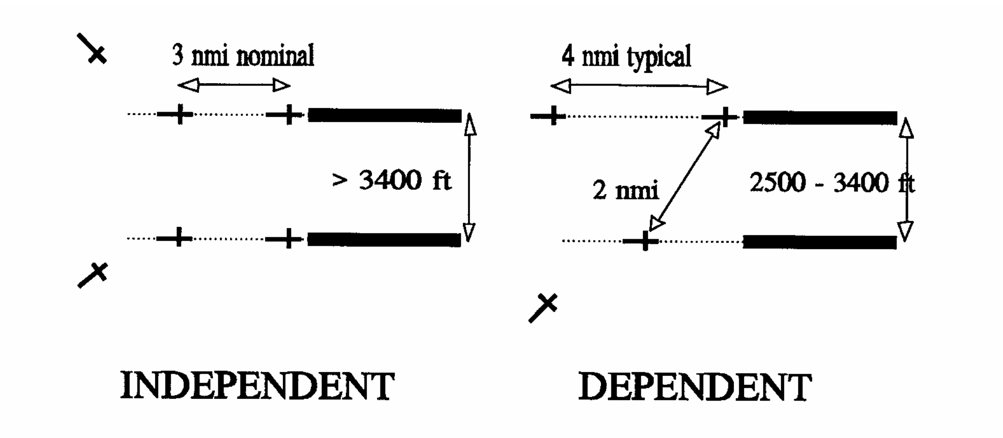

Figure 2-1 Independent and dependent parallel approaches. Derived from source [18]

Other requirements for simultaneous ILS approaches to parallel runways are a maximum intercept angle with the localizer course of 30°, and nominal missed approach tracks diverging by at least 30°, with turns 'as soon as practicable' [30].

For dependent parallel approaches an in-between distance of 2 Nautical Miles (NM) between aircraft on adjacent localizers is prescribed. This diagonal separation brings along a minimum required longitudinal separation of about 4 NM between aircraft on the same runway track. As the minimum longitudinal separation for independent parallel approaches is about 3 NM, the runway capacity when using dependent parallel approaches is significantly less than that for independent approaches [39]. This clearly shows the importance of reducing the minimum required runway spacing for independent parallel approaches (see also Figure 2-1).

2.3 Risk analysis

2.3.1 Identification of hazardous flight phases

This study considers the risks related to independent parallel approaches. Risks also present during approaches to single runways are not taken into account. Such reference implies focusing on the collision risk *between aircraft*. The consequences may be catastrophic: probably loss of both aircraft and death of passengers and crew. The lives of people living in the vicinity of an airport may even be endangered. Evidently, hazardous situations may exist during flight phases containing a relative high uncertainty about the nominal flight trajectory if the runways are closely spaced. Two hazardous flight phases emerge:

- Alignment with the localizer:
  A hazardous situation may exist if one (or both) approaching aircraft overshoots the ILS localizer [3], and deviates towards the adjacent runway, with possibly an endangered aircraft in its path.
- A dual missed approach:
  A hazardous situation may exist if both approaching aircraft initiate a missed approach, especially if the missed approaches are to be initiated along runway direction and/or if there are strong crosswinds.

An aircraft might also be seriously endangered by a wake vortex developed by an aircraft nearby. Up to now, the wake vortex has been ignored in the risk analysis of independent parallel approaches. The gradual reduction of the minimum required parallel runway spacing may raise concerns, especially in case of strong crosswinds. In this Section, the wake vortex problem is also not taken into account.

2.3.2 Identification of suitable risk metrics

There is no single common metric of risk (or safety). There are many different risk metrics which may be used for quantification of the risk of collision with an obstacle or between aircraft. Some of the risk metrics that can be applied for assessing the risk related to air traffic operations are given in Figure 2-2. Note that, in general, a collision may be regarded as a fatal accident, losing adequate separation may be seen as an incident, and the number of fatalities per collision will likely involve all passengers and crew. Other risk metrics can often be derived. In this respect, two types of commonly used risk metrics are individual risk metrics which are based on the risk to an individual being exposed to a risk on a regular basis, and societal risk metrics which take into account the number of persons to be killed in a single event.

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[3] A localizer is the component of an Instrument Landing System (ILS) that provides lateral guidance with respect to the runway centreline.

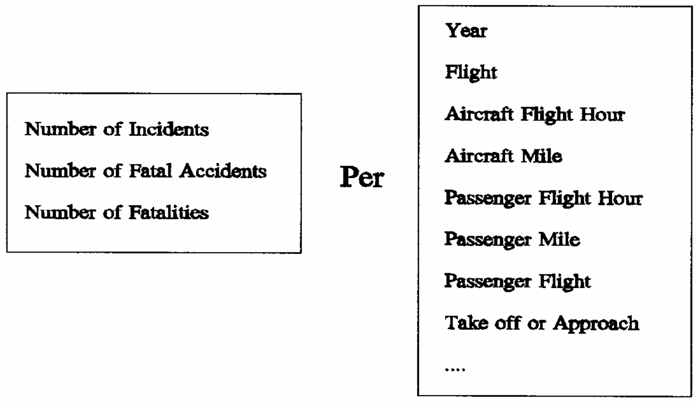

Figure 2-2 Risk metric for air traffic operations (Source [3])

The suitability of a risk metric depends on, among other aspects, the system under consideration, the available data and the required results. In this respect, some considerations leading to the selection of an appropriate risk metric are:

- The risk metric must be attractive and useful for the involved policy makers.
- The risk metric must be able to represent the consequences of possible decisions in an appropriate way. In view of the steady increase in air traffic, this means that the collision probability per year might be more suitable than the collision probability per approach.
- The risk metric must, if possible, not include risks which are outside the scope of the problem under consideration. The risk measure must therefore be restricted to the risk of collision between aircraft, during the approach part of a flight only. Risk measures defined in terms of accidents per flight hour or per mile travelled are not suitable, as the approach takes only a relative small amount of time.
- The risk metric must be used to derive the minimum required parallel runway spacing for independent parallel approaches. For this usage, it is presently not clear if and how to take into account the risk to people living in the vicinity of an airport, as airport surroundings vary widely.
- The risk metric must fit in with present safety requirements. However, worldwide risk criteria are not established for independent parallel approaches. The ICAO single runway approach safety requirement is defined in terms of maximum probability of collision with an obstacle per approach [31]. The FAA uses the collision probability per approach for independent parallel approaches [27]. EUROCONTROL has established Safety Regulatory Requirements for evaluation of ATM related incidents and accidents [78].
- It seems not appropriate to apply societal risk measures for quantification of the risk related to one part of a flight, as passengers and crew are exposed to risks during all parts of a flight. Societal risk measures for aircraft passengers seem only suitable for quantification of the overall collision risk of a flight.

- In other fields (e.g. the fields of surface public transport, hydraulics and civil engineering, chemical processes, and the nuclear field) there is a tendency to use risk measures related to a period of time more often.
- Use of the collision probability per year brings along the possibility that, by conducting a small number of approaches, two parallel runways with a high collision probability per approach can be judged adequately safe. Especially for pilots or crew, this high peak level of risk will be unacceptable.

Considering the above, there may not be *one* most appropriate risk metric. Two suitable risk metrics evolve for the safety analysis of two parallel runways used for landing. Both are defined with respect to the risk of collision *between aircraft* only:

- The collision probability per approach: Commonly used, up to now, for evaluation of the risk during the approach part of a flight. It fits well within the present safety requirements for air traffic operations, but does not take into account an increase in runway capacity.
- The collision probability per year (or its reciprocal, the expected average time interval between two collisions): Easy to interpret. It takes into account the runway capacity, and consequently the steady increase in air traffic. As an aid to planning or decision making, it may therefore be easier to use.

Both risk metrics will therefore be used in this Section.

2.3.3 Adoption of the Target Level of Safety

To determine the minimum required parallel runway spacing, a Target Level of Safety (TLS) needs to be adopted. The TLS represents the level of risk which is considered acceptable. The acceptability of risk depends, naturally, highly on the magnitude of the consequences. In general, safety requirements are based on the principle that an inverse relationship should exist between the probability of occurrence and the magnitude of its consequences. In our case, the consequences could be catastrophic. A collision between aircraft mostly results in loss of both aircraft and death of all passengers and crew, and may even endanger the lives of people on the ground. Evidently, a zero collision probability can not be realized. As, up to now, a worldwide accepted TLS for independent parallel approaches has not yet been established, the question arises how to assess the level of risk which may be considered acceptable. Several methodologies for TLS assessment have been proposed up to now. Some methods worth mentioning for air traffic operations are [24, 29, 37]:

- Air transport as safe as surface public transport (e.g. railway or bus);
- Expected passenger fatality rate in air traffic comparable with population fatality rate due to all causes;
- Air crew risk of accidental death comparable with other occupations;
- Current air traffic accident rates with a factor of improvement;
- Maintaining current air traffic accident statistics;
- Fitting in with present safety requirements for air traffic operations.

Applying these methods does not necessarily lead to the same TLS. Moreover, they depend on the selected risk metric. As a result, several methods are difficult to apply in our situation. The first three methods are usually based on the number of fatalities per distance or per time travelled, which are both not suitable for the approach part of a flight. With regard to the fourth, the problem arises *which* size of the target factor of improvement must be used. From the above methods, the fifth and sixth seem most suited for this study. Note that different actor groups (e.g. airlines, airport authorities, controllers, crew, passengers or policy makers) may support different methods. Airlines often support the first, passengers the second, crew the third, whereas policy makers often support one of the last three methods.

<u>Maintaining current air traffic statistics</u>
Accident data regarding collisions between aircraft during parallel approaches is not available. We develop a method consisting of three steps:

- Assessment of the accident probability per approach:
  The historical accident [4] probability per approach at 'reasonable safe' mainports, with more than about 150000 movements per year, is estimated at $7 \cdot 10^{-7}$ [36].
- Assessment of the fatal accident probability per approach:
  The ratio fatal accidents : non-fatal accidents is of the order 1:4 [34]. This implies a historical fatal accident probability per approach of about 10^{-7}.
- Account for the number of fatalities, and the loss of two aircraft:
  The n^c-criterion [5] is based on the assumption that accidents with n-times larger number of fatalities must correspond to a n^c times lesser probability. Assuming that a collision may bring along about five times more fatalities than an average fatal accident [22], and using the n^c-criterion leads to a TLS for the collision probability per approach of $1 \cdot 10^{-8}$ if c=1.5 and $4 \cdot 10^{-9}$ if c=2.

<u>Fitting in with present air traffic safety requirements</u>
Safety requirements for independent parallel approaches are not yet defined. We develop a method based on the Joint Aviation Requirements (JAR) risk categorisation for ATC *systems*, which relates a number of hazard categories (catastrophic, hazardous/severe, major, minor, no effect) to a maximum probability of occurrence [33]. A collision between aircraft fits in the catastrophic category, for which the maximum probability of occurrence *per flight hour* is 'extremely improbable', and defined at 10^{-9} *per initial cause*. Safety requirements specified per flight hour are however not suitable for the approach part of a flight.

[4] An accident is defined as the occurrence of an unintended ground contact outside the runway [36]. Note that this implies that only *external safety* is being considered, e.g. a crash on the runway is not included in the estimated historical accident probability.
[5] The parameter c can be used to quantify the degree of (in)voluntarity of the people being exposed to a risk, thereby assuming that an involuntary risk requires a larger value of c.

The method now consists of three steps:

- Assess the maximum probability of collision per flight:
  Depending on the world region, the mean flight time may be estimated at 2 to 4 hours [34]. This implies a maximum probability of collision between aircraft of $2 \cdot 10^{-9}$ to $4 \cdot 10^{-9}$ per initial cause.
- Account for the number of initial causes:
  Assuming that there could be 1 to 5 initial causes leading to a collision, implies a maximum probability of collision between aircraft of $2 \cdot 10^{-9}$ to $2 \cdot 10^{-8}$ per flight.
- Assess the TLS for the collision probability per approach:
  Dividing the risk of collision equally between the three main parts of a flight (i.e. take off, en-route, and approach) leads to a TLS of about 10^{-9} to 10^{-8}.

Application of both methods does not motivate the adoption of *one particular* TLS. Problems arising are a large number of numerical assumptions and lack of statistical accident data, leading to considerable uncertainty in TLS assessments. The methods suggest adopting a TLS ranging between one collision in 10^8 and 10^9 approaches, i.e.

$$TLS_{per\,approach} \in \left[1\times10^{-9}, 1\times10^{-8}\right] \qquad (2\text{-}1)$$

The TLS-area for the collision probability per year is derived by assuming on average 200000 approaches per runway per year. This leads to a TLS ranging between one collision in 500 years and one collision in 5000 years, i.e.

$$TLS_{per\,year} \in \left[2\times10^{-4}, 2\times10^{-3}\right] \qquad (2\text{-}2)$$

As a consequence of the difficulties in TLS assessment, the usage of a TLS as an absolute boundary-line between safe and unsafe is hard to justify. Besides, the uncertainty in collision risk assessments is often high, and sensitive to variations in model parameters. The determination of a safe separation standard is therefore also subject to uncertainty. The TLS concept does not really provide the means for taking this uncertainty into account. It is recommended to examine the possibility of broadening the TLS concept, by investigating the development of the ALARP (As Low As Reasonably Practicable) approach for use in aviation risk management [29].

2.3.4 Definition of collision risk judgement scheme

In order to set *the* TLS and/or broaden the TLS concept, policy makers must be consulted. In order to already judge the acceptability of calculated collision risk, a "collision risk judgement scheme" is defined for usage in this study:

- A scenario for which the collision risk is lower than the lowest boundary of the TLS-area, is judged adequately safe.
- A scenario for which the collision risk is higher than the highest boundary of the TLS-area, is judged unsafe. Collision risk reducing measures must be taken.
- A scenario for which the collision risk falls in between both boundaries of the TLS-area, is judged tolerable until the TLS has been set by policy makers. Besides, it is recommended to investigate the feasibility of risk reducing measures.

2.4 Risk model

2.4.1 Overview of the risk model

A risk model is developed for the determination of the selected collision risk measures. The airspace around the airport where the collision risk is evaluated is restricted to the intermediate, final, and missed approach flight phases, thereby assuming that the arrival and initial phases bring along a negligible risk of collision.

The risk model consists of three parts. The first part, the *conditional* collision probability model, developed by Couwenberg [26], describes how to calculate the conditional collision probability between two aircraft *given* the localizer interception times and types of operation (landing or missed approach). The second part describes the nominal flight trajectories and the probability distributions for the deviations from the nominal flight trajectories. The third part takes into account the missed approach rate, dependency between aircraft operations at adjacent runways, initiation altitude of a missed approach, localizer interception times, and air traffic density in order to derive the selected risk measures (collision probability per approach and per year). The remainder of Section 2.4 describes these three parts. A more detailed description of the risk model is given in Speijker [38]. The possibility of intervention when blunders occur is not taken into account. In reality, the collision risk might therefore be somewhat smaller than calculated.

2.4.2 The conditional collision probability model

Four different combinations of operations η^{ij} are considered, consisting of a landing or missed approach for aircraft *i* and a landing or missed approach for aircraft *j*. That is $\eta^{ij} = (\eta^i, \eta^j)$, with $\eta^i = 1,2$ and $\eta^j = 1,2$. The time dependent conditional collision probability between two aircraft *i* and *j* given their localizer interception times and types of aircraft operation (landing or missed approach at a fixed altitude) is now denoted by

$$P_{collision}(t, \eta^{ij}) \qquad (2\text{-}3)$$

where η^{ij} indicates the four possible combinations of type of operations.

Let the flight trajectories of aircraft i and j be represented by (x^i_t, y^i_t, z^i_t) and (x^j_t, y^j_t, z^j_t), where the three vector components give the longitudinal, lateral, and vertical coordinates of the geometric centres of the rectangular bounding boxes about the aircraft respectively. The parameters d_x^i, d_y^i and d_z^i represent the size of aircraft i. In accordance with the ICAO Collision Risk Model (CRM) [33], the aircraft longitudinal position and speed will be taken deterministic. Let the stochastic movement $(X(t),Y(t),Z(t))\}$ now represent the relative position between the centres of the aircraft i and j, i.e.

$$\begin{aligned} X(t) &= X^j_t - X^i_t \\ Y(t) &= Y^j_t - Y^i_t \\ Z(t) &= Z^j_t - Z^i_t \end{aligned} \tag{2-4}$$

Define the *collision area* of aircraft i and j by

$$d_X^{ij} = \frac{d_x^i + d_x^j}{2}, \quad d_y^{ij} = \frac{d_y^i + d_y^j}{2}, \quad d_z^{ij} = \frac{d_z^i + d_z^j}{2} \tag{2-5}$$

Using the fact that a collision occurs when there is a simultaneous overlap of the bounding boxes in all of the three coordinate directions, it follows that:

$$P_{collision}(t,\eta^{ij}) = P\left[|X(t)| < d_x^{ij} \wedge |Y(t)| < d_y^{ij} \wedge |Z(t)| < d_z^{ij} \right]_{\eta^{ij}} \tag{2-6}$$

The pilot controls the aircraft approach position using the navigation signals. The lateral position and vertical position are assumed independent, as these are based on the (independent) ILS localizer and glide slope navigation signals respectively. In case the stochastic aircraft movements in the 3 directions are independent, the conditional collision probability is equal to

$$P_{collision}(t,\eta^{ij}) = P\left[|X(t)| < d_x^{ij} \right] \times P\left[|Y(t)| < d_y^{ij} \right] \times P\left[|Z(t)| < d_z^{ij} \right]_{\eta^{ij}} \tag{2-7}$$

Using the deterministic character of the longitudinal coordinate [33], the following expression for the conditional collision probability between two aircraft is stated:

$$P_{collision}(t_p,\eta^{ij}) = P\left[|Y(t_p)| < d_y^{ij} \right] \times P\left[|Z(t_p)| < d_z^{ij} \right]_{\eta^{ij}}, \; x(t_p) = 0 \tag{2-8}$$

where the passage time t_P is determined from the localizer interception times and the deterministic velocities of both aircraft. Note that $P_{collision}(t, \eta^{ij}) = 0$, if $x(t) \neq 0, \forall t$.

The lateral and vertical overlap probabilities can be determined from the probability density functions $f_{Y_t^i}$ and $f_{Y_t^j}$ by convolution. For the lateral overlap holds:

$$P\left[\left|Y(t)\right| < d_y^{ij}\right] = \int_{-d_y^{ij}}^{d_y^{ij}} f_y(y)dy = \int_{-d_y^{ij}}^{d_y^{ij}} \int_{-\infty}^{\infty} f_{y_t^i}(y+u) f_{Y_t^j}(u)dudy \qquad (2\text{-}9)$$

A similar expression can be derived for the vertical overlap probability. Since the lateral overlap probability is very small, equation (2-9) may be approximated by

$$P\left[\left|Y(t)\right| < d_y^{ij}\right] \approx 2d_y^{ij} \; f_Y(0) = 2d_y^{ij} \int_{-\infty}^{\infty} f_{Y_t^i}(u) f_{Y_t^j}(u)du \qquad (2\text{-}10)$$

The vertical overlap probability can be considerable, and needs to be estimated by numerical integration (e.g. using Simpson's rule).

2.4.3 Determining the flight trajectories

The airspace around the airport where the collision risk is evaluated is restricted to the intermediate, final, and missed approach flight phases. The arrival and initial flight phases are assumed to bring along a negligible risk and are therefore left aside.

The aircraft intercept their localizer at the Intermediate Fix (IF). From the IF, the aircraft are expected to fly along runway direction. During intermediate approach the flight trajectory is kept horizontal. From the Final Approach Point (FAP), an aircraft descends with a glide path angle of about 3°. Several reasons may cause an aircraft to initiate a missed approach at any altitude between the FAP and Decision Height (DH). The missed approach path consists of a curved part and a climb out part. From the Climb Out Point (COP), the aircraft climb under a constant climb out gradient. The missed approach track direction can only be changed from a certain altitude, above the COP. The nominal flight trajectories of aircraft approaching the adjacent parallel runways are sketched in Figure 2-3, and satisfy the requirements for independent parallel approaches, which are described in Section 2.2.

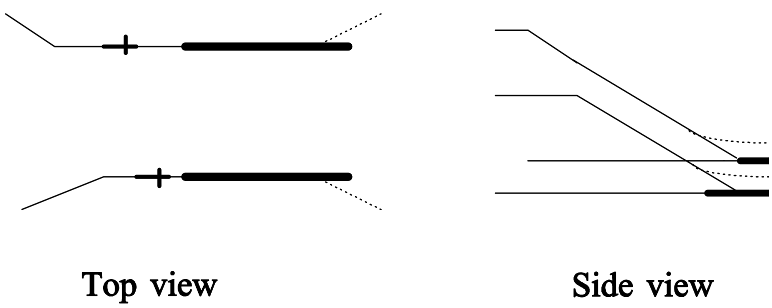

Figure 2-3 Top-view and side-view of the nominal flight trajectories

The probability distributions for the deviations from the nominal flight trajectories during intermediate approach are determined with data collected with the FANOMOS flight trajectory registration system in August 1995 at Schiphol runway 06. The probability distributions for the deviations from the nominal flight trajectory during final approach and missed approach are determined with a method developed by ICAO [31]. For an extensive description, see Speijker [38] and Couwenberg [26]. The deterministic aircraft speed, depending on aircraft category and position, is given in Table 2-2, and satisfies the requirements defined in the PANS-OPS [32].

Table 2-2 Deterministic aircraft speed in knots

Aircraft Category	Intermediate Approach	Final Approach		Missed Approach	
		2000-1000 ft	1000 ft-DH	DH-1000 ft	1000-2000 ft
A	120	95	70	90	100
B	150	120	90	110	140
C	190	150	120	140	200
D	230	170	140	160	230

2.4.4 Determining the identified risk metrics

To obtain the collision probability between two aircraft, the missed approach rate, dependency between aircraft operations at adjacent runways, initiation altitude of a missed approach, and localizer interception times are taken into account. The conditional collision probability between two aircraft *i* and *j* given their localizer interception times, t^{i}_{loc} and t^{j}_{loc} , is defined by

$$P_{collision}(t_{loc}) = \sum_{\eta^i=1}^{2}\sum_{\eta^j=1}^{2} P\left\{\eta^{ij} = \left(\eta^i, \eta^j\right)\right\} \bullet P_{collision}(t_P, \eta^{ij}) \qquad (2\text{-}11)$$

with $t_{loc} = t^{j}_{loc} - t^{i}_{loc}$ as the time difference between the localizer interception times of aircraft *j* and *i*. The probabilities $P_{\eta^{ij}}$ (with $\eta^{i}=1,2$ and $\eta^{j}=1,2$) give the probabilities of the occurrence of the four combinations of type of operations:

$$P_{\eta^{ij}} = P\left\{\eta^{ij} = \left(\eta^i, \eta^j\right)\right\} \qquad (2\text{-}12)$$

These probabilities of occurrence are based on the missed approach rate and the dependency between aircraft operations at adjacent runways. Denote the stochastic missed approach rate by R_{MA}, and let ρ_{dep} represent the extent to which the operations of aircraft *i* and *j* are dependent, where $0 \leq \rho_{dep} \leq 1$. Full independency is given by $\rho_{dep}=0$, and full dependency by $\rho_{dep}=1$. In the latter case there are only two possibilities: a dual landing or a dual missed approach.

The probabilities $P_{\eta^{ij}}$ (with $\eta^i=1,2$ and $\eta^j=1,2$), given realisation r_{MA} of R_{MA} and ρ_{dep} , are estimated by

$$
\begin{aligned}
P_{\eta^{ij}}\ (r_{MA}, \rho_{dep}) &= (1-\rho_{dep})(1-r_{MA})^2 + \rho_{dep}\,(1-r_{MA}) &&, \eta^i=1 \text{ and } \eta^j=1\\
P_{\eta^{ij}}\ (r_{MA}, \rho_{dep}) &= (1-\rho_{dep})(1-r_{MA})\, r_{MA} &&, \eta^i=2 \text{ and } \eta^j=1\\
P_{\eta^{ij}}\ (r_{MA}, \rho_{dep}) &= (1-\rho_{dep})(1-r_{MA})\, r_{MA} &&, \eta^i=1 \text{ and } \eta^j=2\\
P_{\eta^{ij}}\ (r_{MA}, \rho_{dep}) &= (1-\rho_{dep})\, r_{MA}^{\ 2} + \rho_{dep}\, r_{MA} &&, \eta^i=2 \text{ and } \eta^j=2
\end{aligned}
\qquad (2\text{-}13)
$$

Let $f_{R_{MA}}$ denote the probability density function of the missed approach rate and $\bar{\rho}_{dep}$ the best estimate for the dependency parameter. The probabilities $P_{\eta^{ij}}$ may now be stated as

$$
P_{\eta^{ij}} = \int_{r=0}^{1} P_{\eta^{ij}}(r_{MA}, \bar{\rho}_{dep})\, f_{R_{MA}}(r_{MA})\, dr_{MA}\ , \qquad \eta^{ij} = \left(\eta^i, \eta^j\right), \text{with } \eta^i = 1, 2 \text{ and } \eta^{\mathrm{j}} = 1, 2 \qquad (2\text{-}14)
$$

In the absence of statistical data, the missed approach rate must be represented by a (subjective) probability distribution elicited through the use of expert opinion [25]. In this study, R_{MA} is assumed to be Beta distributed with shape parameters p_{MA} and q_{MA} , i.e. $R_{MA} \sim \text{Beta}(p_{MA}, q_{MA})$. For a motivation see Speijker [38]. The parameters p_{MA} and q_{MA} can be determined with a procedure based on elicitation of two percentiles [23]. Next aspect is the initiation altitude of a missed approach. As most missed approaches are initiated at or near DH [31], it is assumed that missed approaches are to be initiated at 200 ft, the DH for ILS Category I.

To obtain the collision probability between two aircraft, the localizer interception times are now taken into account. Considering the *independent* use of the runways, it is assumed that the localizer interception times are uniformly distributed.

Consequently,

$$
P_{collision} = \frac{1}{T_{ij}} \int_{t=0}^{T_{ij}} P_{collision}(t)\, dt \qquad (2\text{-}14)
$$

with T_{ij} such that each possible passage point is taken into account.

The collision probability per approach, $P_{collision\ per\ approach}$, can be determined in a similar way by taking into account the air traffic density as well. A method for determining the collision probability per approach is described in Speijker [38].
The collision probability per year, $P_{collision\ per\ year}$, can be determined from the collision probability per approach by taking into account the number of approaches per runway per year,

n. Because of the fact that *independent* parallel approaches are being performed, a mutual independence between the runway approaches may be assumed, i.e.

$$P_{collision\ per\ year} = 1 - \left[1 - P_{collision\ per\ approach}\right]^n \qquad (2\text{-}15)$$

If $P_{collision\ per\ approach} \ll 1$, this may be simplified by using first order approximation:

$$P_{collision\ per\ year} \approx n \times P_{collision\ per\ approach} \qquad (2\text{-}16)$$

which is equal to the expected number of collisions per year.

2.5 Numerical evaluations

2.5.1 Definition of a baseline scenario

In order to obtain a first, most likely, estimation of the collision risk related to independent parallel approaches, a baseline scenario is defined which satisfies the currently prescribed operational procedures. Its main characteristics are:

- Distance between runway thresholds, (x_d,y_d): The most interesting scenario is specified by x_d=0 and y_d=1035 m (the minimum required parallel runway spacing).
- Traffic density: The time interval between aircraft approaching a runway is 75 s.
- Average number of approaches per runway per year: 200000, reflecting the fact that, in general, during the night only part of runway capacity may be utilized.
- Aircraft speed categories: C and D, for aircraft approaching the adjacent runways.
- Aircraft sizes: 70.51×59.64×19.33 m, corresponding to a Boeing 747.
- ILS Category: I, bringing along the largest uncertainty about the glide path.
- Localizer interception: The angle with the localizer course is between 0° and 30°.
- Intermediate approach altitudes: The aircraft approaching the adjacent runways are expected to fly at altitudes of 2000 ft (right runway) and 3000 ft (left runway).
- Intermediate segment length: 5.0 km, in accordance with the collected flight data.
- Glide path angle: 3°.
- Climb out gradient: 4.0 %.
- Missed approach initiation altitudes: 200 ft, which is the minimum required Decision Height (DH) for ILS category I.
- Missed approach turns: 30° angle of divergence between the nominal missed approach tracks, with turns at an altitude of 500 ft.
- Missed approach rate: Beta distributed stochastic variable with shape parameters p_{MA} =1.17 and q_{MA} =84.66, corresponding to elicited median (50-th percentile) and 5-th percentile of

0.01 and 0.001 respectively. A value of 0.01 (one missed approach in 100 approaches) is also used in the ICAO CRM [31] and in the PANS-OPS [32].

- Dependency parameter , $\bar{\rho}_{dep}$: 0.30, derived by assuming that the main reasons for a dual missed approach are turbulence and windshear (see Speijker [38]).

2.5.2 Numerical results for the baseline scenario

Based on the risk model, a computer program has been implemented in the NLR Information System for Safety and Risk analysis (ISTaR). With this computer program the baseline scenario has been numerically evaluated. The main results are:

- The calculated collision probability per approach is $3.6 \cdot 10^{-9}$.
- The calculated collision probability per year per runway is $7.2 \cdot 10^{-4}$.
- The numerical values of both risk metrics fall within the defined TLS-areas, and may therefore be judged 'tolerable' until the TLS has been set by policy makers.
- The probability of a near miss, which is defined as losing 500 ft vertical and lateral separation without colliding, is $7.44 \cdot 10^{-5}$ per approach, which implies that about 15 near misses are expected to occur per year. This is relatively high and therefore worrying. Note that it would be possible to validate these near miss probability estimates with flight data, once two runways spaced exactly 1035 m are used for independent parallel approaches.
- The maximum conditional probability of an aircraft entering a 2000 ft NTZ during final approach is considerable, and equal to $1.47 \cdot 10^{-2}$ near glide path interception.
- The collision probability during intermediate approach is highest when passage occurs near turn on to the localizer (magnitude about 10^{-7}).
- The collision probability during a dual missed approach is in between about 10^{-6} (when passage occurs near the turn altitude of 500 ft) and 10^{-10} to 10^{-11} (when passage occurs at a much higher altitude), and may be judged acceptable only in case of an early turn.
- The collision probability during final approach maximally reaches a magnitude of about 10^{-9} to 10^{-10}, which is relatively low compared with the most hazardous phases during intermediate approach (near ILS localizer intercept) and a dual missed approach.

The collision probability *during final approach* is already relatively low. Technological improvements and improved operational procedures, leading to further increased safety during final approach, do therefore not significantly lower the collision probability per year. To increase the safety related to independent parallel approaches, the relative high collision probability near both turn on to the localizer and near the turn altitude must be lowered.

Varying the lateral distance between the two parallel runways, while keeping the other parameters according to the baseline scenario, shows that the collision risk increases with a gradually higher rate if the lateral distance decreases (Figure 2-4).

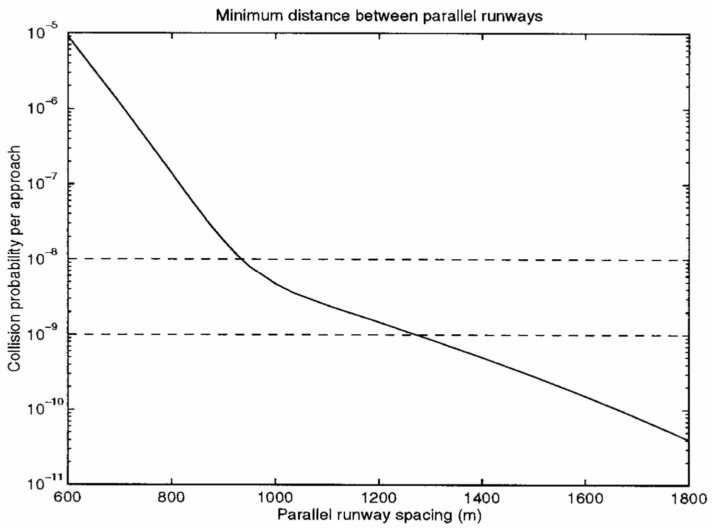

Figure 2-4 Collision probability per year versus parallel runway spacing

Important numerical results, valid under baseline operational conditions, are:

- Below about 600 m runway spacing, a collision is most likely to occur every year. The collision probability per year increases even further if the lateral distance is reduced.
- Below 930 m runway spacing, the collision risk reaches a high and unacceptable level of at least one collision in 100 million approaches (or one collision in 500 years).
- Above 1270 m runway spacing, the collision risk attains a low and acceptable level of at most one collision in 1000 million approaches (or one collision in 5000 years).

Note that the currently required minimum parallel runway spacing of 1035 m (or 3400 ft) falls within the 'tolerable area' of the 'collision risk judgment scheme'.

2.5.3 Sensitivity analysis

Sensitivity analysis shows to which model parameters the risk measures (collision probability per approach and per year) are sensitive. Varying model parameters, while keeping the other conditions in accordance with the baseline scenario, indicates that the risk metrics are sensitive to, especially, the nominal vertical separation during intermediate approach, the angle of divergence between the nominal missed approach tracks, and the missed approach turn altitude. The influence of other missed approach parameters on the collision risk is relative low, but will be larger if the angle of divergence decreases or the missed approach turn altitude increases. It may even be considerable if missed approaches are to be initiated along runway direction. A detailed sensitivity analysis, including numerical computations, is found in Speijker [38].

2.5.4 Collision risk reducing measures

The following metrics are currently prescribed by ICAO for simultaneous and independent parallel approaches, for trying to maintain the required level of safety:

- At least 1000 ft nominal vertical separation during intermediate approach;
- At least 30° angle of divergence between the nominal missed approach tracks, with turns 'as soon as practicable';
- A maximum intercept angle with the localizer course of 30°.

In the following, the effectiveness of each of the first two metrics is numerically evaluated, while keeping the other conditions according to the baseline scenario. The impact of staggered parallel runways on the collision risk is also determined.

- Nominal vertical separation during intermediate approach:
  According to Table 2-3, the risk decreases rapidly if the nominal vertical separation increases. With less than 500 ft, a collision is likely to occur within 1 to 3 years.

Table 2-3 Effectiveness of increasing vertical separation during intermediate approach

Vertical separation	$P_{collision, per approach}$	$P_{collision, per year}$
0 ft	$6.59 \cdot 10^{-5}$	1.00
500 ft	$1.85 \cdot 10^{-6}$	$3.09 \cdot 10^{-1}$
750 ft	$2.75 \cdot 10^{-8}$	$5.48 \cdot 10^{-3}$
1000 ft	$3.60 \cdot 10^{-9}$	$7.20 \cdot 10^{-4}$

Evidently, at least 1000 ft nominal vertical separation is required. A separation of more than 1000 ft will reduce the risk even further. However, the feasibility of this is rather questionable as it probably lowers runway capacity significantly.

- Diverging nominal missed approach tracks, with turns 'as soon as practicable':
  Table 2-4 shows that the risk decreases with a gradually higher rate if the turn altitude decreases. A turn altitude above 500 ft may be judged unacceptable.

Table 2-4 Effectiveness of decreasing turn altitude

Turn altitude	$P_{collision, per approach}$	$P_{collision, per year}$
500 ft	$3.60 \cdot 10^{-9}$	$7.20 \cdot 10^{-4}$
1000 ft	$1.68 \cdot 10^{-7}$	$3.30 \cdot 10^{-2}$
1500 ft	$1.84 \cdot 10^{-6}$	$3.08 \cdot 10^{-1}$
2000 ft	$4.48 \cdot 10^{-6}$	$5.92 \cdot 10^{-1}$

Table 2-5 shows that the risk decreases with a gradually smaller rate if the angle of divergence increases. Worth noticing is that increasing the angle of divergence to more than 20° to 30° hardly reduces the collision risk any further.

Table 2-5 Effectiveness of increasing angle of divergence between missed approach tracks

Angle of divergence	$P_{collision, per approach}$	$P_{collision, per year}$
0°	$4.48 \bullet 10^{-6}$	$5.92 \bullet 10^{-1}$
10°	$2.45 \bullet 10^{-8}$	$4.89 \bullet 10^{-3}$
20°	$3.75 \bullet 10^{-9}$	$7.50 \bullet 10^{-4}$
30°	$3.60 \bullet 10^{-9}$	$7.20 \bullet 10^{-4}$

Clearly, at least 20° to 30° angle of divergence is required, with turns 'as soon as practicable', and not above 500 ft.

- Staggered parallel runways:
  Table 2-6 shows the risk for three longitudinal distances between runway thresholds, x_d , where a positive sign indicates that the 'left runway' is located 'farthest away', and a negative sign the opposite. The collision risk decreases if x_d increases.

Table 2-6 Effectiveness of staggering the parallel runways

x_d	$P_{collision, per approach}$	$P_{collision, per year}$
-2000 m	$1.38 \bullet 10^{-7}$	$2.72 \bullet 10^{-2}$
0 m	$3.60 \bullet 10^{-9}$	$7.20 \bullet 10^{-4}$
+2000 m	$1.53 \bullet 10^{-11}$	$3.06 \bullet 10^{-6}$

Parallel runways should, if possible, be built with some - as large as possible - longitudinal distance between runway thresholds. Independent parallel approaches must then be performed such that the aircraft with the highest located FAP (usually at 3000 ft) approach the runway located farthest away. It turns out that all three numerically evaluated measures are effective in reducing the collision risk. Besides, although not numerically evaluated, it is reasonable to expect that the collision risk decreases if the localizer intercept angle decreases, especially with lacking nominal vertical separation during intermediate approach.

2.5.5 Worst case scenario

The worst case scenario is specified on basis of a large number of numerically evaluated scenarios. Besides 1035 m parallel runway spacing, its main characteristics differing from the baseline scenario are:

- Aircraft size: 95.0×80.0×20 m.
- Traffic density: The time interval between aircraft approaching a runway is 60 s.
- Intermediate approach altitudes: The aircraft approaching the adjacent runways are expected to fly at equal altitudes of 2000 ft.
- Climb out gradient: 2.5%.
- Missed approach tracks: along runway direction (i.e. no turns specified).

Under these worst case operational conditions, the collision probability per approach is $1.38 \bullet 10^{-4}$, which is definitely unacceptable. A collision is even most likely to occur a couple of times per year! Especially the lacking nominal vertical separation during intermediate approach, and the insufficient nominal lateral distance during a dual missed approach are responsible for this unacceptable high risk of collision. The collision probability is considerable when passage occurs near turn on to the localizer (magnitude about 10^{-4} to 10^{-3}) or, in case of a dual missed approach, when passage occurs above about 1000 ft (magnitude about 10^{-4} to 10^{-2}).

Numerical evaluations show that the collision risk reduces into the defined *tolerable* area of $[1\times10^{-9}, 1\times10^{-8}]$ by application of the following two measures:

- 1000 ft nominal vertical separation during intermediate approach;
- 30° angle of divergence between the missed approach tracks, with turns at 500 ft.

Varying the lateral distance between the runways shows that increasing the parallel runway spacing is not practicable in reducing the risk under worst case conditions. Increasing the runway spacing to *4240* m reduces the collision probability per approach to $1.0 \bullet 10^{-8}$, and increasing to *5140* m is necessary for reduction to $1.0 \bullet 10^{-9}$!

2.6 Conclusions

In this study a probabilistic risk analysis regarding the risk of collision between aircraft performing independent parallel approaches has been described. Two suitable risk metrics evolved for the risk analysis of two parallel runways used for landing: the collision probability per approach and the collision probability per year, defined with respect to the risk of collision between aircraft. Application of two methods for TLS assessment provided *TLS-areas*, defining ranges for the TLS used in this study:

$$TLS_{per\,approach} \in \left[1\times10^{-9}, 1\times10^{-8}\right] \; or \; TLS_{per\,year} \in \left[2\times10^{-4}, 2\times10^{-3}\right] \qquad (2\text{-}17)$$

Because of problems arising in assessment and usage of the TLS, it is recommended to examine the possibility of broadening the TLS concept. In order to set *the* TLS and/or broaden the TLS concept, policy makers must be consulted.

A risk model was developed and implemented for determination of the collision risk. Application of the risk model to a number of scenarios, with varying parallel runway spacing, and under different operational conditions, showed that:

- The collision probability between two aircraft can be considerable and unacceptable under certain conditions, especially near turn on to the localizer and during a dual missed approach;
- Technological improvements and improved operational procedures, leading to an increased safety during final approach, do <u>not</u> significantly lower the collision probability per approach.

Numerical evaluations showed that the following measures are essential, and must be prescribed, for trying to maintain the collision risk at a low and acceptable level:

- At least 20° to 30° angle of divergence between the nominal missed approach tracks, with turns 'as soon as practicable', and not above 500 ft;
- At least 1000 ft nominal vertical separation during intermediate approach;
- Some - as large as possible - longitudinal distance between the runway thresholds of the parallel runways. Besides, the approaches must then be performed such that the aircraft with the highest FAP approach the runway located 'farthest away'.

Provided that these measures are applied and assuming that a TLS from the specified TLS-areas is used, independent parallel approaches may be judged adequately safe if the runway spacing is greater than 1270 m, and unsafe if the spacing is lower than 930 m.

Acknowledgements
This study was performed at the request of the Dutch Civil Aviation Authorities. The support of Erwin Lassooij, who brought forward the results to the ICAO Obstacle Clearance Panel, was especially appreciated.

3 Risk analysis of simultaneous missed approaches on Schiphol converging runways 19R and 22

3.1 Introduction

The increase in air traffic implies that for busy airports, such as Schiphol, new and advanced ATM procedures are being developed. For some proposed ATM procedures, ICAO regulations do not exist and a safety assessment incorporating the role of ATC and pilots is required. This study concerns a risk analysis of simultaneous missed approaches on runways 19R and 22, where the Obstacle Clearance Altitude (OCA) of runway 22 is proposed to be reduced from 350 ft to values less than 200 ft. The current OCA of 350 ft has been established as from ILS installation in 1993, when a ‘bend’ in the ILS localizer signal just before 200 ft was noted. According to Westerveld [46], the ILS localizer signal is of sufficient quality to allow the proposed reduction of the OCA.

A reduction of the OCA may allow the use of runway 22 in actual CAT-I weather conditions, which will support the optimisation of the arrival scheduling, in particular for forecasted CAT-I conditions. However, a reduction of the OCA moves the decision point of making a missed approach closer to the runway threshold. This will affect the distance between the prescribed missed approach trajectories of runways 19R and 22, which could result in an increase of the collision risk. The primary objective of the research can be formulated as follows [40]:
The quantification and evaluation of the risks of simultaneous missed approach procedures on runways 19R and 22, up to and including ILS CAT I circumstances.

The next Section 3.2 describes the currently prescribed (missed) approach procedures for runways 19R and 22, including requirements concerning the usage of this runway combination, the role of ATC and pilots. Section 3.3 deals with the adoption of a risk criteria framework to judge the acceptability of collision risk, including identification of suitable metrics and assessment of safety requirements for the collision risk between aircraft. Section 3.4 describes the extension of an existing risk model to enable determination of the collision risk. This extended model is developed through an integral usage of three NLR tools: ISTaR, TOPAZ, and FANOMOS. In Section 3.5, sixteen representative scenarios, with varying operational aspects, will be evaluated and the worst case scenario will be identified. The role of ATC monitoring and instructions and some possible future procedural changes are investigated, thereby examining the necessity of possible risk reducing measures. Based on the numerical results and the identified hazards, Section 3.6 contains the safety criticality assessment of the proposed reduction of the OCA to values below 200 ft, and some operational feedback concerning the necessity of (re)design of the proposed procedures for runways 19R and 22. The conclusions and recommendations with respect to the safety of the independent usage of runway 22 as a CAT-I ILS runway will be given in Section 3.7.

3.2 Identification of requirements and procedures

3.2.1 Schiphol runway combination 19R and 22

Runway 19R (recently re-numbered to 18C) is one of the primary runways for arriving aircraft. The runway 19R is favourable because of noise restrictions and the minimum impact on the other runways. Arrivals on runway 22 are not favourable with respect to noise as the approach is right across the centre of Amsterdam. Combined use of 19R and 22 is in principle limited to inbound peak time periods, and in general not allowed during the night.

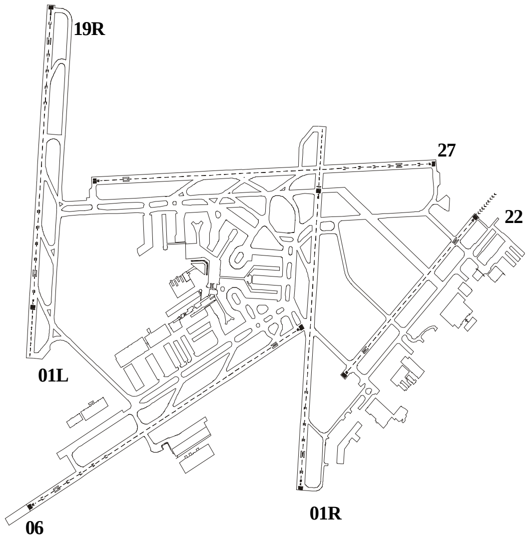

Figure 3-1 Schiphol runway lay-out (before opening of the Polderbaan)

3.2.2 Aircraft missed approach procedures

The missed approach procedure for runway 19R is straight ahead on runway track, whereas the procedure for runway 22 prescribes a left turn to track 160° MAG, i.e. the required track change is 223°-160°=63° [45]. For safety reasons, the turn may only be initiated after completion of the initial missed approach phase [32], which comprises an aircraft type dependent task breakdown. The manoeuvre during the initial missed approach phase necessitates concentrated attention of the pilot especially when establishing climb and changes in configuration, and it is assumed that the guidance equipment cannot be fully utilised. No requirements to change the flight direction are acceptable in this phase. The initial approach phase may require up to 30-40 seconds (or 1.0 to 1.8 NM travelled) before *at the earliest* lateral navigation can be adjusted and the turn *initiated.* Relevant missed approach rulemaking normally covers only a special case for the initiation of a missed approach: no visual contact at decision height due to low clouds and/or reduced visibility in fog. Although it can be argued that low-visibility is the most critical reason when considering obstacle clearance, there are other missed approach triggering reasons, resulting in a variety of possible initiation altitudes from DH to 2000 ft or more [41, 45].

3.2.3 Air Traffic Control procedures

ATC is responsible for the safe and efficient management of air traffic on and around the airport [47, 48]. Tower Control maintains control of the aircraft from the point that the aircraft is established on ILS localiser until either the aircraft

- leaves the runway and is transferred to the ground controller, or
- initiates a missed approach and is transferred to approach control for new line up for landing.

The tasks for the controller focus on final approach sequencing, monitoring of the (missed) approach, provision of a landing clearance and the necessary R/T communications. Usually two different tower controllers manage the aircraft on the arrivals for 19R and 22, using different frequencies for communication with aircraft conducting a missed approach [41]. Pilots will not automatically be aware of the other aircraft initiating a missed approach other than from visual reference or when being informed by ATC. Although the procedure for runway 19R does not prescribe a turn, in reality ATC often instructs aircraft conducting a missed approach on this runway to also initiate a turn away from the nominal trajectory for runway 22 [43], and will also provide instructions (e.g. “turn right”, “turn left”, “climb to”) to avoid collisions.

3.2.4 Differences between current and proposed procedures

This study focuses on the situation of runways 19R and 22, where the OCA for runway 22 will be reduced from 350 to values below 200 ft. This reduction might allow a DH of 200 ft, enabling the use of runway 22 in actual CAT-I weather conditions. The missed approach procedure for runway 19R will not be changed, provided that an acceptable level of safety can be obtained. It is also not expected that a change in procedure for runway 22 will have an effect on ATC tasks / procedures or communication, or will have an effect on the approaches to runway 19R. Most important aspect is that the point where a missed approach is initiated, *when the missed approach is based on visibility conditions or unstabilized approach*, moves to a point further down the approach for runway 22 (the nominal distance to threshold reduces from about 1.1 NM to 0.6 NM). The missed approach path for runway 22 will move closer to the missed approach path for runway 19R, which is a factor that might increase the risk of collision. Runway selection is based on meteorological data that has a resolution of 100ft. The tower supervisor will probably decide *not* to use the runway combination 19R/22 when a broken cloud base of 200 ft is reported, since the margin with the 200ft DH is too small. Therefore the lowest (forecasted) ceiling for the selection of runway 22 as landing runway will be reduced from a broken cloud base (BKN[6]) of 400 ft to BKN 300 ft, which is a factor that might influence the missed approach rate [41].

[6] BKN denotes the altitude at which the clouds are broken. A BKN 400 ft implies a (forecasted) broken cloud base at 400 ft.

3.3 Risk criteria framework

3.3.1 Introduction

Up to now, the most commonly used risk criteria framework for the collision risk between aircraft in the airport surroundings include:

- A single risk metric defined in terms of the collision risk probability per approach;
- A risk requirement based on the Target Level of Safety (TLS) approach.

As an example, previous research studies undertaken for the Civil Aviation Authorities proposed a risk criteria framework based on a maximum collision risk probability per approach of between 10^{-8} and 10^{-9} [2, 49]. Research studies for the European Commission and Eurocontrol show a tendency to also investigate the possible application of:

- risk metrics that convey the costs and benefits of possible decisions more clearly, and
- risk requirements that are based on the As-Low-As-Reasonably-Practicable approach.

Risk (or safety) requirements are usually based on the principle that an inverse relationship should exist between probability of occurrence and magnitude of its consequences.

3.3.2 Identification of suitable collision risk metrics

The suitability of risk metrics for the collision risk between aircraft is studied [2, 41, 49]. A rationale is developed and applied for evaluating the suitability of possible risk metrics. Two suitable risk metrics to regulate and control collision risk around the airport are proposed:

1. *Collision probability* per movement (i.e take off or landing):
   Commonly used for evaluation of risk events during the approach and take off part of a flight. It fits well within the present safety requirements for air traffic operations, but does not take into account an increase in runway capacity.
2. *Collision probability per year* (or expected average time interval between 2 risk events):
   This metric takes into account the runway capacity and the steady increase in air traffic. As an aid to planning and decision making, it might therefore be more appropriate to use.

Economic risk might be used as an informative metric to convey costs and benefits of possible decisions more clearly [41]. Since economic risk is open to more than one interpretation, this metric should not be used for regulation (i.e. no controls should be based on it).

3.3.3 Target Level of Safety (TLS) approach

The TLS approach is based on a division of the risk continuum into two regions, where the TLS provides the boundary value between safe and unsafe. A TLS specifies a maximum acceptable level of assessed risk (i.e. point estimate). Several methods for TLS assessment have been used [49], and methods based on historical accident data – sometimes factored for improvement – are most popular. Some existing and proposed TLS in aviation are [41]:

1. *Existing TLS for collision with obstacles (ICAO-OCP)*:
   Maximum collision probability per approach of 1.0×10^{-7} .
2. *Existing TLS for mid-air collisions (ICAO-RGCSP)*:
   Maximum collision risk per flight hour per dimension of 5×10^{-9} .
3. *Existing TLS for aircraft accidents during all flight phases (ICAO-AWOP)*:
   Maximum aircraft accident risk of 1.0×10^{-7} per flight hour or 1.5×10^{-7} per movement.
4. *Existing TLS for aircraft accidents during approach and landing (ICAO-AWOP)*:
   Maximum aircraft accident risk of 1.0×10^{-8} per movement.
5. *Existing TLS for failure conditions of individual aircraft systems (JAR-25)*:
   Maximum probability of occurrence per flight hour of 1.0×10^{-9} per system failure condition.
6. *Proposed TLS for accidents with an ATM contribution (Eurocontrol-ESARR4)*
   Maximum probability of ATM directly contributing to an accident of a commercial air transport aircraft of 2.5×10^{-8} accidents per flight hour or 3.5×10^{-8} per movement.

Note that some applications of the TLS concept (e.g. the first and second) provide detailed guidelines for the numerical method to be used for assessment of the risk.

3.3.4 As-Low-As-Reasonably-Practicable (ALARP) approach

The ALARP approach is based on a banded assessment of decision structure, which contains a tolerable region bounded by maximally negligible and minimally unacceptable levels of risk. Within the tolerable region the risk must be proven to be ALARP in order to be acceptable [51, 52]. Cost-Benefit Analysis (CBA) is a method that can be used to demonstrate that any further risk reduction in the tolerable region is impracticable. Up to now, ALARP has mainly been used in industries other than aviation (e.g. the chemical, offshore, nuclear and some transport industries). Recently development of the ALARP approach has been investigated within the context of RVSM in European Civil Aviation Conference (ECAC) countries [51]. It was concluded that for aviation there seems to be no case for replacing any accepted TLS with ALARP. However, since most practical applications of ALARP use fixed risk criteria like the TLS to determine the ALARP region, there appear to be grounds for *combining* the TLS and ALARP for aviation risk management for certain studies. An advantage of ALARP might be that it provides a rationale for reduction and mitigation of risks.

3.3.5 Adoption of safety requirements

On behalf of the CAA, it was decided to judge the acceptability of the estimated collision risk by a relative comparison of the collision probability per approach of the current and proposed situation for runway 22. Moreover, the magnitude of the absolute risk value will be compared with the EUROCONTROL proposed TLS for accidents with an ATM contribution [78].

3.4 Risk assessment model

3.4.1 Risk assessment methodology and tools

For the assessment of the collision risk related to simultaneous missed approaches on Schiphol runways 19R and 22, three NLR methodologies and tools are integrated and used:

- NLR's Information System for Safety and Risk analysis (ISTaR);
- NLR's Traffic Organization and Perturbation AnalyZer - Simultaneous Missed Approaches toolset (TOPAZ-SMA);
- NLR's Flight Track and Aircraft Noise Monitoring System (FANOMOS).

As the basis for the development of the collision risk assessment model use is made of the TOPAZ methodology to assess accident risks for ATM operations [53, 58]. Note that the TOPAZ-SMA toolset development is described in detail in Blom et al. [42]. TOPAZ supports a spiral development cycle that is of the form:

A. Design of an ATM operational concept.
B. Assessment of the ATM concept, resulting in a cost-benefit overview.
C. Detailed analysis of the assessment results, resulting in recommendations to improve the ATM concept.
D. Review of ATM concept development strategy and plan.
E. Back to A: adapted and/or more detailed ATM concept design using the results from C resulting in a new or optimised ATM concept.

The TOPAZ methodology is based on a stochastic modelling approach towards risk assessment and has been developed to provide designers of advanced ATM with safety feedback following on a (re)design cycle, see Figure 3-2.

During the assessment cycle four stages are sequentially conducted:

1. Identification of operation and hazards (upper left boxes in Figure 3-2)
2. Mathematical modelling (right boxes in Figure 3-2)
3. Accident risk assessment (middle box in Figure 3-2)
4. Feedback to operational experts (lower left box in Figure 3-2)

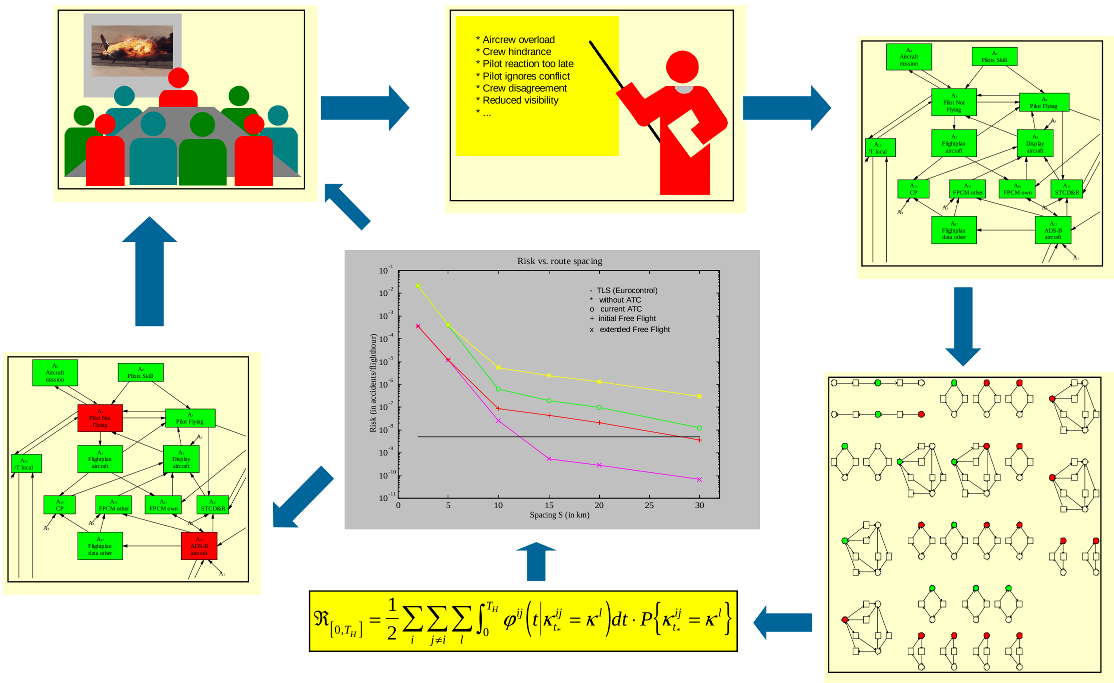

Figure 3-2 TOPAZ risk assessment cycle

3.4.2 Identification of hazards

The main issues lie in the fact that, contrary to all other published procedures at Schiphol, the missed approach procedure for runway 22 is not a procedure straight ahead on runway track and prescribes a left turn to track 160 ° MAG at the Missed Approach Point (MAPt). Humans involved (flight crew and ATC) must act according to the published procedures, nevertheless it must be considered that the flight crew delays, forgets, or chooses not to initiate a turn early in the missed approach. Therefore reasons for not complying with the published procedure were identified:

- The ATCOD incident database of the LVNL [44] was used to derive baseline reasons in relation to aircraft conducting a missed approach on runways 19R and 22;
- For the turning missed approaches, possible hazards as well as the impact of these hazards on the aircraft turning track (including location where the turn will be initiated, turn radius, and vertical climb performance) were assessed [41];
- For the missed approaches straight ahead on runway track, possible hazards were supplemented with hazards derived during previous NLR research studies.

A brainstorm session was held, where representatives of NLR, Dutch CAA, and LVNL discussed possible hazards that might occur. The following relevant factors were noted [43]:

- Although the missed approach procedure for runway 19R does not prescribe a turn, in reality ATC often instructs aircraft conducting a missed approach on this runway to also initiate a turn away from the missed approach turning trajectory for runway 22;

- The Jeppesen approach plate [7] for runway 22 might lead to confusion of pilots conducting a missed approach. The fact that the ILS plate also contains information for a Non-Precision Approach (NPA) procedure might lead to pilots interpreting the information wrongly, e.g.:
  - The MAPt and required turn can be interpreted as being located *before* the DH;
  - The visibility criteria may be interpreted as being equal to 1200 m (applicable to the NPA procedure) instead of the 1800 m applicable to the ILS procedure;
- Runway 22 has currently no ILS CAT-I approach and runway lighting, but will be equipped with stopbars in the near future.
- The Jeppesen approach plates for runways 19R and 22 differ from the AIP approach plates on significant details, e.g. Jeppesen omits the mentioning of specific procedures that apply in case of a missed approach under communication failure.

3.4.3 Missed approach model

A statistical model for the uncertainties about the missed approach flight phase has been developed [41]. This model accounts for the specific nature of the procedures for runways 19R and 22, where the latter includes a turning trajectory with turns ‘as soon as practicable’.

Probability distributions for the lateral and vertical deviations

For the straight missed approaches, the ICAO CRM data is used [31]. However, for the rare turning missed approaches, reliable data can not be obtained easily. Therefore, in co-ordination with the CAA, it was decided to use FANOMOS turning departure data – together with an assessment of the impact of the main differences with turning missed approaches – to represent deviations about the turning missed approach path, as being the best feasible modelling option. Schiphol departure data has been analysed using ISTaR goodness-of-fit tools [41].

Probability distribution for the missed approach turning point

A statistical model for the missed approach turning point, representing a probability distribution for the time required before lateral navigation can be adjusted and the turn initiated has been developed. This model is based on expert knowledge of (airline) pilots at NLR.

An example of elicited duration times for the task breakdown of the Boeing 737/Airbus A320 is given in Table 3-1. Task duration and sequencing depends on aircraft type, therefore similar tables have been elicited to represent turn behavior of pilot flying other aircraft approaching 19R and 22 [41].

[7] An approach plate is an aeronautical chart that visualizes and explains the approach procedure to a specific airport runway. Jeppesen is a company that specializes in aeronautical charting and navigation services, flight planning, pilot supplies.

Table 3-1 Boeing 737 / Airbus A320 Missed approach task breakdown

Task	Earliest possible time	50% percentile	95% percentile	End time
1: Decision to initiate missed approach	T0	2 seconds	3 seconds	T1
2: Triggering go-around FD mode	T1	1 second	3 seconds	T2
3: Thrust change for go-around	T2	6 seconds	9 seconds	T3
4: Adjusting pitch angle	T1 + 1 second	4 seconds	8 seconds	T4
5: Raising flaps for climb-out	T1 + 2 seconds	6 seconds	10 seconds	T5
6: Raising the gear	T4	3 seconds	10 seconds	T6
7: Engaging the autopilot	T6 & passed 1000 ft	1300 ft	1600 ft	T7
8: Turn, adjust lateral navigation	T6 & passed 400 ft	600 ft	900 ft	T8
9: Level off, adjust vertical navigation	passed altitude of 2000 ft – (10% of climb rate)	1700 ft	1900 ft	T9

Reasons and altitude for missed approach initiation

It is assumed that the statistics for the baseline reasons and likely altitude for initiation of a missed approach is based on a combination of λ_{DH}% at DH and 100-λ_{DH}% based on other reasons. Table 3-2, which shows the reasons and likely altitude for initiation of a missed approach, is used [41, 42]. Note that the columns indicate the type of probability distribution used. A Dirac density function is used in case the reason implies a Missed Approach (MA) initiation at a specified altitude. For the other reasons, as the MA initiation altitude might vary, a uniform distribution is chosen. For the parameter λ_{DH} a value of 20% is chosen.

Table 3-2 Reasons and probability density of height for initiation of a missed approach

	Density type	**Dirac**	**Dirac**	**Dirac**	**Uniform**	**Uniform**
Reason	**Percentage**	**100 ft**	**300 ft**	**600 ft**	**600-1200 ft**	**100-1200 ft**
Runway occupied	27.2%	4.5%	22.7%			
Unstable approach	20.4%		6.8%	4.5%	2.3%	6.8%
Turbulence	6.8%	4.5%				2.3%
Flap problems	13.6%			2.3%	4.5%	6.8%
Wind-shear	22.7%	11.3%	6.8%	2.3%	2.3%	
Weather	2.4%					2.4%
Other	6.9%	2.3%	2.3%			2.3%
Percentage	100%	22.6%	38.6%	9.1%	9.1%	20.6%

Missed approach rates for runways 19R and 22

Reliable data on the percentage of executed missed approaches is difficult to obtain, especially with respect to particular airports or runways. LVB [45] mentions frequencies in the order of 0.001 to 0.002 per approach, on the basis of worldwide KLM data. During the brainstorm session [43], it was noted that the rate for runway 22 will probably be higher than average, because taxiing aircraft have to make a sharp turn when leaving this runway, i.e. the Runway Occupancy Time (ROT) is relatively high. Within this study, for the missed approach rates of runways 19R and 22 reference values of 0.002 and 0.01 respectively have been chosen.

Probability distribution for the aircraft vertical climb performance

Since the majority of conflict situations is expected to occur after the aircraft have reached the missed approach level altitudes, the following aspects have been analyzed:

- The elapsed time necessary for different aircraft to climb to final missed approach altitude;
- The percentages of different aircraft that have climbed to final missed approach altitude as a function of distance from runway threshold.

3.4.4 Integration of mathematical models

For the integration of the mathematical models the Dynamically Coloured Petri Net (DCPN) approach is used. An advantage of this approach is that human factors issues, reaction times of involved actors, and system performance can all be modeled and analyzed. A modular system engineering type of representation for the double missed approach scenario has been identified by taking for each main functionality in the ATM scenario one module, and additionally taking for each aircraft in the system a module describing its trajectory. If an ATM module is aircraft specific, then such a module is introduced for each of the aircraft. Modules A refer to an aircraft individually. Modules B may affect several aircraft. An overview of these modules is:

A1	Level of skill of pilot	B1	Level of skill of Tower controller
A2	Level of performance of pilot not flying	B2	Level of performance of Tower controller
A3	Level of performance of pilot flying	B3	Surveillance
A4	Aircraft module	B4	ATC system
A5	Aircraft airborne system	B5	Communication, global
A6	Aircraft landing system	B6	Navigation support, ground
A7	Cockpit display and computer	B7	Level of maintenance, ground
A8	Type of weather	B8	Runway degradation
A9	Navigation equipment aircraft		
A10	Communication, local		
A11	Level of maintenance, aircraft		

The ATM modules and their interrelations are depicted in Figure 3-3. For the aircraft module a RASMAR specific local Petri net representing the aircraft evolution is modelled.

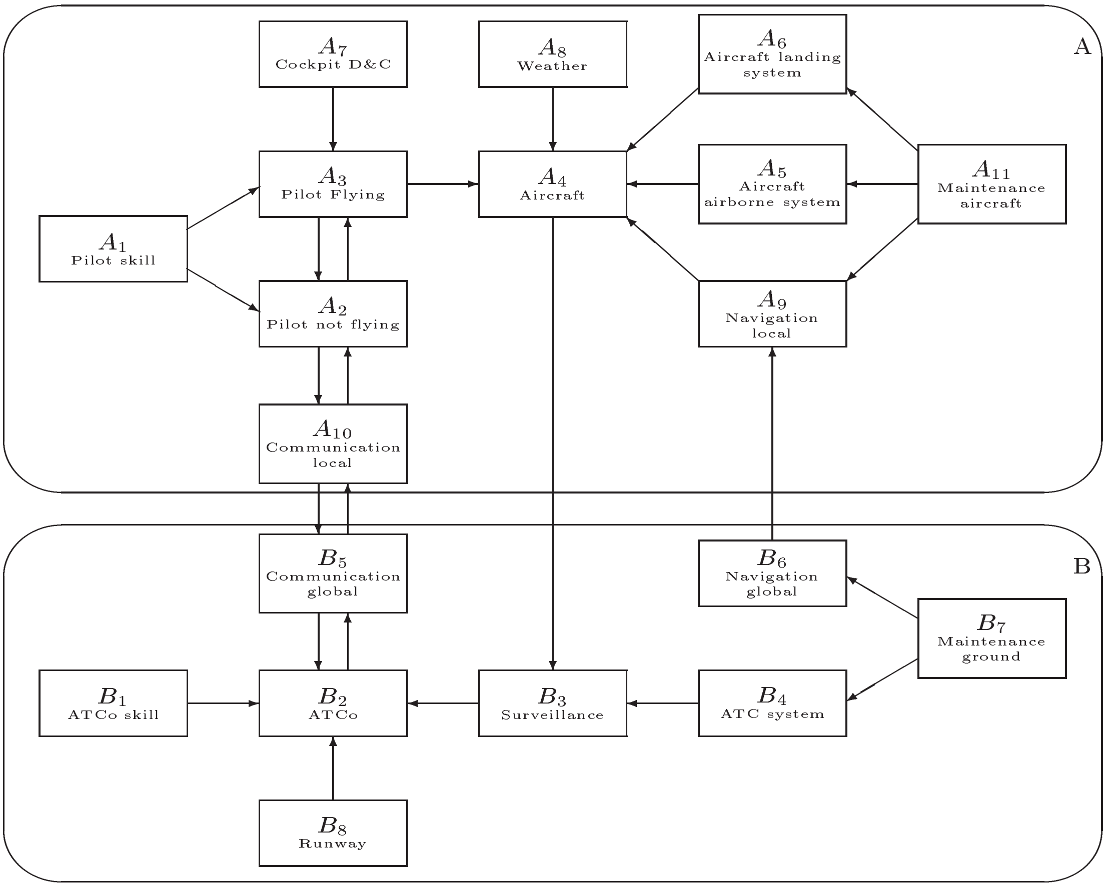

Figure 3-3 Functional representation of ATM modules and their interrelations.

3.4.5 Collision risk given a double missed approach

To determine the collision risk given a simultaneous (double) missed approach on runways 19R and 22, a Collision Risk Tree (CRT) is constructed. In the following, first the collision risk concept is described, taking into account the diversity of different aircraft types that may approach runways 19R (mainly Mediums and Heavies) and 22 (Lights and Mediums only).

Collision risk concept

Let $u_t^i := (x_t^i, y_t^i, z_t^i)$ and $v_t^i := (\dot{x}_t^i, \dot{y}_t^i, \dot{z}_t^i)$ be the 3D location and 3D velocity of aircraft *i*, and let *x*, *y* and *z* refer to the 3 dimensional axis system. Let $u_t^{ij} := u_t^i - u_t^j$ be the distance between 19R aircraft *i* and 22 aircraft *j* at time *t* and let $v_t^{ij} := v_t^i - v_t^j$ be the relative velocity of 19R aircraft *i* and 22 aircraft *j* at time *t*. Define D^{ij} as the collision area of $\{u_t^{ij}\}$, such that $u_t^{ij} \in D^{ij}$ means that aircraft *i* and *j* have collided.

The collision area D^{ij} is a rectangular box, defined as $[-d_x^{ij}, d_x^{ij}] \times [-d_y^{ij}, d_y^{ij}] \times [-d_z^{ij}, d_z^{ij}]$, with $d_c^{ij} \overset{\Delta}{=} \left(d_c^i + d_c^j\right)/2$ and where the parameters d_x^i, d_y^i and d_z^i represent the size of aircraft i respectively. The first *incrossing* – occurrence of process $\{u_t^{ij}\}$ entering the area D^{ij} – defines a collision. Following Bakker and Blom [50], the risk is expressed as the expected number E_{ic} of incrossings, or collisions, between aircraft conducting a simultaneous missed approach on runways 19R and 22 in an appropriate time-interval:

$$E_{ic} = \int_0^{T_{ij}} \varphi^{ij}(t)\, dt \tag{3-1}$$

where $\varphi^{ij}(t)$ is the incrossing rate between aircraft i and aircraft j, which is defined as

$$\varphi^{ij}(t) \overset{\Delta}{=} \lim_{\Delta \downarrow 0} \frac{P(u_t^{ij} \notin D^{ij}, u_{t+\Delta}^{ij} \in D^{ij})}{\Delta}$$

In the sequel time T_{ij} is always parametrised such that there is a negligibly small probability that the aircraft pair (i,j) collides after final time T_{ij}.

Aircraft type combinations

Twelve aircraft type combinations κ^{ij} are considered, consisting of 3 aircraft i on runway 19R and 4 aircraft j on runway 22. That is $\kappa^{ij} = (\kappa^i, \kappa^j)$, with $\kappa^i=1,2,3$ and $\kappa^j=1,2,3,4$. The 19R aircraft i are heavy and medium weight aircraft, where Boeing 767/Boeing 747 is representative for heavy aircraft, and Boeing 737/Airbus A320 and Fokker 50 are representative for medium aircraft. The 22 aircraft j are medium and light aircraft, where Boeing 737/Airbus A320 and Fokker 50 are representative for medium aircraft, and Swearingen Metro II and Cessna 172 are representative for light aircraft.

Conditional incrossing risk

Expressing the number of incrossings in equation (3-1) as a sum of the risks related to the possible aircraft type combinations gives

$$E_{ic} = \sum_{\kappa^i=1}^{3} \sum_{\kappa^j=1}^{4} \int_0^{T_{ij}} \varphi_{\kappa}^{ij}(t)\, dt \cdot P\left\{\kappa^{ij} = \left(\kappa^i, \kappa^j\right)\right\}$$

where $\varphi_{\kappa}^{ij}(t)$ is the conditional incrossing rate between aircraft i and aircraft j, defined as

$$\varphi_{\kappa}^{ij}(t) \overset{\Delta}{=} \lim_{\Delta \downarrow 0} \frac{P(u_t^{ij} \notin D^{ij}, u_{t+\Delta}^{ij} \in D^{ij} \mid \kappa^{ij} = \kappa)}{\Delta}$$

The following equation is derived in [42], using [50]:

$$E_{ic} = \sum_{\kappa^i=1}^{3} \sum_{\kappa^j=1}^{4} \sum_{c=x,y,z} \int_{\tau_c^{ij}}^{T_{ij}} \int_{\underline{D}_c} \left\{ \int_0^{\infty} v_c^{ij} \; p_{u_t^{ij} v_{c,t}^{ij} | \kappa^{ij}} \left(\underline{u}_c^{ij}, -d_c^{ij}, v_c^{ij} | \kappa \right) dv_c^{ij} \right.$$
$$\left. + \int_{-\infty}^{0} - v_c^{ij} \; p_{u_t^{ij} v_{c,t}^{ij} | \kappa^{ij}} \left(\underline{u}_c^{ij}, d_c^{ij}, v_c^{ij} | \kappa \right) dv_c^{ij} \right\} \; d\underline{u}_c^{ij} \; dt \cdot P\left\{ \kappa^{ij} = \left(\kappa^i, \kappa^j \right) \right\}$$
$$= \sum_{\kappa^i=1}^{3} \sum_{\kappa^j=1}^{4} \sum_{c=x,y,z} I_c^{ij}\left(\kappa^i, \kappa^j \right) \cdot P\left\{ \kappa^{ij} = \left(\kappa^i, \kappa^j \right) \right\} \tag{3-2}$$

with

$$I_c^{ij}(\kappa) \stackrel{\Delta}{=} \int_{\tau_c^{ij}}^{T_{ij}} \int_{\underline{D}_c} \left\{ \int_0^{\infty} v_c^{ij} \; p_{u_t^{ij} v_{c,t}^{ij} | \kappa^{ij}} \left(\underline{u}_c^{ij}, -d_c^{ij}, v_c^{ij} | \kappa \right) dv_c^{ij} \right.$$
$$\left. + \int_{-\infty}^{0} - v_c^{ij} \; p_{u_t^{ij} v_{c,t}^{ij} | \kappa^{ij}} \left(\underline{u}_c^{ij}, d_c^{ij}, v_c^{ij} | \kappa \right) dv_c^{ij} \right\} \; d\underline{u}_c^{ij} \; dt \tag{3-3}$$

where $p_{u_t^{ij} v_{c,t}^{ij} | \kappa^{ij}}(\cdot)$ is the conditional probability density function for the aircraft relative position and velocity, $\underline{D}_c$ is equal to collision area D^{ij} but without the c-th component, and $\underline{u}_c^{ij}$ is equal to the aircraft relative position u_t^{ij} without the c-th component, $c = x,y,z$. Also, for an aircraft i on runway 19R and an aircraft j on runway 22, stopping times τ_c^{ij} for $c=x,y,z$ are defined as follows

$$\tau_c^{ij} \stackrel{\Delta}{=} \inf\left\{ t; \left| u_{c,t}^{ij} \right| = d_c^{ij} \right\}$$

By definition of $I^{ij}(\kappa) = \sum_{c=x,y,z} I_c^{ij}(\kappa)$, collision risk given a double missed approach is equal to:

$$P_{collision \,|\, double\ missed\ approach} = E_{ic} = \sum_{\kappa^i=1}^{3} \sum_{\kappa^j=1}^{4} I^{ij}\left(\kappa^i, \kappa^j \right) \cdot P\left\{ \kappa^{ij} = \left(\kappa^i, \kappa^j \right) \right\} \tag{3-4}$$

The values for the probabilities $P\left\{ \kappa^{ij} = \left(\kappa^i, \kappa^j \right) \right\}$ are derived from statistical FANOMOS data giving the percentages of landing heavy/medium/light aircraft on Schiphol runways 19R and 22. Note that the TOPAZ evaluations of equation (3-4) will be executed for 16 key scenarios, each producing a value for the collision risk given a double missed approach.

3.4.6 Determination of collision risk metrics

Below a description is given of the mathematical procedure to derive the collision probability per approach and per year. They are expressed on the basis of collision risk given a double missed approach, and other relevant missed approach procedure aspects. These are:

- Missed approach rates for runways 19R and 22, denoted with r_{19R} and r_{22} respectively;
- Dependency factor ρ_{dep} , representing the extent to which missed approaches initiation on runways 19R and 22 are dependent, where $0 < \rho_{dep} < 1$ and $\rho_{dep}=1$ gives full dependency;
- Probability metrics for the adherence to the published missed approach procedures:
  - Probability that the missed approach on 19R is straight ahead on runway track λ_{19R} ;
  - Probability that the missed approach on 22 is straight ahead on runway track λ_{22} .

In co-ordination with the Civil Aviation Authorities, 16 scenarios $k \in \{1,2,\ldots,16\}$ have been selected. The *scenario dependent* collision probability per approach, Risk (k), is given by

$$Risk\ (k) = P_{collision\ \ per\ \ approach}\ (k)\ =\ P_{double\ \ MA} \cdot P_{collision |\ double\ MA}(k)$$

where the occurrence probability of a simultaneous missed approach is given by

$$P_{\text{double MA}} = (1-\rho_{dep})\, r_{19R} r_{22} + \rho\ \ r_{19R}$$

The probability of a collision per approach is determined by

$$\begin{aligned} P_{\text{collision per approach}} = P_{\text{double MA}} \cdot \{ &(1-\lambda_{19R})(1-\lambda_{22}) Risk_{T\,;\,\text{T}} + \lambda_{19R}(1-\lambda_{22}) Risk_{S\,;\,\text{T}} \\ &+ (1-\lambda_{19R})\lambda_{22} Risk_{T\,;\,\text{S}} + \lambda_{19R}\lambda_{22} Risk_{S\,;\,\text{S}} \} \end{aligned}$$

where the subscript of Risk indicates the execution of a straight missed approach (S) or turning missed approach (T) on runways 19R and 22 respectively.

To determine the collision probability per approach for a given DH and given missed approach level altitudes, therefore 4 scenarios need to be numerically evaluated with regard to the collision risk given a double missed approach, using equations (3-1) to (3-4). To quantify the current (DH=350 ft) and proposed situation (DH=200 ft), 8 scenarios are required. The next step is to determine the collision probability per year, using the runway statistics of runways 19R and 22. Combined use of runways 19R and 22 is only applied during *peak* time periods. Using statistics on the total number of approaches, divided into *night*, *peak*, and *off peak* time periods [44], the collision probability per year can be determined by (note that N is determined by the total number of approaches to runways 19R and 22 [41]).

$$P_{collision\ \ per\ \ year} = 1-[1-P_{collision\ per\ approach}]^{N}$$

3.5 Collision risk assessment

3.5.1 Definition of key representative scenarios

In close co-ordination with the CAA and LVNL, 16 key scenarios have been selected. These scenarios are determined by four main procedural aspects and are given in Table 3-3.

- Decision Height at runway 22 — 200 ft, 250 ft, 300 ft, and 350 ft
- Final Missed Approach Altitudes (FMAA) — 2000 ft and/or 3000 ft
- Missed Approach Turn on 22 — YES (turn as soon as practicable) or NO
- ATC induced MA Turn on 19R — YES (turn as soon as practicable) or NO

Table 3-3 Key representative scenarios

Scenario	MA Turn on 19R	DH runway 22	FMAA 19R / 22	MA Turn on 22
1	YES	350 ft	2000 ft / 2000 ft	YES
2	YES	300 ft	2000 ft / 2000 ft	YES
3	YES	250 ft	2000 ft / 2000 ft	YES
4	YES	200 ft	2000 ft / 2000 ft	YES
5	NO	350 ft	2000 ft / 2000 ft	YES
6	NO	200 ft	2000 ft / 2000 ft	YES
7	YES	350 ft	3000 ft / 3000 ft	YES
8	YES	200 ft	3000 ft / 3000 ft	YES
9	YES	200 ft	2000 ft / 3000 ft	YES
10	YES	200 ft	3000 ft / 2000 ft	YES
11	YES	350 ft	2000 ft / 2000 ft	NO
12	YES	200 ft	2000 ft / 2000 ft	NO
13	YES	350 ft	3000 ft / 3000 ft	NO
14	YES	200 ft	3000 ft / 3000 ft	NO
15	NO	350 ft	2000 ft / 2000 ft	NO
16	NO	200 ft	2000 ft / 2000 ft	NO

In the current situation of the Schiphol converging runways 19R and 22, the DH of runway 22 is 350 ft, whereas in the proposed situation the DH will be reduced to 200 ft. For both the current and proposed situation the following cases can be distinguished (see also Table 3-4):

Straight MA's — Aircraft approaching 19R and 22 make a straight missed approach;

Nominal Case — Aircraft approaching 22 make a turning missed approach and aircraft approaching 19R make a straight missed approach;

ATC Corrected Case — Aircraft approaching 22 make a straight missed approach, and ATC instructs missed approaching aircraft on 19R to initiate a turn;

Turning MA's — Aircraft approaching 22 make a turning missed approach, and ATC instructs missed approaching aircraft on 19R to also initiate a turn.

Table 3-4 Current and proposed scenarios, with final MA altitudes of 2000ft

	Current DH on RWY 22 is 350ft	**Proposed DH on RWY 22 is 200ft**
Straight MA's	scenario 15	scenario 16
Nominal Case	scenario 5	scenario 6
ATC Corrected Case	scenario 11	scenario 12
Turning MA's	scenario 1	scenario 4

In addition to these scenarios, eight more scenarios will be evaluated to also support other possible changes in the missed approach procedures for runways 22 and 19R. These are:

- Decision Height on Runway 22 in between 350 ft and 200 ft (e.g. scenarios 2 and 3);
- Final Missed Approach Altitude on Runway 22 and/or 19R raise from 2000 ft to 3000 ft (scenarios 7, 8, 9, 10, 13, 14).

It was shown that the probability of a collision per approach can be expressed in terms of collision risk values given a double missed approach (determined for the 16 scenarios), and in terms of parameters which represent relevant missed approach procedure aspects (see Section 3.4.6). The parameter values chosen are defined in Speijker [41] and given in Table 3-5 below.

Table 3-5 Parameter values for the missed approach procedure aspects[8]

MA procedure aspect	**Symbol**	**Interval**	**Reference value**	**Worst value**	**Best value**
Pr{MA on 19R is straight}	λ_{19R}	[0,1]	**0.2**	0.9	0.1
Pr{MA on 22 is straight}	λ_{22}	[0,1]	**0.15**	0.5	0.05
Missed approach rate 19R	r_{19R}	[1/1000,1/100]	**0.002**	0.01	0.001
Missed approach rate 22	r_{22}	[1/200,1/50]	**0.01**	0.02	0.005
MA correlation factor	ρ_{dep}	[0,1]	**0.05**	0.1	0.005

The collision probability per approach and per year will be determined for the reference value, worst value and best value case, where it is assumed that these values are equal for the current (DH = 350 ft) and proposed situation (DH = 200 ft). Subsequently a sensitivity analysis is performed for the missed approach procedure parameters, where each of the parameter values is varied between the best and worst values as given in Table 3-5.

[8] The first two rows indicate occurrence probabilities per missed approach. The third and fourth row both indicate occurrence probabilities per approach. The fifth row assumes that a simultaneous missed approach on runways 19R and 22 is initiated.

3.5.2 Collision risk given a double missed approach

The collision risk given a double missed approach is determined for all 16 key representative scenarios, through 16 fold execution of the 3 step-procedure:

1. Determination of *conditional incrossing risk* for each of the 12 aircraft type combinations;
2. Determination of *incrossing risk* for each of the 12 aircraft type combinations;
3. Determination of *collision risk given a double missed approach*.

Step 1: Determination of conditional incrossing risk

Equation (3-4) is numerically evaluated using the TOPAZ-SMA toolset [42]. This leads to an assessment of the risk that a missed approaching aircraft on runway 19R collides with aircraft conducting a missed approach on runway 22. For the *nominal case* scenarios 5 (with DH = 350 ft) and 6 (with DH = 200 ft) the numerical results for each of the possible aircraft combinations are given in Table 3-6 and Table 3-7 (these tables provide estimates for the conditional incrossing risk (calculated using equation (3-1)). Similar tables have been determined for the other scenarios.

Table 3-6 Conditional incrossing risk values for scenario 5

Scenario 5 Missed Approach Straight on 19R; Missed Approach Turn on 22; Final Missed Approach Altitudes are 2000 ft; DH runway 22 is 350 ft			
Conditional Incrossing risk	Heavy 767/747 on RWY 19R	Medium 737/320 on RWY 19R	Medium F50 on RWY 19R
Medium 737/320 on 22	9.3×10^{-8}	2.0×10^{-8}	1.6×10^{-8}
Medium F50 on 22	7.0×10^{-8}	1.5×10^{-8}	1.1×10^{-8}
Light SW II on 22	2.5×10^{-6}	9.3×10^{-7}	6.9×10^{-7}
Light C172 on 22	1.7×10^{-6}	5.7×10^{-7}	4.0×10^{-7}

Table 3-7 Conditional incrossing risk values for scenario 6

Scenario 6 Missed Approach Straight on 19R; Missed Approach Turn on 22; Final Missed Approach Altitudes are 2000 ft; DH runway 22 is 200 ft			
Conditional Incrossing risk	Heavy 767/747 on RWY 19R	Medium 737/320 on RWY 19R	Medium F50 on RWY 19R
Medium 737/320 on 22	1.4×10^{-7}	3.2×10^{-8}	2.5×10^{-8}
Medium F50 on 22	1.1×10^{-7}	2.2×10^{-8}	1.8×10^{-8}
Light SW II on 22	3.2×10^{-6}	1.1×10^{-6}	8.4×10^{-7}
Light C172 on 22	2.3×10^{-6}	7.8×10^{-7}	5.1×10^{-7}

The above tables show that the collision risk varies considerably for different types of aircraft combinations approaching the runways 19R and 22. It appears that the collision risk increases in case of light aircraft conducting a missed approach on runway 22. This is caused by the fact that light aircraft climb quicker than heavy aircraft. In relation with the specific configuration of the two runways 19R and 22, this implies that the 'vertical overlap probability' is much higher for the case with light aircraft (e.g. SW II or C172) conducting a missed approach on runway 22.

Step 2: Determination of incrossing risk
The values for the probabilities $P\{\kappa^{ij} = (\kappa^i, \kappa^j)\}$, representing the probabilities that each of the possible twelve aircraft type combinations occur, are derived from the statistical data for the percentages of landing heavy/medium/light aircraft on runways 19R and 22 as obtained from FANOMOS**.** The results are presented in Table 3-8.

Table 3-8 Probability distribution of the twelve aircraft type combinations

Aircraft type combination probabilities	Heavy 767/747 on RWY 19R	Medium 737/320 on RWY 19R	Medium F50 on RWY 19R
Medium 737/320 on 22	0.0935	0.166	0.166
Medium F50 on 22	0.0935	0.166	0.166
Light SW II on 22	0.0165	0.029	0.029
Light C172 on 22	0.0165	0.029	0.029

The *incrossing risk* values for each of the twelve possible aircraft type combinations can now be determined by taking the entry-wise product of Table 3-8 with the conditional incrossing risk values (e.g. Tables 3-6 and 3-7 for the nominal cases). The numerical incrossing risk value tables for all 16 key scenarios are given in Blom et al. [42].

Step 3: Determination of collision risk given a double missed approach
The collision risk given a double missed approach can now be determined by using equation (3-4). Below the numerical results are presented according to the following procedural aspects:

- Variations in Decision Height (DH) on runway 22;
- Variations in turning versus straight missed approaches on 19R and 22;
- Variations in missed approach altitudes.

Variations in Decision Height on runway 22
Table 3-9 and Figure 3-4 show the probability of a collision given a double missed approach for the scenarios with turning missed approaches on both runways as function of Decision Height (DH values are 200, 250, 300 and 350ft) with FMA altitude equal to 2000ft (i.e. scenarios 1-4). The results shows that the risk decreases only slightly for an increasing value of the DH.

Table 3-9 Impact of Decision Height of Runway 22 on conditional collision risk

Scenario	DH on Runway 22	Collision risk
1	350 ft	9.0×10^{-9}
2	300 ft	9.3×10^{-9}
3	250 ft	1.0×10^{-8}
4	200 ft	1.1×10^{-8}

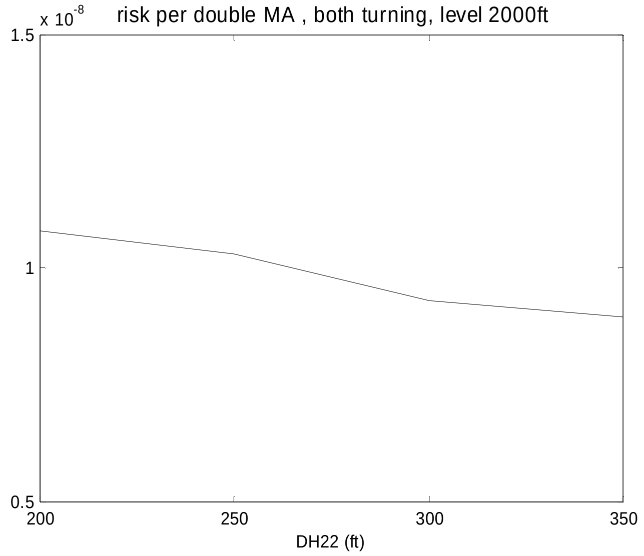

Figure 3-4 Impact of DH runway 22 on conditional collision risk

Variation in turning versus straight missed approaches on 19R and 22

For the four cases in Table 3-4 the collision risk given a double missed approach with final MA altitudes of 2000 ft are given in Table 3-10. As expected, the risk is highest with straight missed approaches on 19R and 22, and lowest with turning missed approaches on 19R and 22. The latter can be seen in Table 3-11 with final MA altitudes of 3000ft.

Table 3-10 Conditional collision risk with final MA altitudes of 2000ft

	Current **DH on RWY 22 is 350ft**	**Proposed** **DH RWY 22 is 200ft**
Straight MA’s	3.6×10^{-3}	3.6×10^{-3}
Nominal Case	1.7×10^{-7}	2.3×10^{-7}
ATC Corrected Case	1.2×10^{-7}	1.2×10^{-7}
Turning MA’s	9.0×10^{-9}	1.1×10^{-8}

Table 3-11 Conditional collision risk with final MA altitudes of 3000ft

	Current **DH on RWY 22 is 350ft**	**Proposed** **DH on RWY 22 is 200ft**
Straight MA's	-	-
Nominal Case	-	-
ATC Corrected Case	1.2×10^{-7}	1.2×10^{-7}
Turning MA's	9.0×10^{-8}	1.1×10^{-8}

The above two tables show that – for each of the 4 cases - the impact of the proposed reduction of the DH from 350 ft to 200 ft on the conditional collision risk given a double missed approach is relative low. The numerical results also show the following:

- The collision risk attains an unacceptably high level when the approaching aircraft both make a straight missed approach, and ATC does not intervene (*straight MAs*);
- The impact of ATC instructions – "turn right!" – to aircraft missed approaching runway 19R *in case of a preceding*[9] ***straight*** *missed approach on runway 22* is considerable, and can be seen as a very efficient collision risk reducing measure (*ATC corrected case*);
- The impact of ATC instructions – "turn right!" – to aircraft missed approaching runway 19R *in case of a preceding* ***turning*** *missed approach on runway 22* is noticeable, and can be seen as a measure to further reduce the collision risk, if necessary (*Turning MA's*);
- The impact of raising *both* final missed approach altitudes from 2000 ft to 3000 ft is – with the exception of the *Turning MA's* low, and may be seen as a risk neutral change.

Variation in final missed approach altitude

Table 3-12 below shows the conditional collision risk given a double missed approach for the turning MA scenarios with proposed DH of 200 ft, and with varying final MA altitudes.

Table 3-12 Conditional collision risk with DH 22 is 200 ft, and varying final MA altitudes

Scenario	**MAA 19R / 22**	**Collision risk with Turning MA on 19R and 22**
4	2000 ft / 2000 ft	1.1×10^{-8}
8	3000 ft / 3000 ft	1.1×10^{-8}
9	2000 ft / 3000 ft	3.0×10^{-10}
10	3000 ft / 2000 ft	8.8×10^{-11}

[9] A *preceding missed approach on runway 22* implies that the missed approach on 19R is initiated shortly after initiation of a missed approach on runway 22 (simultaneously and before the aircraft on runway 22 reaches it final missed approach altitude).

It turns out that the impact of increasing *one* of the final missed approach altitudes from 2000 ft to 3000 ft lowers the collision risk significantly, and may therefore be implemented safely. The collision risk is comparable in case the missed approach level altitudes of 19R and 22 are equal.

3.5.3 Collision risk per approach and per year

The collision risk per approach and per year are calculated for the current DH (350 ft) and the proposed DH (200 ft), with final missed approach altitudes of 2000 ft, through execution of the procedure described in section 3.4.6. Three values are provided – based on sensitivity analysis – showing the uncertainty about the calculated reference risk value.

Table 3-13 Collision risk per approach

	Current DH_{22} = 350ft	**Proposed DH_{22} = 200ft**
Reference Value	**1.3×10^{-8}**	**1.3×10^{-8}**
Worst Value	6.4×10^{-8}	6.3×10^{-8}
Best Value	3.2×10^{-9}	3.2×10^{-9}

Table 3-14 Collision risk per year

	Current DH_{22} = 350ft	**Proposed DH_{22} = 200ft**
Reference value	**1.3×10^{-4}**	**1.3×10^{-4}**
Worst value	6.4×10^{-4}	6.3×10^{-4}
Best value	3.2×10^{-5}	3.2×10^{-5}

Subsequently a sensitivity analysis is performed for the missed approach parameters, where each of the parameter values is varied between best and worst values as given in Table 3-5, while keeping the other parameters in accordance with the reference values.

The above tables and the sensitivity analysis show that the collision risk per approach and per year are comparable for the current DH (350 ft) and proposed DH (200 ft). This is due to the fact that the distance between the points of closest approach during a double missed approach is more or less the same for the current and the proposed procedure. This implies that a reduction of the OCA to values below 200 ft is risk neutral within a broad spectrum of changes.

3.5.4 Impact of the assumptions

Some model assumptions have been adopted. To assess the impact of all assumptions on the calculated collision risk, a qualitative analysis of the expected direction and magnitude of the impact of the assumptions has been undertaken. The overall conclusion of the analysis is that most assumptions have a negligible effect on the calculated risk. Assumptions that do have a noticeable impact (i.e. major or significant) are pessimistic, i.e. due to the model assumptions in reality the collision risk is smaller than that calculated. Noteworthy pessimistic assumptions are that Traffic Collision Avoidance System (TCAS) is switched off and that pilots do not use see-and-avoid. The first has a major impact, whereas the second has a significant impact under good visibility conditions and a negligible impact in actual CAT-I weather conditions.

Besides the model assumptions, a number of parameters have been used to represent relevant missed approach procedure aspects. Most important parameters are:

- Missed approach rates for runways 19R and 22, denoted with r_{19R} and r_{22} respectively;
- Probability metrics for the adherence to the published missed approach procedures:
  - Probability that the missed approach on 19R is straight ahead on runway track α_{19R} ;
  - Probability that the missed approach on 22 is straight ahead on runway track α_{22} .

From the calculated worst, reference, and best value for the collision risk – as given in section 3.5.3, Tables 3-13 and 3-14 – it is concluded that these parameters have a significant impact.

The conclusion can be drawn that the magnitude of the collision probability per approach is less than the reference value calculated, provided that the following conditions are satisfied:

- *The missed approach rate for runways 19R is less than 0.2 %;*
- *The missed approach rate for runway 22 is less than 1.0 %;*
- *The probability that the missed approach on runway 19R is straight ahead is less than 0.2;*
- *The probability that the missed approach on runway 22 is straight ahead is less than 0.15.*

Note that – following Westerveld [46] – it is assumed that the ILS of runway 22 functions well below 350 ft. The risk of Controlled Flight Into Terrain (CFIT) is therefore not considered.

3.6 Safety and operational feedback

3.6.1 Safety criticality assessment

To judge the acceptability of the collision risk, it was decided to execute a two-fold comparison of the *reference* value for the collision probability per approach:

- A relative comparison of the current and proposed situation for runway 22;
- An absolute comparison with the EUROCONTROL proposed TLS for accidents with an ATM contribution, i.e. 3.5×10^{-8} accidents per movement

It was shown that a reduction of the DH of runway 22 from 350 ft to 200 ft is risk neutral, and that moreover the absolute value of risk is less than the EUROCONTROL proposed TLS. The conclusion can be drawn that – provided that certain conditions are satisfied – the independent use of runway combination 19R / 22 in actual CAT-I weather conditions is adequately safe.

This conclusion is also valid for the possible future situation, where the final missed approach altitude is raised from 2000 to 3000 ft and/or the wind criteria for the use of runway combination 19R / 22 is changed toward 20/7 knots. The latter is expected to have a negligible impact on the collision risk between aircraft approaching the runway combination 19R and 22.

3.6.2 Key safety bottlenecks and criticalities

It is clear that – provided that certain conditions are satisfied – the proposed reduction of the OCA of runway 22 to 200 ft may be judged adequately safe. From a safety perspective, of importance is to also locate the factors that contribute most to the collision risk. This might allow for further safety improvements if appreciated. The key safety bottlenecks are those that might lead to either a missed approach executed straight ahead on track of runway 22 or might lead to aircraft not conducting an ATC induced turn on runway 19R:

1. Reasons for aircraft conducting a straight missed approach on runway 22;
2. Reasons for aircraft not conducting an ATC induced missed approach turn on runway 19R;
3. Reasons for aircraft not conducting an ATC induced missed approach climb.

Investigation of the related causal factors could provide additional insight into the criticalities.

3.6.3 Measures to improve and monitor safety

Although the proposed reduction of the OCA from 350 ft to values less than 200 ft is risk neutral, the following recommendations are provided to further improve the level of safety:

Design the new AIP approach plates in such a way that current possible confusion of pilots on the position of the Missed Approach Point, required turn, and visibility criteria is alleviated:

- *Turning missed approach:*
  For a missed approach following a precision approach, turns may be prescribed at a designated Turning Point (TP) or altitude/height or ‘as soon as practicable’ [32]. For non-precision approaches a MAPt must be specified, and turns must commence at a designated TP (i.e. the MAPt) or at a specific altitude/height. The present approach plate identifies a turning point for the LOCalizer (LOC) Glide Slope unserviceable (GS u/s) approach. No specific guidelines are given for turn initiation for the ILS approach, it may be assumed that the turn should be initiated ‘as soon as practicable’. Noteworthy is that the LOC GS u/s MAPt lies *before* the point where the Decision Altitude (DA) is crossed on a full ILS approach. It is recommended that:
    - The words ‘as soon as practicable’ are added for the MA following an ILS approach;
    - To avoid possible confusion, the MAPt for the LOC GS u/s approach should lie behind the point where the ILS GS intersects the DA. With a DH of 195 ft, this means that the MAPt for the LOC u/s should lie not earlier than 0.6 NM before the runway threshold.

- *Required visibility:*
  Presently, the required visibility for the ILS procedure is higher than for the LOC GS u/s approach. This might lead to confusion for pilots in marginal visibility conditions. It is recommended to either decrease the required visibility for the ILS approach or, just to avoid this confusion, increase the required visibility for the published non-precision approach.

Monitor the FMS missed approach coding by different database manufacturers
Missed approach segments are routinely coded in the Flight Management System (FMS) to aid lateral navigation in a missed approach segment. The coding of the missed approach may pose some problems for database manufacturers because ‘as soon as practicable’ is not easily translated into a FMS waypoint. Because of the potential criticality of the initiation point of the missed approach from runway 22, the CAA is encouraged to specifically monitor the FMS implementation of the published missed approach procedure by the different database manufacturers.

Monitor the reasons and circumstances related to missed approaches
The reasons and circumstances that may lead to aircraft initiating a missed approach as well as the missed approach rate are aspects that are relatively uncertain. It is therefore recommended that ongoing safety monitoring activities – such as the ATCOD data base of Air Traffic Control the Netherlands (the LVNL) – are continued, possibly to be extended with the following:
- Information about position of missed approach initiation (altitude / distance to threshold);
- Information about the position of initiation of a turn (time after initiation of missed approach or altitude or distance from / passed threshold)
- Information about the reason for initiation of a missed approach.

Furthermore, the LVNL may explicitly request aircraft executing a missed approach from runway 22 to submit a company report, which can then be analyzed.

3.7 Conclusions and recommendations

3.7.1 Conclusions
A probabilistic safety assessment of the collision risk related to simultaneous missed approaches on Schiphol converging runways 19R and 22 has been carried out, focusing on the proposed reduction of the OCA of runway 22 from 350 ft to values less than 200 ft. This reduction will allow a DH of 200 ft, enabling the use of runway 22 in actual CAT-I weather conditions.

Two suitable risk metrics – collision probability per movement and per year – have been identified. On basis of a review of safety requirements, some guidelines on how to judge the acceptability of collision risk results have been given. An existing risk model has been extended to enable determination of the collision risk between aircraft simultaneously conducting a missed approach on runways 19R and 22. This model is developed through an integral usage of 3 NLR tools: ISTaR, TOPAZ, and FANOMOS. Application to 16 scenarios showed that:

- The collision risk may attain an unacceptably high level under certain conditions, e.g. when aircraft on 19R and 22 both make a straight missed approach, and ATC does not intervene;
- ATC monitoring and instructing – "turn right!" or "climb to!" – to aircraft conducting a missed approach on runway 19R *in case of a preceding **straight** missed approach on runway 22* is required. It is explicitly stated that such ATC instructions are ***not*** necessary *in case of a preceding **turning** missed approach on runway 22*.

Provided that the identified risk reducing measures are applied, the proposed reduction of the OCA of runway 22 to 200 ft is risk neutral within a broad spectrum of missed approach procedural aspects, and may be judged adequately safe. This conclusion is also valid for the situation where the final missed approach altitude is raised from 2000 to 3000 ft.

3.7.2 Recommendations

Although the proposed reduction of the OCA from 350 ft to 200 ft is risk neutral, the following recommendations are provided to further improve the level of safety:

1. Design the new AIP approach plates in such a way that current possible confusion of pilots on the position of the MAPt, required turn, and visibility criteria is alleviated;
2. Monitor the FMS missed approach coding by different database manufacturers;
3. Monitor the reasons and circumstances in relation to missed approaches on 22, e.g. through yearly inspection of the ATCOD incident database of the LVNL.

It is also recommended that Dutch interest groups discuss internally and agree upon a risk criteria framework to regulate and control collision risk around Dutch airports.

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4 Probabilistic safety assessment of wake vortex separation distances for single runway arrivals

4.1 Introduction

During the last four decades overall system safety (e.g. accident risk per flight hour) of the United States National Airspace Systems (NAS) and the European Air Transport System has improved despite the growth in number of operations conducted [59, 63]. This has been achieved primarily through the introduction of improved technology in the cockpit and in Air Traffic Control which has improved safety at a rate in excess of the rate of growth in operations [74]. Researchers have concluded that as the air transportation system reaches its capacity limits, the introduction of new technology to improve overall network system safety yields diminishing returns. Instead the next lever to improve safety is through improving airspace “flow” safety in the presence of increased volume and complexity.

The evaluation of the safety of the airspace flow involves the evaluation of the accident risk in a system that exhibits stochastic behavior. For example, analysis of safe wake vortex separation distances for the procedures proposed by NASA and the FAA [66] require the analysis of the effect of wake vortex, generated by lead aircraft, and encountered by trailing aircraft for a given arrival (departure) procedure. The analysis requires inclusion of stochastic models of wake vortex evolution, wake vortex encounter, and aircraft/pilot response. The analysis must be conducted for a heterogeneous mix of aircraft under different weather conditions flying flight paths with statistical variations [68]. Traditional quantitative safety methods, designed for evaluation of technologies/products, such as the Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA), are not easily applied due the dynamic stochastic nature of the system behavior, and the absence of historic data for rare-events [57, 70]. Qualitative safety methods, such as Hazard Analysis, provide a first estimate of risk prediction, but are inherently based on the assessments of experts. As a consequence, 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 [11].

NLR has developed a quantitative method for wake vortex safety analysis (WAVIR), which is based on Probabilistic Safety Assessment (PSA). Analysis and simulation of the airspace flow safety is conducted through Monte Carlo simulations of rare-events that are precursors to accidents. WAVIR has been used by NLR to evaluate wake vortex separation standards for the European S-Wake research program [10, 62]. WAVIR is also being used in the European projects for ground based wake vortex prediction and detection (ATC-Wake) (Section 5) and cockpit instrumentation for wake vortex detection and avoidance (I-Wake) (Section 6).

Figure 4-1 Wake vortices generated by a Boeing 747 aircraft

This study describes the WAVIR tool for evaluation of wake vortex separation distances between fleets of heterogeneous aircraft approaching a single runway under different operational, weather, and wind conditions. Section 4.2 provides an overview of wake vortex separation procedures during approach and landing. Section 4.3 provides a historic account of how separation distances have been determined in the U.S. Section 4.4 presents the newly proposed wake vortex risk requirements and illustration of the method to derive safe and appropriate separation minima. Section 4.5 describes the WAVIR tool. Section 4.6 provides the main results from the probabilistic safety assessment as carried out in the S-Wake project. A comparison of the main results with incident/accident data obtained at Heathrow airport is included in Section 4.7. Finally, Section 4.8 provides the conclusions and recommendations.

4.2 Wake vortex separation standards

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. During application of these static separation standards during Instrument Flight Rules (IFR) operations, no fatal accidents have been reported in the U.S. [65]. Wake vortex separation standards have a significant impact on airport departure and arrival capacity especially at the busiest hub airports [67]. For this reason the National Aeronautic and Space Administration (NASA), the Federal Aviation Administration (FAA), as well as several European agencies have been developing technologies and procedures for increased arrival and departure flows at airports through reduced separation standards without an impact on safety [66].

Figure 4-2 Wake vortices generated by a Boeing 727 aircraft

Reduced separation standards are largely made feasible by increased understanding of the impact of ambient weather conditions on wake vortex transport and decay. Modern models of wake vortex behavior show that with calm winds and no atmospheric turbulence, wake vortices last significantly longer than vortices in high atmospheric turbulence conditions [71]. Currently three concepts of operation are under consideration by NASA and the FAA [66, 67] 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 [55] to enable dependent parallel runway arrival operations with parallel runways separated by less than current standard (2500 ft) under weather conditions that favor reduced wake vortex separation. Mid-term procedures involve modification of separation distances for departures under weather conditions that favor reduced wake vortex separation. Long-term procedures and systems to execute dynamic separation distances are based on measurements of existing weather conditions [60, 69, 71, 97].

4.3 Determining wake vortex separation

4.3.1 History of wake vortex separation minima in the United States

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 analysis 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 [65]. By using smoke towers and probing aircraft (Boeing 737-100, Sabre F-86, NASA CV-990) the wake vortices of a Boeing 747 and a Boeing 707-320C were characterized. This data provided the basis for wake vortex separation rules adopted by the FAA:

- VFR rules – following aircraft remain above of the flight path of the leading aircraft, and
- IFR rules – minimum radar-controlled wake vortex 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 [73, p. 8]. This was considered impractical to implement and was dropped in favor of categorization by weight. With a few exceptions, weight exhibits relatively good correlation with wingspan. Several adjustments to the wake vortex separation distances have been made during the 1980's and 1990's. It should be noted that separation distances have usually been increased with as main exception a reduction from 3 NM to 2.5 NM spacing for similar sized aircraft and short runway occupancy times.

4.3.2 Current practice regulations for single runway arrivals

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. National regulation exists in USA and United Kingdom (UK). Different provisions governing wake turbulence separation minima are published by ICAO, and depend on the wake turbulence category of the leading aircraft and the equipment available to them to provide separation [32, 79, 103]. ICAO makes a clear distinction between normal IFR separation minima and wake turbulence induced separation minima. According to the ICAO Air Traffic Services Planning Manual [103], wake vortex separation minima are to reduce the wake vortex hazard. Figure 4-3 provides the ICAO wake vortex separation minima for single runway arrivals.

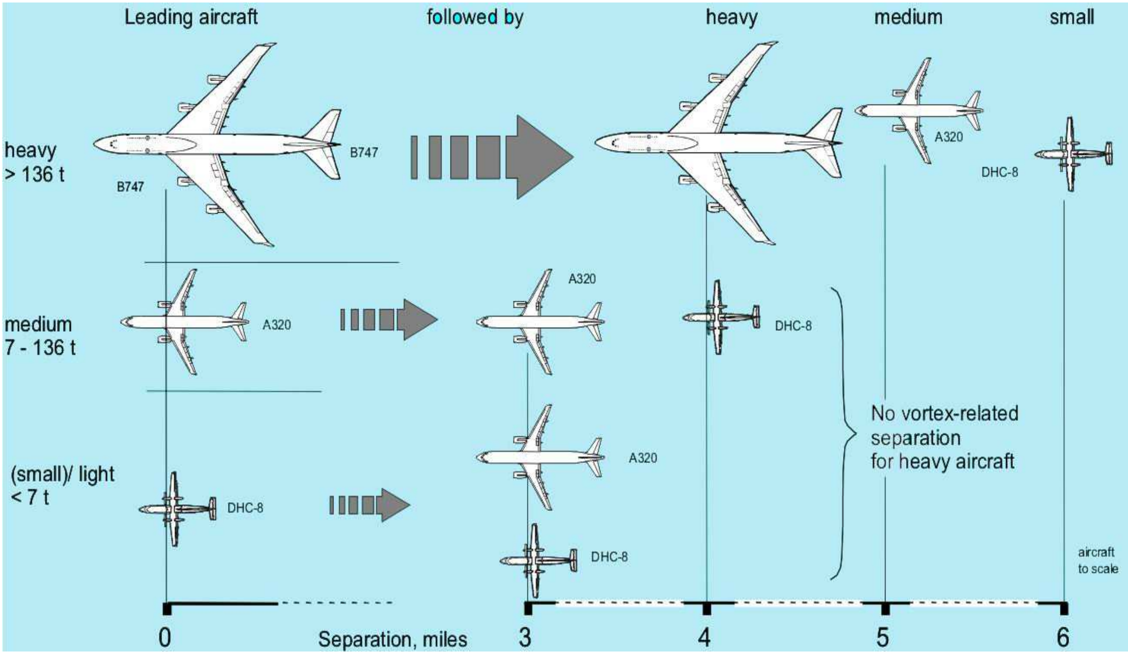

Figure 4-3 ICAO Separation Minima for Single Runway Arrivals

These separation minima should be applied to aircraft in the approach and departure phases of flight in the circumstances when an aircraft is operating directly behind another aircraft at the same altitude or less than 300 m below; or both aircraft are using the same runway or parallel runways separated by less than 760 m. Wake turbulence separation is not provided to Visual Flight Rules (VFR) arrivals, nor to IFR on visual approach. In these cases it is up to the pilot to provide adequate spacing from preceding arriving or departing aircraft.

4.3.3 Classical Methodologies for Determining Separation Distances

Three methodologies have been used to define safe separation standards [65]:

- Experimental Flight Test
- Historic Operational VFR data analysis
- Analytical modelling.

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 [65]. 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

The approach uses the fact that safe operations were consistently conducted between 1976 and 1994 by aircraft pairs operating under “see-and-avoid” VFR separation rules at separation distances below the IFR separation distance regulations. This data was used as the basis for the reduction of the separation distance between aircraft lighter than the B757 to 2.5 NM.

Analytical Modeling

An alternative procedure for determining safe separation distances was developed during the 1980’s using a probabilistic approach for a pair of aircraft used as a normalizing condition [65]. First, a wake vortex hazard model was used to assess the threshold strength of a vortex that is hazardous for a trailing aircraft. Second, vortex decay measurements were processed to give an empirical model for vortex decay expressed as a probability of the vortex strength remaining above a given value as a function of wake vortex age. Finally, data from these two models were combined to determine the probability of a hazardous encounter for a given separation time.
If the separation distance for the most commonly occurring aircraft pairs can be considered to be “safe” (based on historic data from 1976 to 1994), then safe separation distances of other aircraft pairs can be computed using these models. This method is distinct from the other two, because it accepts that a zero encounter probability is unrealistic and therefore resorts to establish a probabilistic level of safety. As the aviation system reaches the capacity limits induced by current separation standards, the importance of understanding the impact on safety risk of different separation standards and procedures must be addressed. There are several fundamental questions that must be resolved:

1. What is the safety level of the current standards?
2. Are the standards overly conservative?
3. Can the standards safely be reduced?

These questions cannot be answered with previous models and require more comprehensive models and analysis than can be provided by the approaches listed above.

4.4 Newly proposed wake vortex risk based policy making

4.4.1 Wake vortex risk requirements

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

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

A method to derive safe and appropriate separation minima for different operational and weather/wind conditions is now introduced. This method is based on:

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

Risk requirements based on the Target Level of Safety (TLS) approach are proposed. It should be noted that the use of the As Low As Reasonably Practicable (ALARP) approach was also considered. However, the usage of ALARP is not recommended for considering the issue of wake vortices because it is a small proportion of the overall landing risk. The approach followed in reference 4 is largely based on historical data, resulting in the proposed TLS values for the risk event probabilities per *queued* movement given in Table 4-1. Note that the TLS value for catastrophic accidents is based on the assumption that 2% of the landing risk is due to wake vortices and that about 50% of landing movements are queued.

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

Table 4-1 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}

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

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

4.4.2 Illustration of method to derive safe separation minima

Figure 4-4 illustrates the proposed risk based policy making procedure to derive safe and appropriate separation distances for different operational and weather conditions. It is proposed that the most stringent of the four requirements determines the required separation minima [10]. Note that the derived separation minima (as determined with WAVIR) currently refer to the minimum separation distance *along the entire arrival path.* Airports might relate the required separation minima to specific points (e.g. the threshold or the Outer Marker).

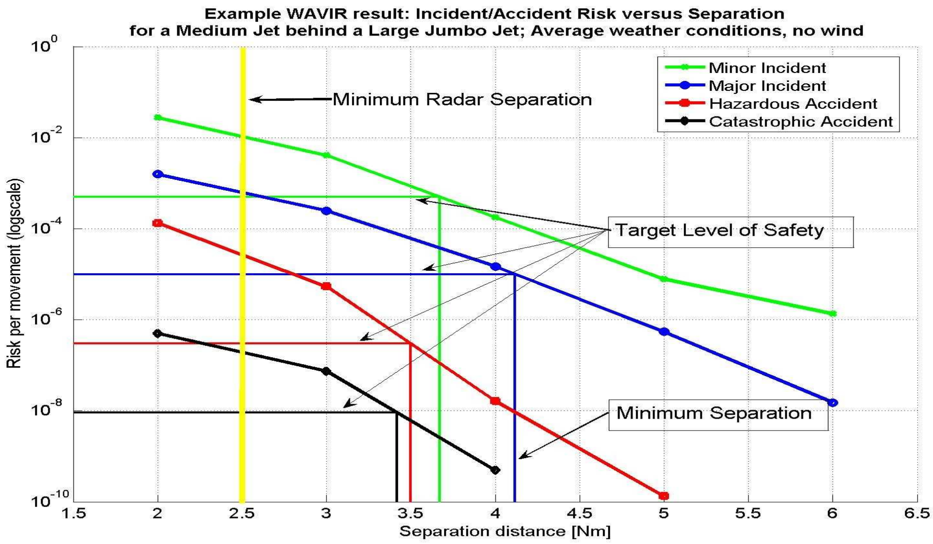

Figure 4-4 Risk management procedure to derive safe and appropriate separation minima

4.5 WAke Vortex Induced Risk assessment (WAVIR) tool

The WAVIR tool was developed by NLR [3, 4, 10, 72] specifically to improve the ability to address the issues outlined at the end of the section above. In view of the probabilistic nature of aircraft arrival and departure flows, the wake vortex phenomena, and pilot's response to wake vortex encounters, WAVIR uses a probabilistic approach. This approach enables an assessment of the safety level related to different separation distances and under various operational, procedural, weather and wind conditions. The modules are incorporated in the WAVIR toolset as in the screenshot shown in Figure 4-5 [10] (see Appendix A for the mathematical details).

The WAVIR toolset is composed of the following 4 modules:

- Flight Path Generation;
- Wake Vortex Evolution;
- Wake Vortex Encounter;
- Separation Distance Prediction.

Flight Path Generation (FLIGHT_PATH):
This module generates the lateral and vertical flight path trajectories, and airspeed, for the lead and trailing aircraft on arrival and approach. The flight path trajectories are computed using samples from probability distributions. The computation also takes into account profiles and speeds associated with the published arrival procedures, ATC speed control, aircraft dependent Final Approach Speeds. This module also computes actual separation distance and time as function of the longitudinal position. It generates input data that is used by the Wake Vortex Evolution and the Wake Vortex Encounter models

Wake Vortex Evolution (VORTICES):
This module performs Monte Carlo simulations of the evolution of a wake vortex pair generated by the lead aircraft. The wake vortex is computed in a 2D crossplane or ‘gate’ (perpendicular to the flight track) at several locations along the flight path. The computation takes into account probability distributions of the lead aircraft position and speed (from FLIGHT_PATH Generation) as well as probability distributions of wind and weather conditions. Using the actual separation information (from FLIGHT_PATH), the wake vortex data is analysed at the time the trailing aircraft sequences the gates (i.e. the same longitudinal position).

Wake Vortex ENCOUNTER:
This module combines the wake vortex data (from VORTICES) and probability distributions of the trailing aircraft position and speed (from FLIGHT_PATH). Monte Carlo simulations are performed with the Wake Vortex Encounter model. Computed metrics for encounter severity are roll control ratio, maximum bank angle, and loss of height. The encounter classification is currently based on maximum bank angle and encounter altitude.

Separation Distance Prediction (RISK):
This module computes separation minima on basis of maximum acceptable level of risk. The WAVIR tool currently identifies potential wake vortex risk events as follows:

- Minor Incident;
- Major Incident;
- Hazardous Accident;
- Catastrophic Accident.

Wake Vortex encounters that result in a loss of height larger than the initial altitude of encounter are considered to be Catastrophic Accidents. All other encounters are classified in one of the other three potential risk events.

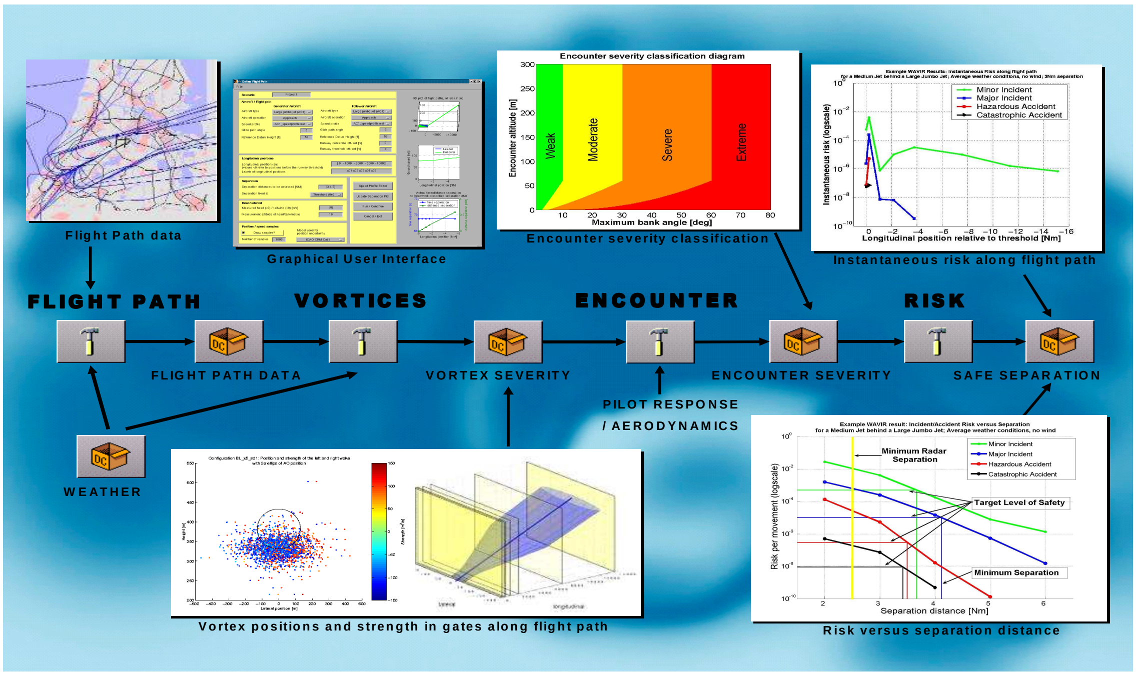

Figure 4-5 Screenshot of WAVIR tool (SPINEware [75] provides middleware)

How to Use WAVIR

WAVIR has been used in the European S-Wake project to assess the safety level of current practice single runway flight operations. A safety assessment is carried out in nine steps:

1. <u>Define the "Gates" on the Flight Path</u>: To represent the wake induced risk along the aircraft flight path, a set of relevant longitudinal positions along the proposed aircraft flight path x is determined, where the instantaneous risk will be evaluated. In each of these 'gates', the wake evolution and wake encounter simulations will be performed.
2. <u>Initialize Flight Path Evolution Generator</u>: Samples of aircraft (lateral and vertical) position and speed in the selected gates (see Figure 4-6) are obtained with the flight path evolution model. Speed profiles representing the aircraft movements are also needed as input for this model (Figure 4-7 represents the aircraft speed profiles at Heathrow airport).
3. <u>Initialize the Wake Vortex Generator</u>: The input parameters for the probabilistic wake vortex evolution model are specified. These consist of deterministic stochastic parameters. The stochastic parameter distributions are based on empirical data and/or state-of-the-art literature. Crosswind and headwind needs to be specified, as well as the atmospheric conditions (through the Eddy Dissipation Rate and Brunt-Väissällä frequency). Figures 4-8 and 4-9 represent the atmospheric conditions at Heathrow.

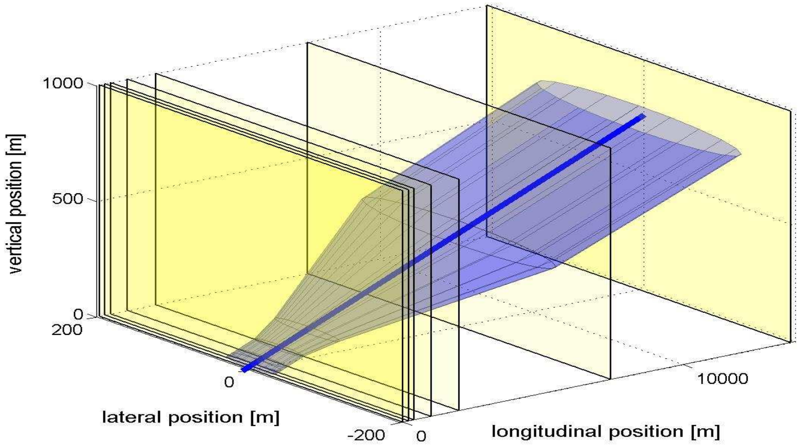

Figure 4-6 Approach glide path safety corridor with an example selection of gates

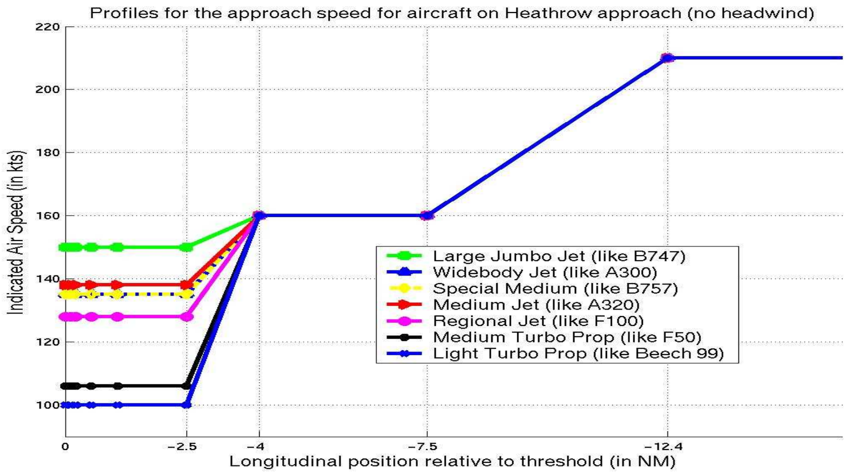

Figure 4-7 Aircraft speed profiles

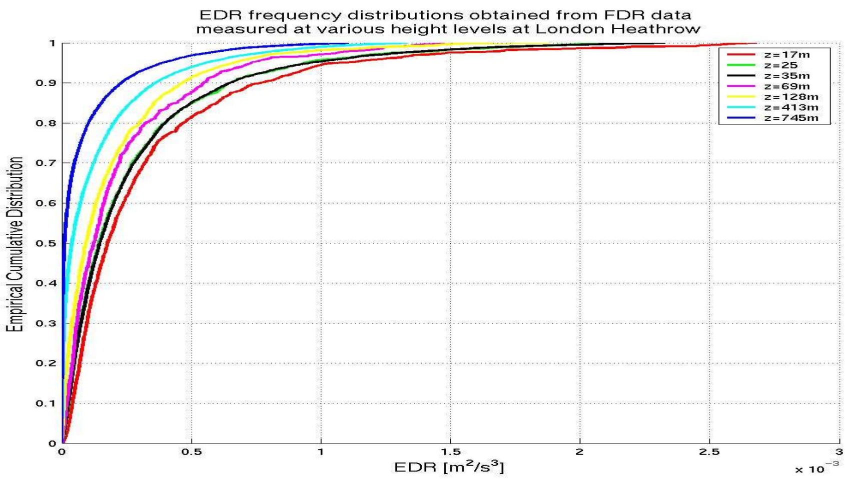

Figure 4-8 Frequency distribution of Eddy Dissipation Rate at various height levels

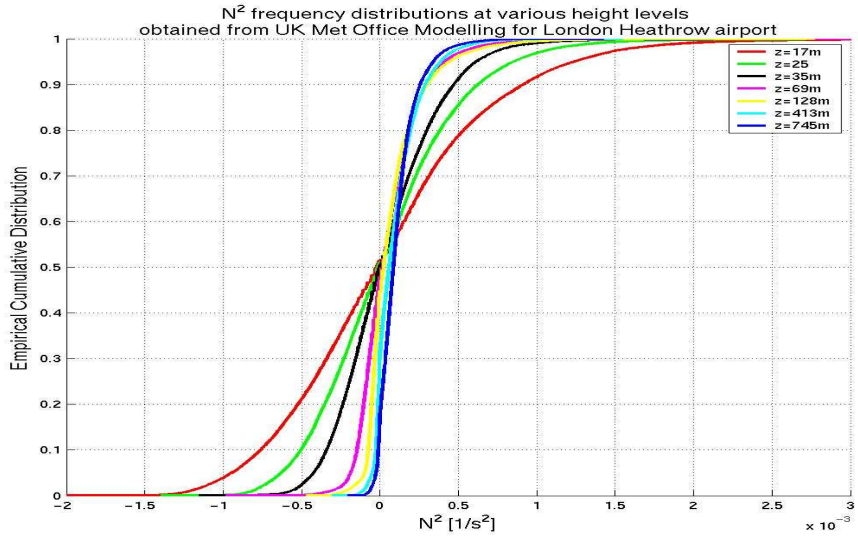

Figure 4-9 Frequency distribution of Brunt-Väissällä frequency at various height levels

4. <u>Run Wake Vortex Generator:</u> Monte Carlo simulations are run with the wake vortex evolution model for the case that the wake vortex is generated when the leading aircraft has longitudinal position *x*. Lateral and vertical positions, strength, and core radius of the vortices are computed as a function of time. The results are analyzed at the time instant when the vortices have the same longitudinal co-ordinate as the follower aircraft. This time instant has been computed with the flight path evolution model, which incorporates the wind speed in longitudinal direction (i.e. influence of head- / tailwind on aircraft ground speed). The time instant also depends on the prescribed separation distance or time. This analysis is repeated for the various prescribed separations (distances or times).
5. <u>Compute Wake Vortex Flow Field for Lead Aircraft at Each of the Gates:</u> Using a dedicated probability density fitting procedure that accounts for dependencies between the lateral and vertical position, the strength, and the core radius of the wake vortex pair, the joint distribution of the wake vortices position, strength, and core radius is obtained in each of the gates. This step is repeated for each separation standard to be evaluated, and provides the probabilistic wake vortex flow field behind the lead aircraft at all the gates.
6. <u>Compute Wake Vortex Encounter:</u> Monte Carlo simulations are carried out to simulate the wake vortex encounter. In this step the joint distribution from step 5 is used and distributions of the position of the follower aircraft are used. Samples of the follower aircraft (lateral and vertical) position and speed in the selected gates are obtained with the flight path evolution model. Encounter metrics such as maximum bank angle, altitude of encounter and loss of height are obtained. This step provides the encounter severity probabilities in the different gates (for each of the specified separations). The simulated encounters are classified into four categories: *Weak*, *Moderate*, *Severe*, and *Extreme*, according to the attained maximum bank angle versus encounter altitude.

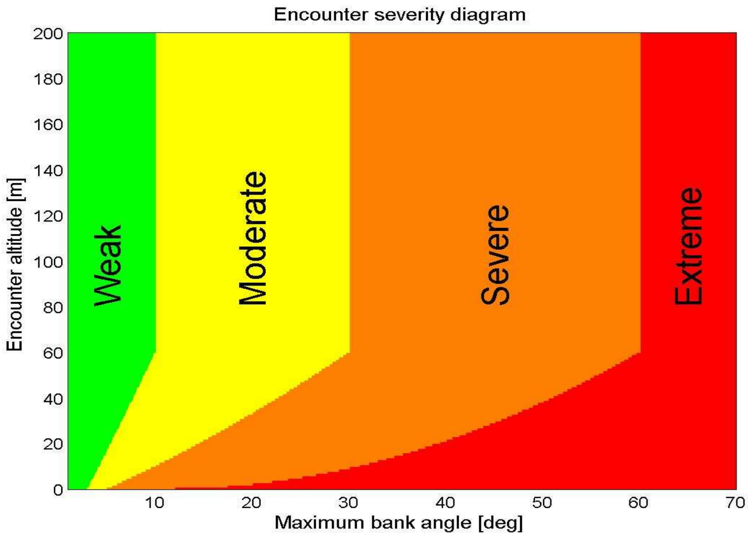

Figure 4-10 Encounter severity classification scheme

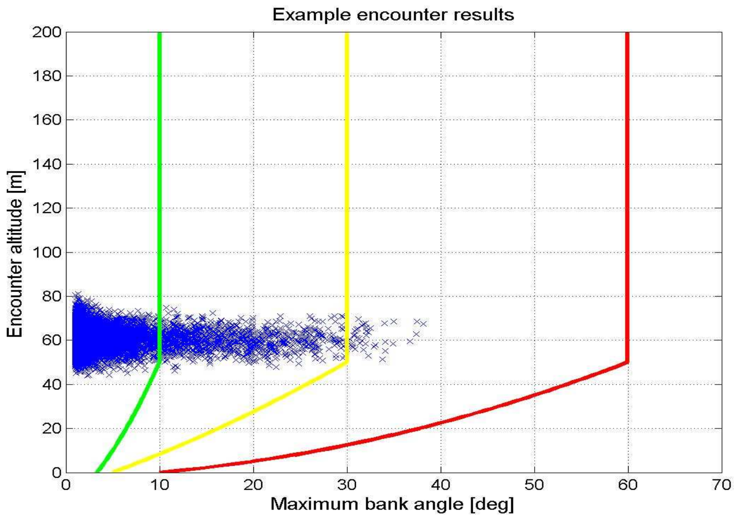

Figure 4-11 Example wake encounter simulation results

7. Compute Incident/Accident Risk Curves: The wake-induced incident/accident risk due to a wake vortex that is generated when the leading aircraft was at position *x* is evaluated. This step provides the instantaneous risk curves (minor incident, major incident, hazardous accident and catastrophic accident) showing the risk to trailing aircraft along the proposed aircraft flight track. As an example, Figures 4-12 – 4-15 show – for each of the defined risk events, i.e. *minor incident, major incident, hazardous accident, and catastrophic accident* – the instantaneous risk as a function of distance from the runway threshold (in average weather conditions). The results clearly show that - for single runway arrivals - the highest risk occurs near the runway threshold.

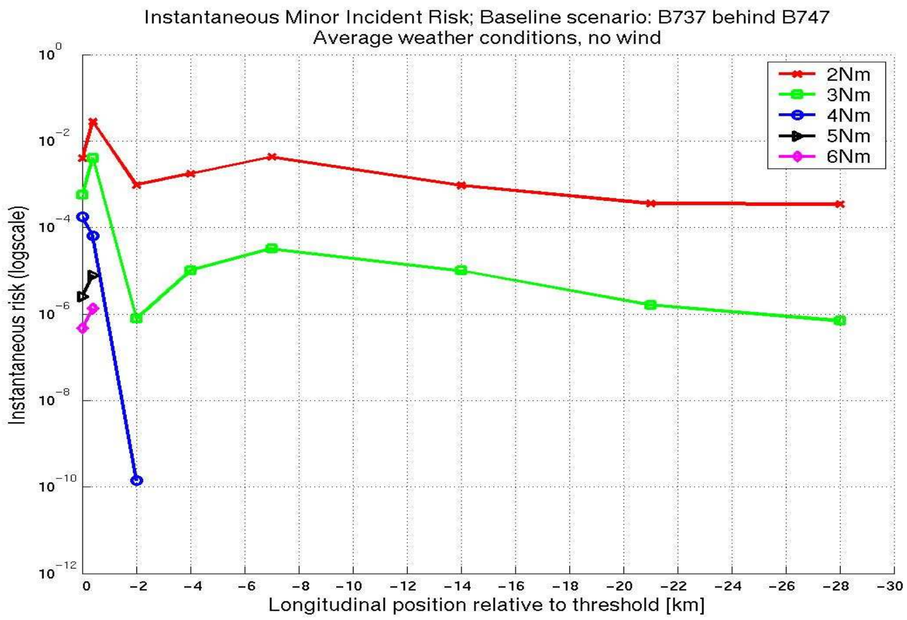

Figure 4-12 Instantaneous minor incident risk along the glide slope

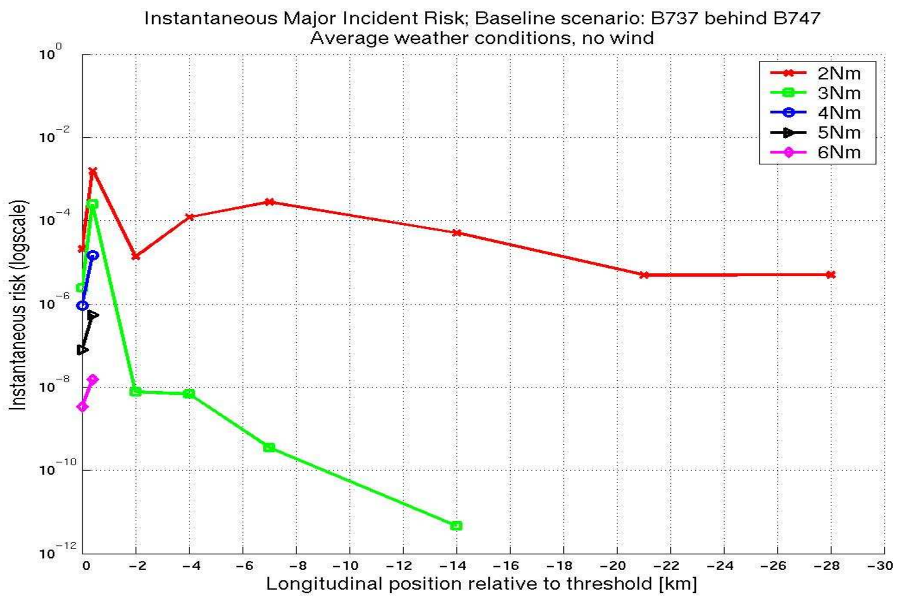

Figure 4-13 Instantaneous major incident risk along the glide slope

8. Compute Incident/Accident Risk Per Movement: The wake-induced incident/ accident risk is obtained by integrating over *x* the risk obtained in Step 7. This step, which is repeated for different prescribed separation standards, provides the four incident/accident risk curves as functions of the separation distance.

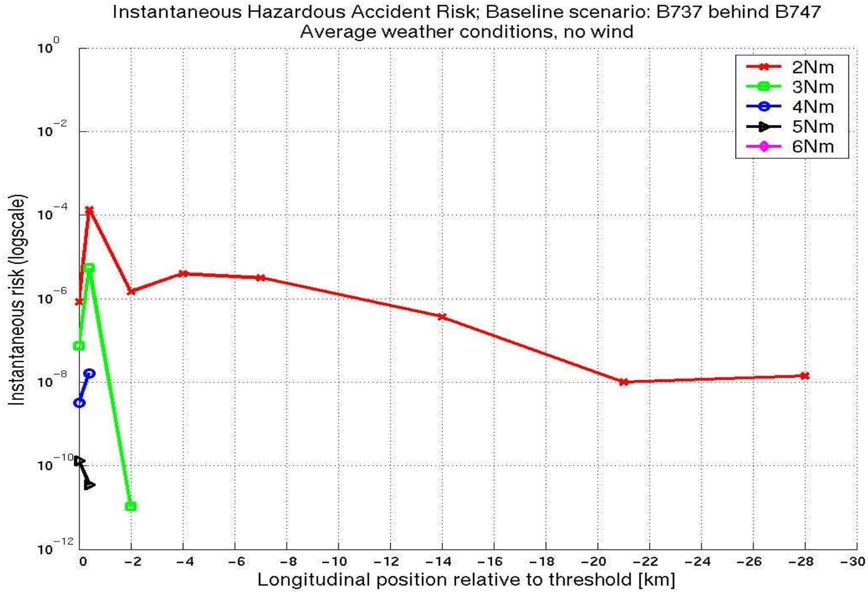

Figure 4-14 Instantaneous hazardous accident risk along the glide slope

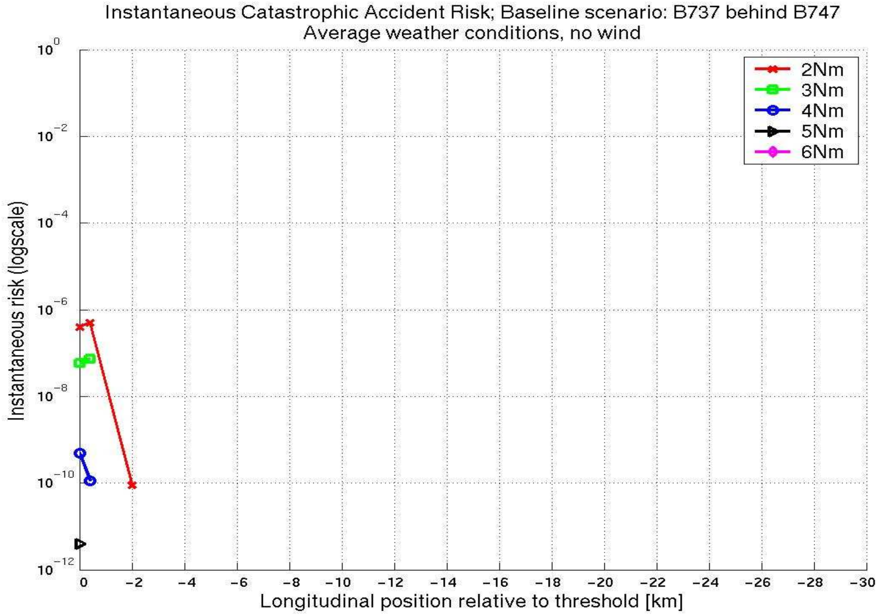

Figure 4-15 Instantaneous catastrophic accident risk along the glide slope

9. <u>Assess Minimum Required Separation Distance:</u> Application of a risk management procedure – based on the requirement that all four TLS values should be fulfilled – provides the required separation minima under different operational, weather and wind conditions. Figure 4-4 illustrates such end results obtained for a Boeing 737 landing behind a Boeing 747.

4.6 Wake vortex risk assessment of single runway arrivals

4.6.1 Description of scenarios

For a variety of wind conditions, the wake vortex induced risk has been analyzed. The impact of crosswind, head- and tailwind has been assessed for a variety of leader and follower combinations. 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 (see also Table 4-2):

- 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.

Table 4-2 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

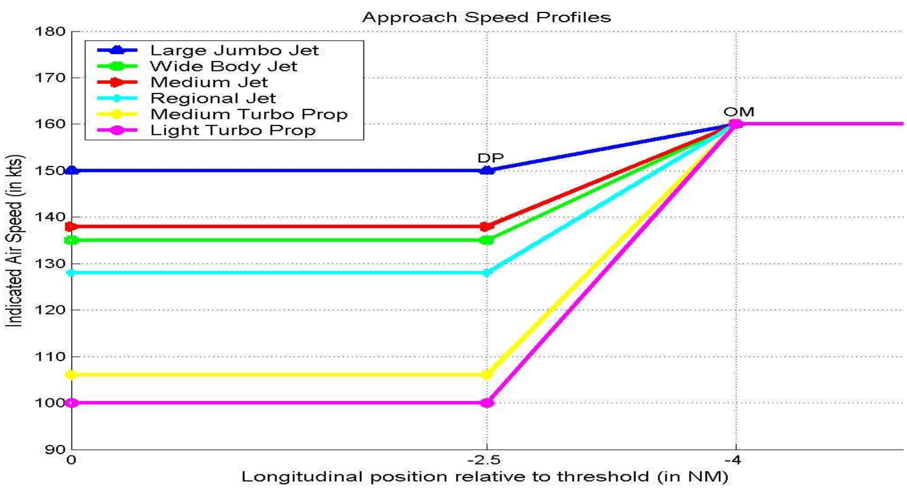

Figure 4-16 Nominal approach speed profiles

Analysis of wake induced risk is done in a number of longitudinal positions up to about 7.5 NM from the runway thresholds, i.e. up to about 2500 ft height (see Table 4-3).

Table 4-3 Longitudinal positions where wake vortex severity is evaluated and their relation between distance to runway threshold and height along the glide path

Label	x1	x2	x3	x4	x5	x6	X7
Distance (m)	0	200	400	1000	2000	7408	13813
Distance (NM)	0.00	0.11	0.22	0.54	1.08	4.00	7.46
Height (m)	16	26	37	68	121	404	740
Height (ft)	52	86	120	223	395	1324	2425

Position x6 and x7 correspond to the OM and FAP at London Heathrow. The other points are taken close to the runway threshold, since the expectation is that the wake vortex induced risk is highest near the runway threshold.

Especially a combination of cross- and tailwind is expected to be dangerous. Strong headwind will be beneficial for the relative vertical position of encountering aircraft and the wake vortex. Tailwind has an opposite effect: vortices will be transported in the same direction as the follower aircraft is flying thereby decreasing the vertical distance between vortex and aircraft. There is no need to analyse strong tailwind conditions, since runways are usually approached with headwind conditions. Wind scenarios are given in Figure 4-17.

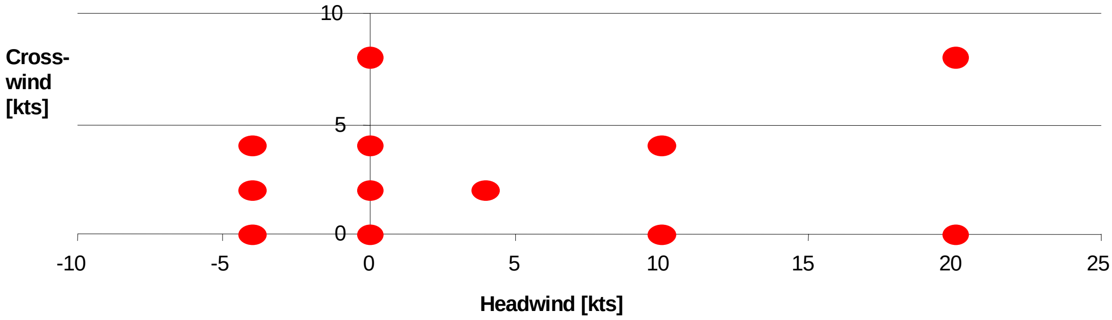

Figure 4-17 Investigated head- and crosswind scenarios

Frequency distributions of Eddy Dissipation Rate (EDR) and Brunt- Väissällä frequency at various height levels have been determined using London Heathrow meteorological data from UK Met Office [10]. The EDR data comes from processed Flight Data Recordings (FDR) data (also collected in S-Wake) and the Brunt-Väissällä frequency data is obtained with a model representing the London Heathrow climatology. Figures 4-8 and 4-9 show the frequency distribution of the Eddy Dissipation Rate and the Brunt-Väissällä frequency at various height levels along the approach glide path. This has been used in the Sarpkaya wake evolution model.

Note that 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.

4.6.2 Risk assessment results

An initial safety assessment showed that the impact of ATM procedural aspects on wake vortex risk is relatively small [10]. This is due to the fact that the largest risk contribution evolves from possible encounters near to the runway threshold (with consequently a small impact of e.g. different glide path angles, different glide slope intercept altitudes). This implies that changes in ATM procedures at present will not allow safe reduction of wake vortex separation distances without the use of new wake vortex avoidance systems. The results also indicate that to enhance capacity, weather and wind conditions favourable to reduce risk in the runway threshold area should be exploited. An extended safety assessment was made, focusing on impact of weather with the atmospheric conditions according to the weather climatology of Heathrow (see Figures 4-8 and 4-9). This safety assessment was further focused on the impact of wind conditions. Different head-, tailwind and crosswind conditions were considered. Results are given below.

Safe separation distances behind a Large Jumbo Jet

The wake vortex induced risk for four different types of follower aircraft: a Large Jumbo Jet, a Medium Jet, a Regional Jet, and a Light Turbo Prop is determined. Application of the S-Wake risk management framework provides safe separation distances under different wind conditions. The Figures 4-18 to 4-21 show the safe separation distances for a Large Jumbo Jet, Medium Jet, Regional Jet, and a Light Turbo Prop (all behind a Large Jumbo Jet). Note that the yellow line indicates the current prescribed wake vortex separation minima for the aircraft combination under consideration. The purple line indicates the radar separation minima (always 2.5 NM). It appears that the situation with a small crosswind of 1 m/s is most unfavourable. As can be seen, in addition to crosswind (drifting of the vortices out of the flight corridor), also strong headwinds are efficient in reducing the risk to follower aircraft. For most scenarios, the results show that the current separation minima are sufficient.

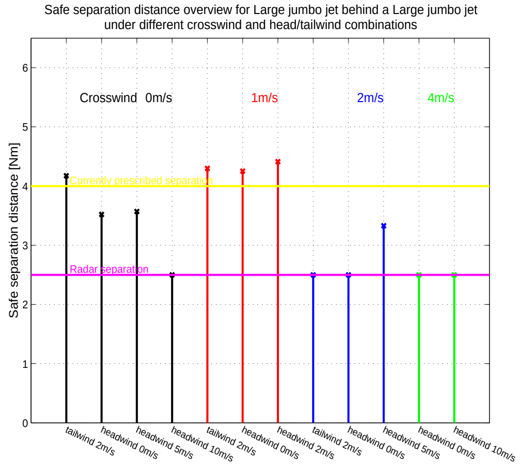

Figure 4-18 Safe separation distance for a Large Jumbo Jet behind Large Jumbo Jet

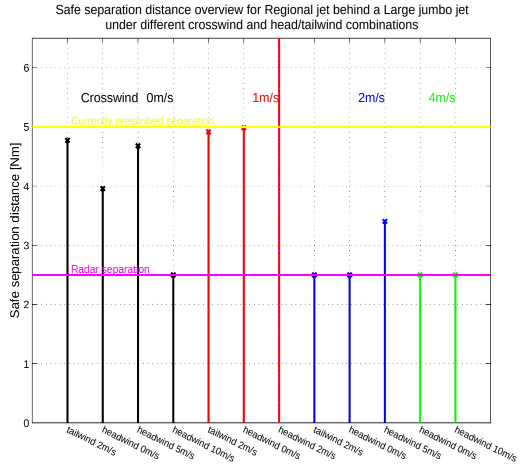

Figure 4-20 Safe separation distance for a Regional Jet behind Large Jumbo Jet

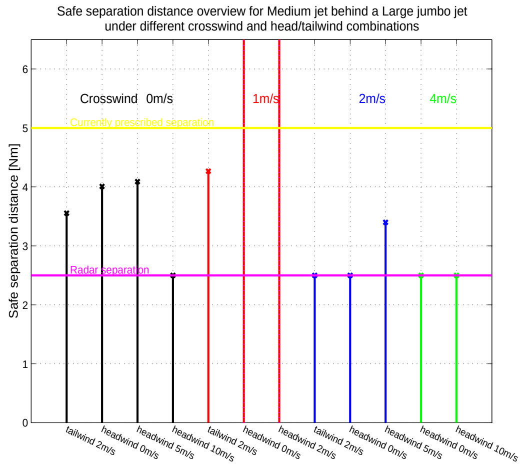

Figure 4-19 Safe separation distance for a Medium Jet behind Large Jumbo Jet

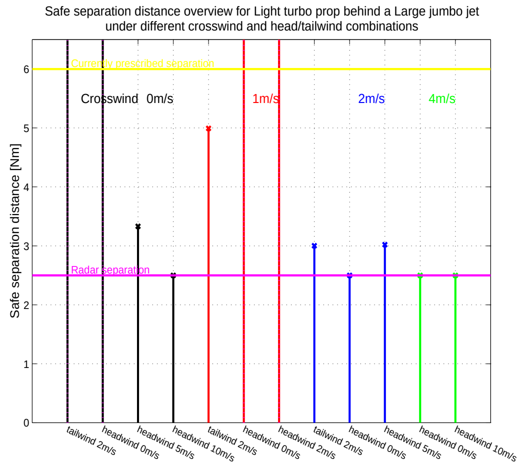

Figure 4-21 Safe separation distance for a Light Turbo Prop behind Large Jumbo Jet

<u>Safe separation distances behind a Medium Jet</u>

The wake vortex induced risk for four different types of follower aircraft: a Large Jumbo Jet, a Medium Jet, a Regional Jet, and a Light Turbo Prop (all behind a Medium Jet) is determined. Application of the risk management framework provides safe separation distances under different wind conditions. The risk analysis showed that radar separation can be applied for Medium Jet and Large Jumbo Jet follower aircraft under all wind conditions. The Figures 4-22 and 4-23 show the safe separation distances for a Regional Jet and a Light Turbo Prop respectively. Again, in addition to crosswind, strong headwinds are also very efficient in reducing the risk to follower aircraft. In general, the results show that the current separation minima are sufficient.

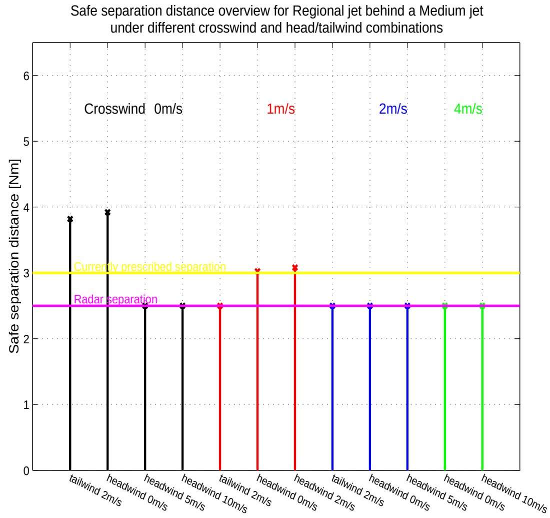

Figure 4-22 Safe separation distance for a Regional Jet behind Medium Jet

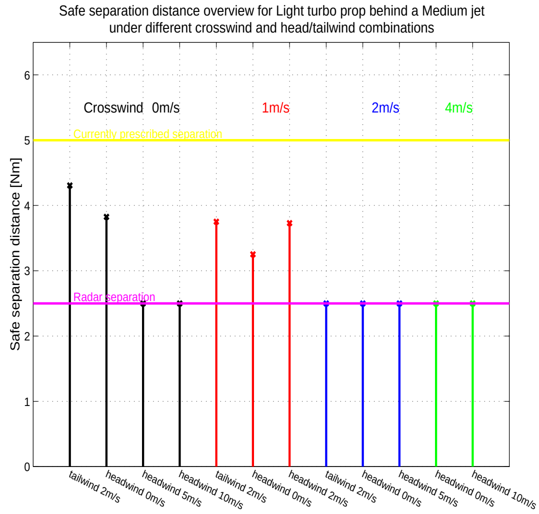

Figure 4-23 Safe separation distance for a Light Turbo Prop behind Medium Jet

Most unfavourable wind conditions

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

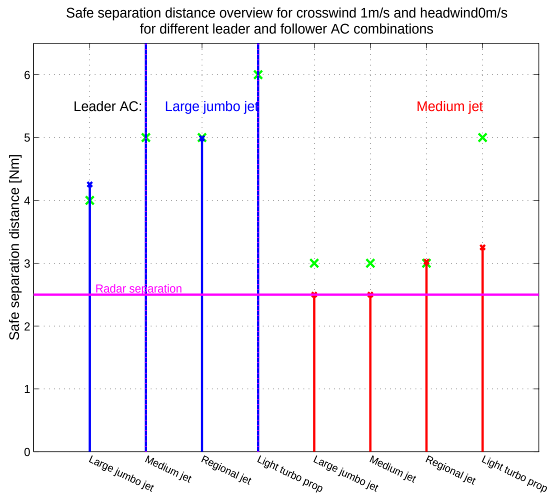

Figure 4-24 Safe separation distance for a small crosswind of 1 m/s

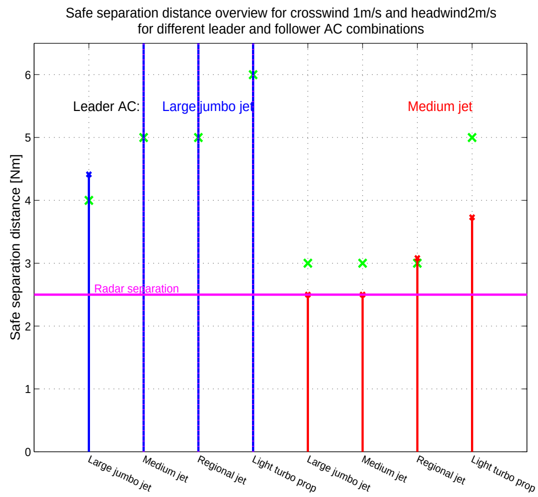

Figure 4-25 Safe separation distance for a crosswind of 1 m/s and a headwind of 2 m/s

Favourable wind conditions

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

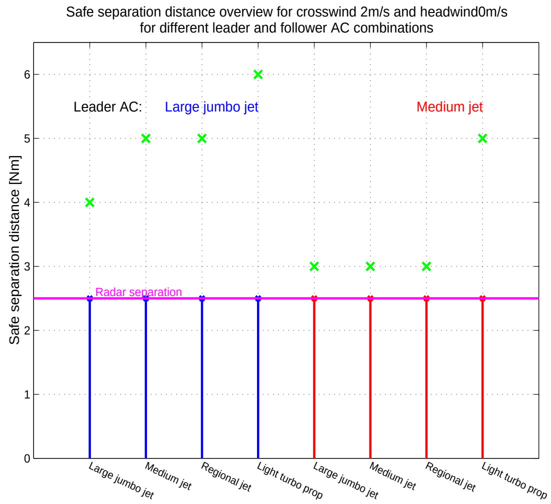

Figure 4-26 Safe separation distance for a crosswind of 2 m/s

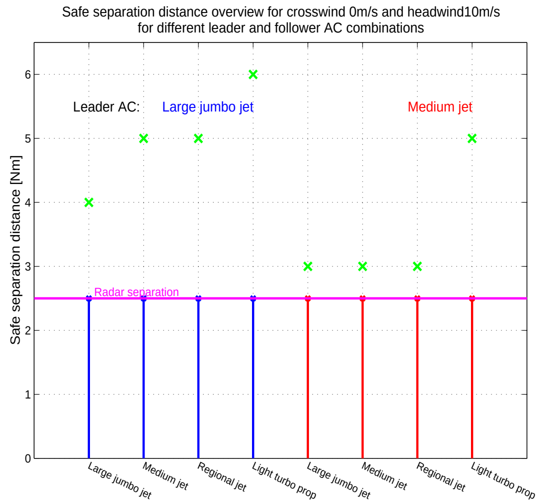

Figure 4-27 Safe separation distance for a headwind of 10 m/s and no crosswind

Unfavorable Wind Conditions for Reduced Wake Vortex Separation

Figures 4-24 and 4-25 provides the safe separation distances for a light crosswind of less than 2 m/s (3.7 knots). The WAVIR computed safe separation distance is also shown in each cell in Tables 4-4 and 4-5 with the ICAO standard in parentheses.

Table 4-4 Safe separation distances for a small crosswind of 1 m/s and no head- or tailwind. WAVIR computed safe separation distance (ICAO standard separation distance)

Lead / ***Follow***	***Large Jumbo Jet***	***Medium Jet***
Large Jumbo Jet	*4.25 NM (4.0 NM)*	*2.5 NM (3.0 NM)*
Medium Jet	*6.5 NM (5.0 NM)*	*2.5 NM (3.0 NM)*
Regional Jet	*5.0 NM (5.0 NM)*	*3.25 NM (3.0 NM)*
Light Turbo prop	*6.5 NM (6.0 NM)*	*3.5 NM (5.0 NM)*

Table 4-5 Safe separation distances for small crosswind of 1 m/s and headwind 2 m/s. WAVIR computed safe separation distance (ICAO standard separation minima)

Lead ***Follow***	***Large Jumbo Jet***	***Medium Jet***
Large Jumbo Jet	*4.5 NM* *(4.0 NM)*	*2.5 NM* *(3.0 NM)*
Medium Jet	*6.5 NM* *(5.0 NM)*	*2.5 NM* *(3.0 NM)*
Regional Jet	*6.5 NM* *(5.0 NM)*	*3.0 NM* *(3.0 NM)*
Light Turbo prop	*6.5 NM* *(6.0 NM)*	*3.75 NM* *(5.0 NM)*

It appears that the WAVIR computed safe separation distance increases slightly with a small headwind as compared to the situation without head- or tailwind. This is due to the fact that the vortices rebound in the area close to the ground. With a small headwind, the rebounding vortices will move closer to into the flight path of the follower aircraft. The situation with a small tailwind of 1 m/s is not shown, but the WAVIR computed safe separation distances are more or less the same as the safe separation distances shown in Table 4-5.

Favorable Wind Conditions for Reduced Wake Vortex Separation

Table 4-6 and Table 4-7 provide the safe separation distances for a sufficiently strong crosswind (larger than 2 m/s, 3.7 knots) and for a strong headwind of at least 10 m/s (18.5 knots) respectively. Note that the safe separation distance computed by WAVIR is much lower than those in Figures 4-24 and 4-25.

Table 4-6 Safe separation distances for a crosswind of 2 m/s (3.7 knots). WAVIR computed safe separation distance (ICAO standard separation distance)

Lead ***Follow***	***Large Jumbo Jet***	***Medium Jet***
Large Jumbo Jet	*2.5 NM* *(4.0 NM)*	*2.5 NM* *(3.0 NM)*
Medium Jet	*2.5 NM* *(5.0 NM)*	*2.5 NM* *(3.0 NM)*
Regional Jet	*2.5 NM* *(5.0 NM)*	*2.5 NM* *(3.0 NM)*
Light Turbo prop	*2.5 NM* *(6.0 NM)*	*2.5 NM* *(5.0 NM)*

Table 4-7 Safe separation distances for a headwind of 10 m/s (18.5 knots) and no crosswinds. WAVIR computed safe separation distance (ICAO standard separation distance)

Lead / Follow	Large Jumbo Jet	Medium Jet
Large Jumbo Jet	*2.5 NM (4.0 NM)*	*2.5 NM (3.0 NM)*
Medium Jet	*2.5 NM (5.0 NM)*	*2.5 NM (3.0 NM)*
Regional Jet	*2.5 NM (5.0 NM)*	*2.5 NM (3.0 NM)*
Light Turbo prop	*2.5 NM (6.0 NM)*	*2.5 NM (5.0 NM)*

4.6.3 Initial estimate for the minimum required separation distance

The results of the quantitative safety assessment of the current practice are also visualized in Figure 4-28. 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 (at the runway threshold) were 3.0, 4.0, and 5.0NM.

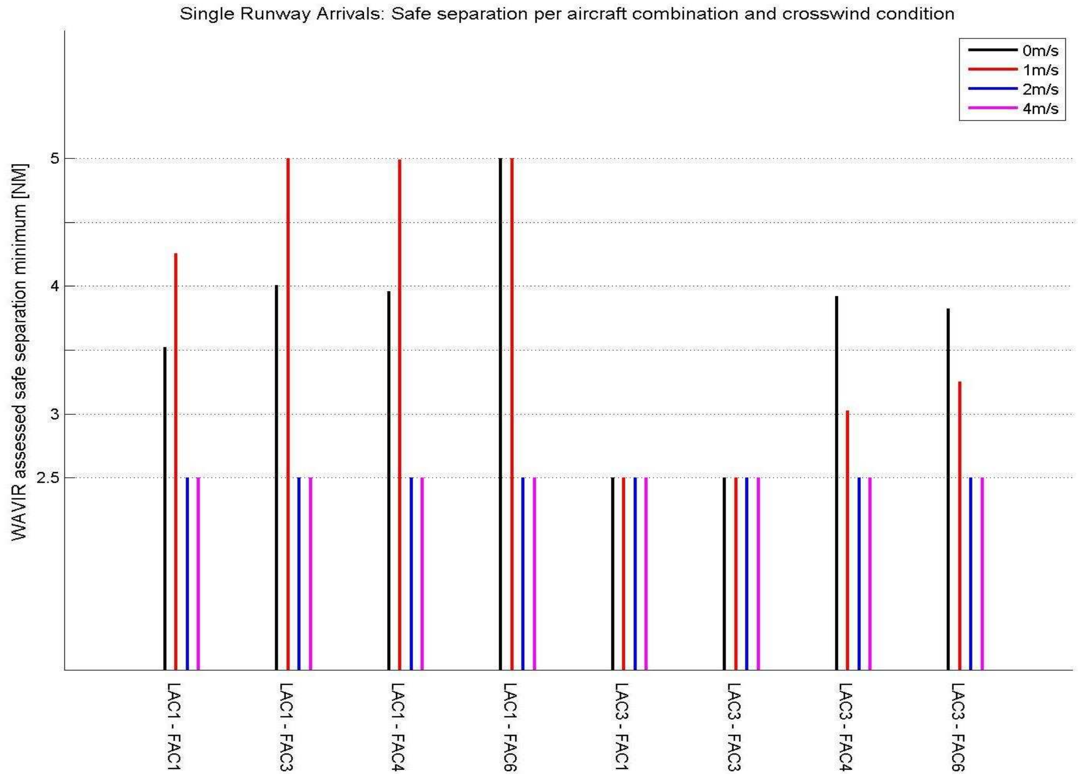

Figure 4-28 Overview of WAVIR assessed separation minima for single runway arrivals

In case reduced wake vortex separation would be applied to all aircraft combinations, Table 4-8 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 (and operation) is used, and the system components meet certain performance requirements (see Speijker et al. [13, 15]).

Table 4-8 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

4.7 Comparison with wake encounter data

NATS has been collecting voluntary pilot reports since 1972. However, it is not known how close the reported rate of encounters is to the actual rate of encounters. In addition, only limited information is available from the reported encounters on the severity of the encounters. As a result, these data are not reliable enough for a comprehensive assessment of the current wake vortex safety levels around major airports. S-Wake therefore also aimed at developing, implementing and validating an algorithm for the automatic processing of Flight Data Recordings (FDRs) from all incoming British Airways (BA) aircraft at London Heathrow [62]. This algorithm was developed by NLR and is now known as WAVENDA. An initial validation of this Wake Vortex Encounter (WVE) detection algorithm was performed by NATS, which shows that it can successfully identify WVEs from flight data. Subsequently, an extensive data collection was performed for incoming flights at London Heathrow. It covered a one-year period from September 2001 to August 2002. A detailed overview of this data collection activity is provided in De Bruin [62], but it included:

- The collection of segments of FDR data from flights of BA aircraft into London Heathrow. In total 30,000 FDR flight segments were successfully gathered.
- The application of WAVENDA to the collected FDR data segments in order to:
  a) create a limited set of parameters (including meteorological data along the flight path) for each successfully processed FDR output segment;
  b) detect the occurrence of WVEs in the processed FDR output segments (about 210) and, in that case, store a more extended set of parameters for further analysis.

- The storage of all these data in the Heathrow Data Base (HDB). This enables correlation between FDR meteorological data and ground based meteorological data, determination of actual radar separations between trailing aircraft and identification of the wake generating aircraft and the local atmospheric conditions when a WVE is detected.

The WVE results from the statistical analysis of FDRs, which were conducted by NATS using the HDB database, focused on investigation of relationships between vortex encounter parameters and situational parameters such as time separation and wind vector. As an example of the preliminary WVE results, Figure 4-29 shows a plan-view of the London Heathrow area (covering all four approach corridors) with the locations of the WVEs detected by WAVENDA (light purple dots). The radar tracking locations of the WVE aircraft are shown as well (dark blue dots). Clearly, WVEs occur both along the ILS flight path and along flight segments joining onto the ILS path.

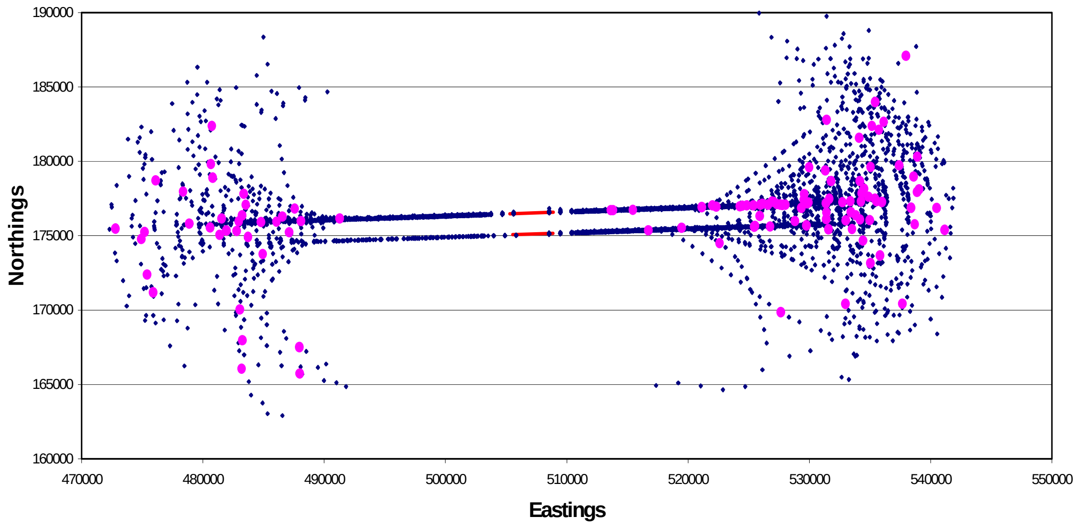

Figure 4-29 Top view of London Heathrow area, with radar flight tracking (dark dots) and WVE positions detected by WAVENDA from FDR data analysis (light dots)

Analysis of voluntary pilot reports

The additional analysis of voluntary pilot reports for WVEs, as performed in S-Wake [62], did produce two interesting results useful as comparison with the above risk assessment results:

Result 1: The rate of WVEs appears to increase rapidly (see Figure 4-30) when aircraft are spaced more than 10 to 15 seconds below the separation minimum. The likelihood of an encounter is relatively constant when the separation is above the minimum. The precise weather conditions (e.g. level of turbulence) for all these encounters are unknown but the crosswinds are generally below 3 - 4 m/s for heights below 4,000 ft (see *Result 2* below). *Result 1* does therefore confirm that the current separations (expressed in terms of time) have been set at appropriate levels, at least for the meteorological conditions in which WVEs are reported. Indeed the separation is insufficient to eliminate WVEs completely even for separations much larger than the ICAO minima. This suggests that the current ICAO minima might not always suffice in certain meteorological conditions. *Result 1* does not, however, exclude the possibility that significantly smaller (but safe) separations are possible under certain weather conditions: see *Result 2* for example.

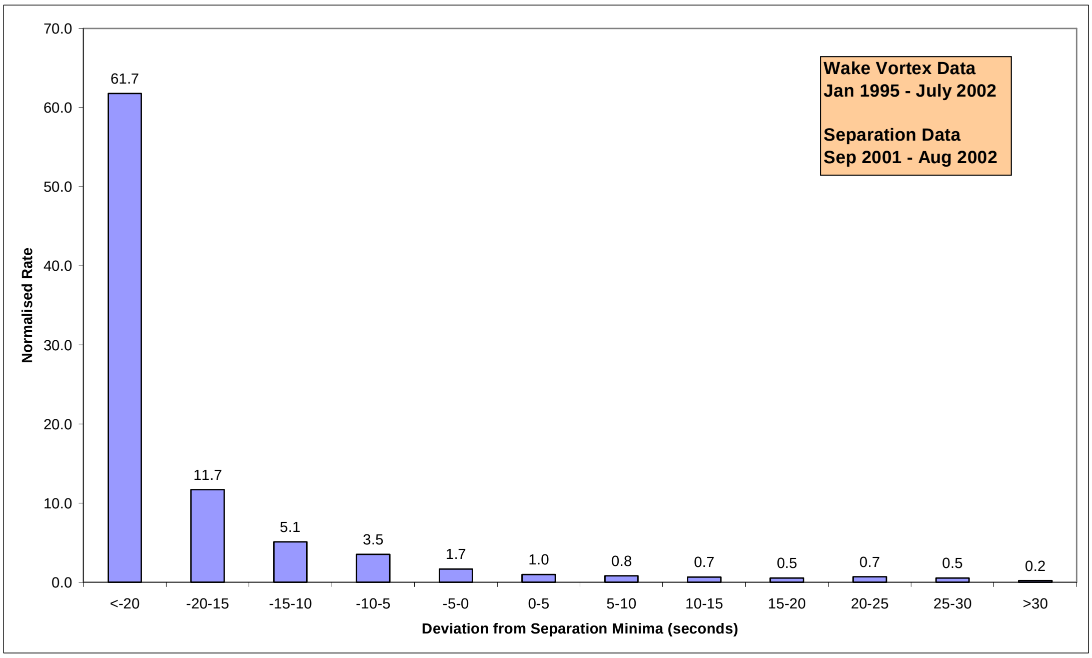

Figure 4-30 Relative WVE Rates (WVE rate for nominal separations normalised to 1) for Voluntary Reported Encounters

Result 2: For leader and follower aircraft established on the glide slope, the rate of WVEs is considerably reduced when the crosswind is above a critical level (about 3 to 4 m/s). Figure 4-31 shows the distributions of crosswinds at encounter and also the overall crosswind climatology at Heathrow as derived from the FDR data. As far as possible, the reported encounters relate solely to incidents where both leader and follower aircraft were established on the ILS at heights less than 4,000ft. Although some caution must be applied to the information from voluntary pilot reports, Figure 4-31 clearly shows that the size of the crosswind seen at Heathrow is higher than the crosswind experienced at encounter for much of the time. *Result 2* also supports one of the main conclusions i.e. that separations can potentially be reduced substantially for crosswinds above a critical level (because vortices would be transported out of the approach corridor). Section 4.6 suggests that the critical level may be as low as 2m/s. If vortices are to be avoided for distances further away from threshold (where the approach corridor is wider) greater crosswinds will be required (as the statistical data analysis suggests).

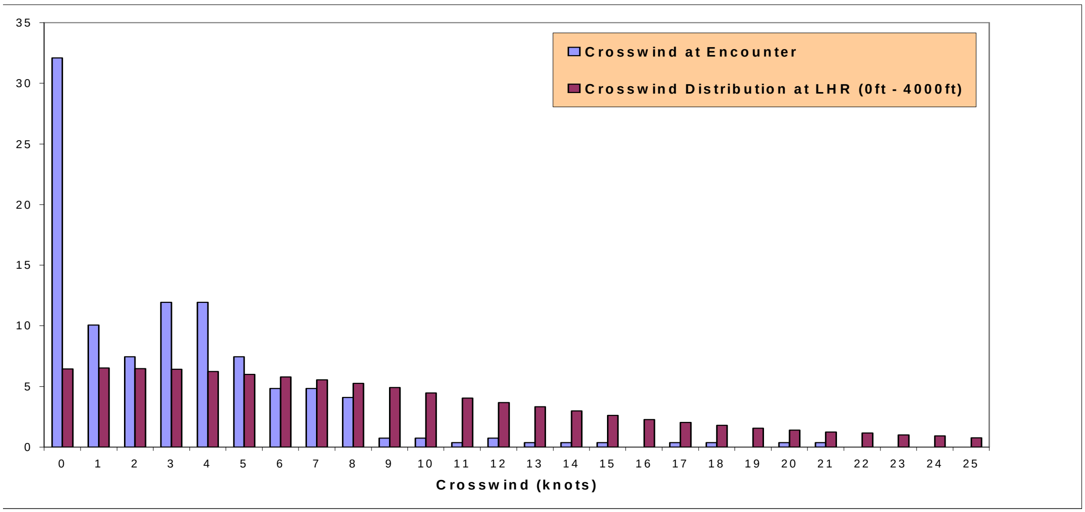

Figure 4-31 Crosswind Distribution for Voluntary Reported Encounters compared with the London-Heathrow crosswind climatology

In the 'WAke Vortex Evolution and wake vortex ENCounter' (WAVENC) project, a statistical analysis of the European Turbulent Wake Reporting Log (ETWIRL) reported wake encounters was made [104, 105]. Exploring the ETWIRL data-base (with about 120 reported cases) enabled a preliminary statistical analysis to be made of the conditions during wake encounter. As shown in Figure 4-32, most encounters occur during the approach phase (at reasonable low altitude) and/or in light cross-wind conditions. Combining this information with the other statistical data leads to the conclusion that WAVENDA detects few encounters at low altitudes [S-Wake, 62].

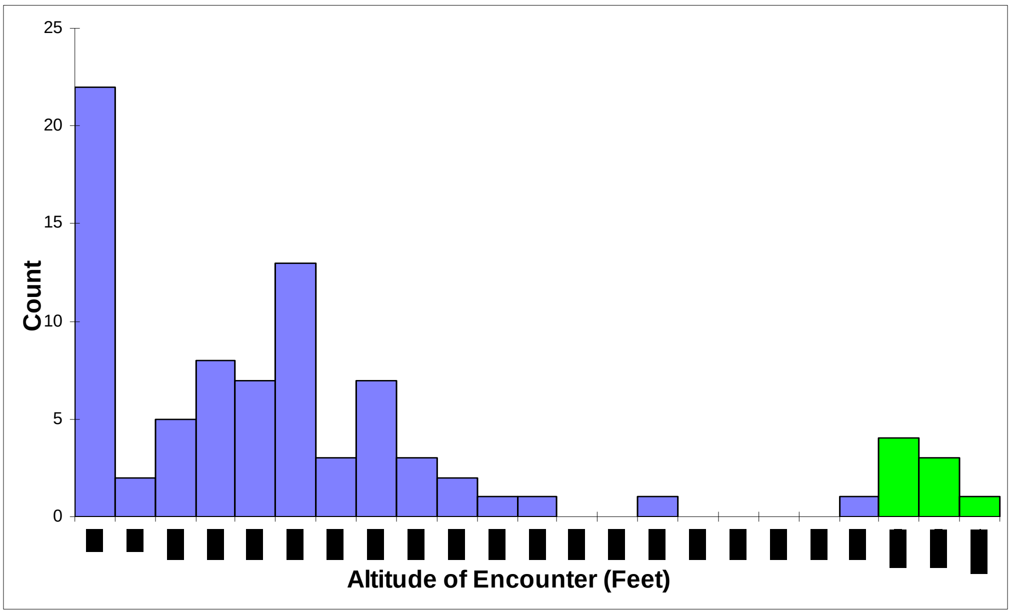

Figure 4-32 Statistical analysis of ETWIRL data-base (120 samples) with flight data recordings of wake vortex encounters (Source: [104, 105])

4.8 Conclusions and recommendations

4.8.1 Conclusions

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

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

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

4.8.2 Recommendations

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

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

With respect to validation, it is recommended to analyse the data collected within the Heathrow Data Base (HDB) in more detail. So far, only partial sets of encounter data have been analysed and compared with the results from the probabilistic safety assessment. Further validation activities shall focus on specific elements of the individual sub-models (e.g. wake evolution in *ground effect*), thereby taking into account validity, applicability and limitations of these sub-models (e.g. the wake encounter models do also *not* perform well *close to the ground*). The relation between encounter severity (bank angle versus loss of height) and the four risk events is a key element that needs to be further validated with actual encounter data as well, possibly using a validated aircraft performance model as developed for Eurocontrol [87].

Acknowledgements
The author acknowledges the European Commission for providing (part of) the funding for this study. The author is especially grateful to the comments and suggestions of Anton de Bruin (the S-Wake coordinator), Gerben van Baren (both NLR), and Simon Mason (NATS). The author is also grateful to NASA (Wayne Bryant, Fernando Rico Cusi) and the George Mason University (George Donohue, Lance Sherry, John Shortle) for the joint contribution to DASC 2004 [11].

5 Safety assessment of ATC-Wake single runway departures

5.1 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 improvements when using the ATC-Wake system and to assess the required crosswind values for which the “ATC-Wake mode”, with reduced aircraft separation, can be applied. 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 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 separation time will vary along the flight track and 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 Appendix A and Section 4). The effect of failures of ATC-Wake system components 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 [78].

Section 5.2 describes the ATC-Wake single runway departure operation. Section 5.3 describes the risk assessment methodology. Section 5.4 contains a description of the simulation scenarios. Risk assessment results are presented Section 5.5. Section 5.6 presents the conclusions and recommendations. Appendix A provides the mathematical model used for the risk assessment.

5.2 Single runway departure operation

5.2.1 Current practice regulations ad 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 [32, 79, 103]. 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 5-1. 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 5-1 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 5-1 below.

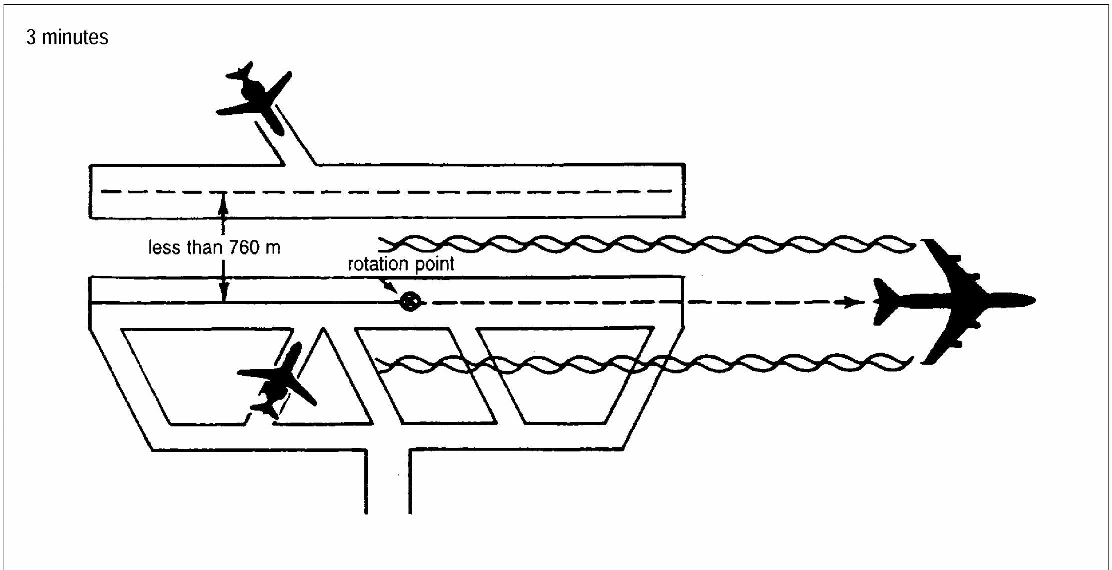

Figure 5-1 Three minutes separation for departing aircraft

5.2.2 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 [12, 13, 14, 16, 17, 20, 54]. The ATC-Wake operation consists of two phases that can be summarised as follows [54]:

- 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 5-2. For departures this concerns the area encompassing rotation points (second half of the runway) and the area encompassing the first turn in the climb phase (note that noise abatement procedures might be applicable).

Table 5-2 Wake vortex prediction and detection areas

Type of Area	Description	Position and Size
Departure Area 1	Area encompassing rotation points	Position: 2^{nd} 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 exist 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 5-2. The detection is performed along the extension of the runway axis and approximately up to a distance of 10 NM from the runway.

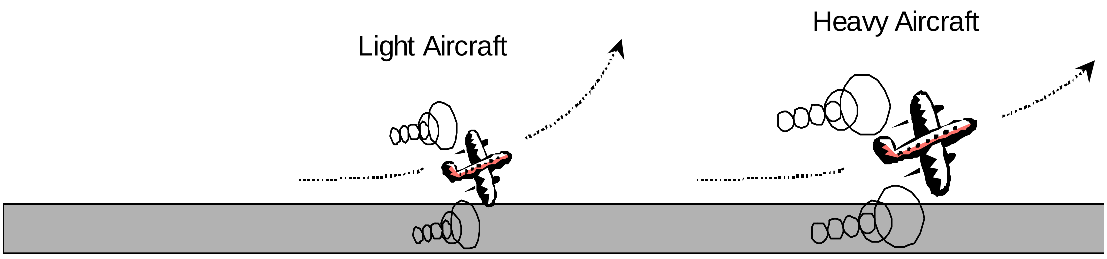

Figure 5-2 Departure rotation points and climb profiles

In this study, it is assumed 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 5-3 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 5-3 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.

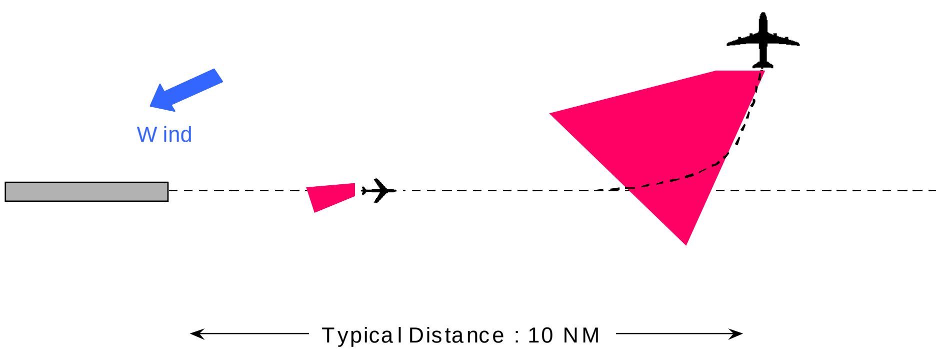

Figure 5-3 Example of vortex vectors for departures

The ATC-Wake system will include four main specific (functional) components (see Table 5-4 and Figure 5-4), which will also interface with several existing ATC system components.

Table 5-4 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 departure 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 5-5.

Table 5-5 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)

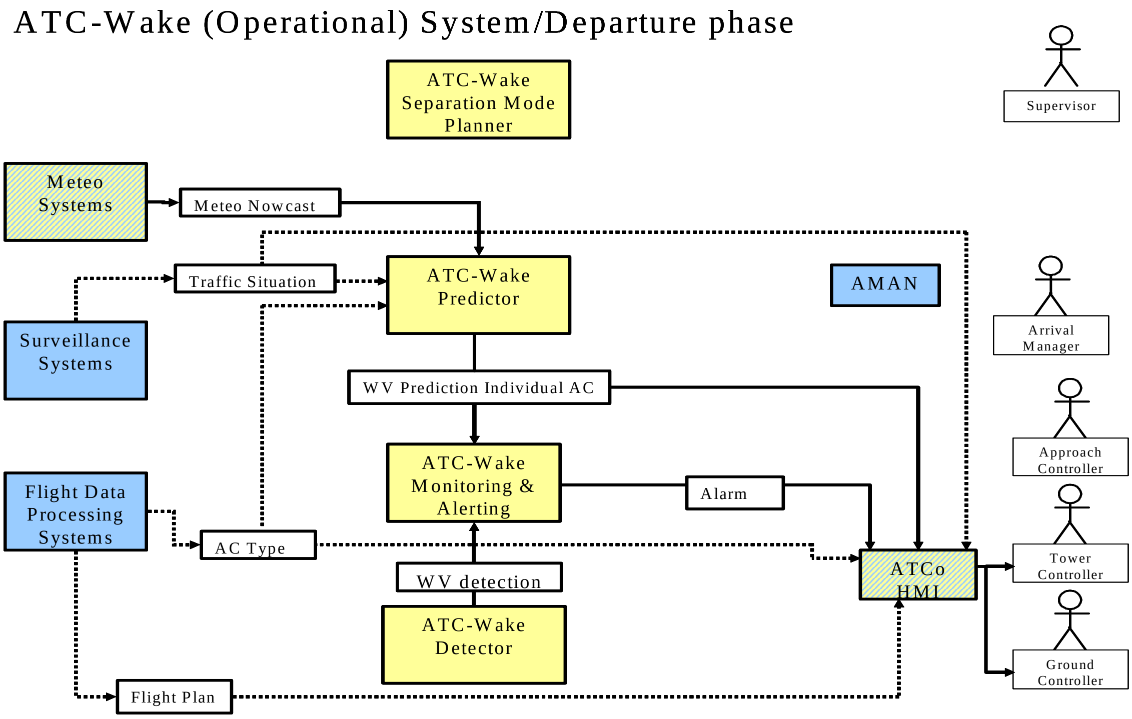

Figure 5-4 ATC-Wake Operational System and its functional flow during the departures

5.3 Risk assessment methodology

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. 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 separation time will vary along the flight track and will usually not be exactly the same as the separation time advised by the ATC-Wake system.

The WAVIR methodology is used to assess wake vortex induced risk in the case of failure of one or more ATC-Wake components. In this case, 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) [106]. 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 (Section 4). The assessment of the wake vortex induced risk is carried out with the risk assessment model described in Appendix A. The effect of failures of ATC-Wake system components and the hazards related to the ATC-Wake operation are investigated in a qualitative way, with the assumption that failure conditions with severe consequences must be extremely improbable and minor failure conditions may be probable [78]. Variations in the initial aircraft separation time are not considered in this study (see [107]).

5.4 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 5-6 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 5-7 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 5-8):

- 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 5-8 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 5-5 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. These 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.

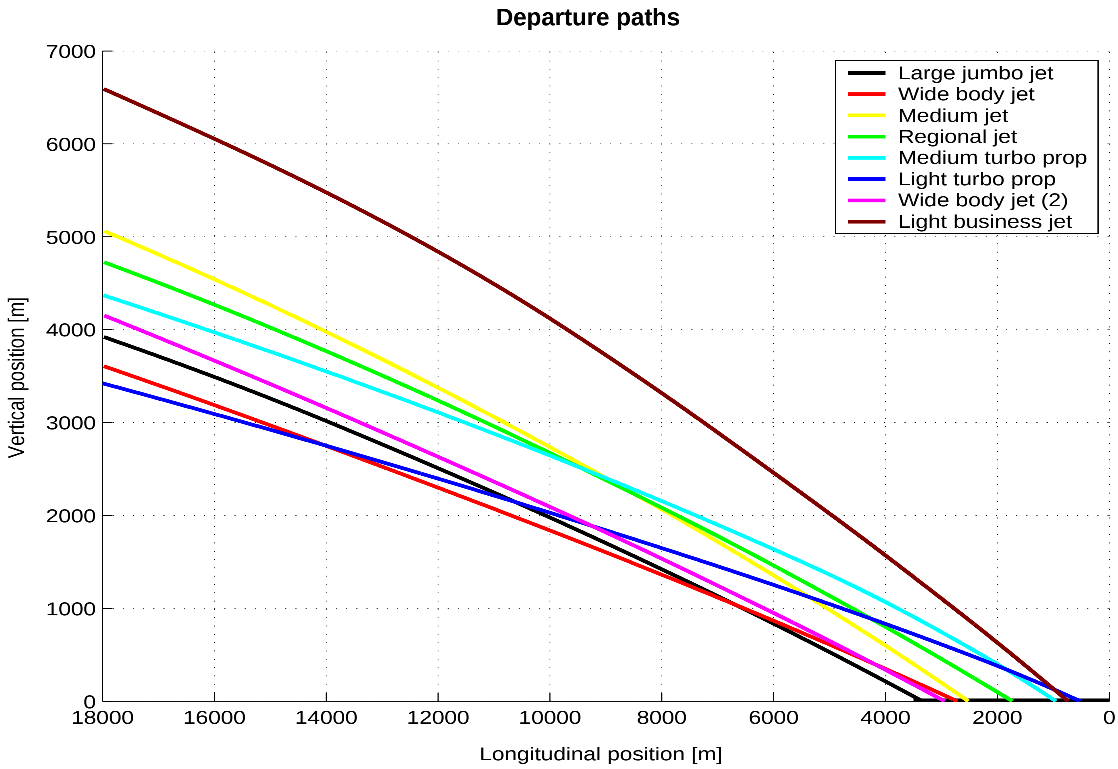

Figure 5-5 Vertical profiles of departing aircraft types based on the BADA database

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 [76, 77]. 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 [80] 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 [9, 10].

Two encounter models are available, the Extended Roll Control Ratio model (ERCR) and the Reduced Aircraft Pilot Model (RAPM) (see Appendix A). 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.

5.5 Risk assessment

5.5.1 Qualitative risk assessment

The risks associated with the ATC-Wake operation have been identified with the NLR Qualitative Safety Assessment (QSA) methodology. In various brainstorming sessions with operational experts, hazards have been identified that could occur in the considered operation. Identified potential safety bottlenecks for ATC-Wake departure operations 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 tower controllers are used to work based on their outside view.

Table 5-9 provides an assessment of the effect of the ATC-Wake system component failures. 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. Failure conditions with severe consequences must be extremely improbable and minor failure conditions may be probable [78]. 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.

It appears that the Monitoring and Alerting system and Meteorological Forecast and Now-casting systems are crucial and sufficient accuracy and reliability shall be guaranteed.

Table 5-9 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.
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.

Description	Effect	Classification	Comment
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.
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.

5.6 Quantitative risk assessment

5.6.1 Wake vortex induced risk

Figure 5-10 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 5-7). Risk assessment results for cross wind conditions of 0, 1, 2, 3, 4, and 5 m/s are provided in Figures 5-11 until 5-16 [15]. 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 6. The full details of the quantitative safety assessment are provided in Speijker et al. [84], 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 5-17, in Section 5.6.2). 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 5-6 until 5-9 present the incident/accident risk curves for a Regional Jet departing under different crosswind conditions (no head- or tailwind) behind a Large Jumbo Jet.

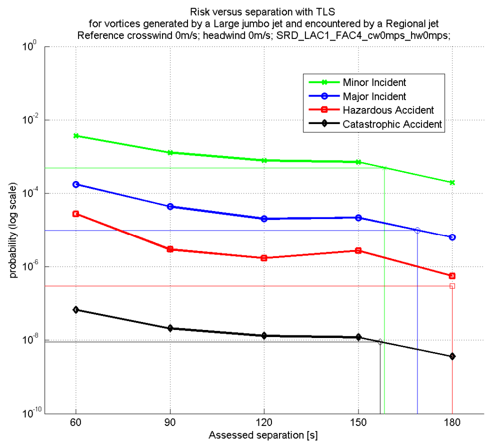

Figure 5-6 Risk with crosswind 0 m/s

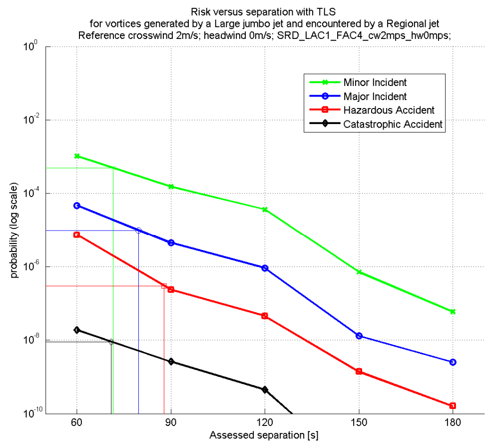

Figure 5-8 Risk with crosswind 2 m/s

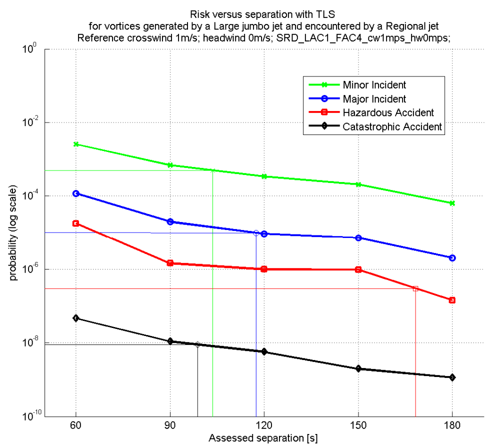

Figure 5-7 Risk with crosswind 1 m/s

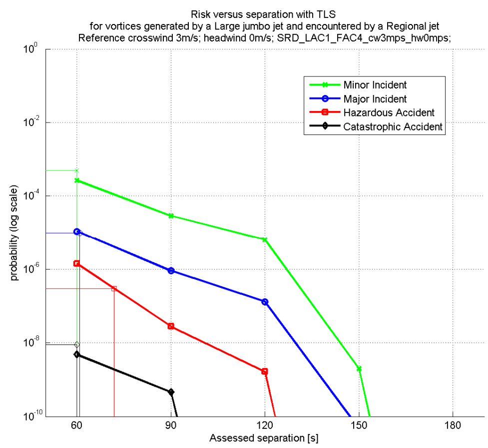

Figure 5-9 Risk with crosswind 3 m/s

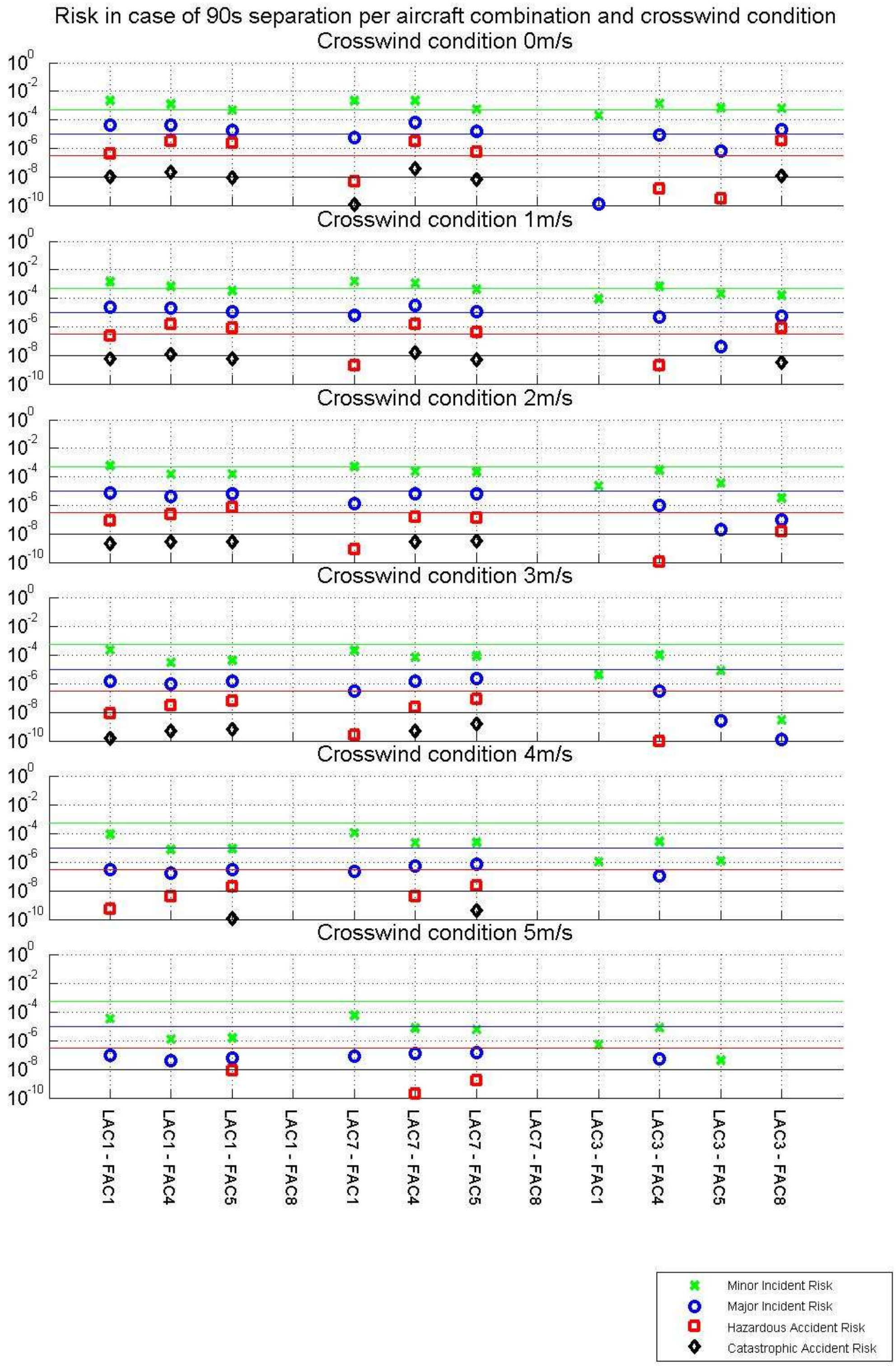

Figure 5-10 Overview of risk results in case of 90 seconds separation

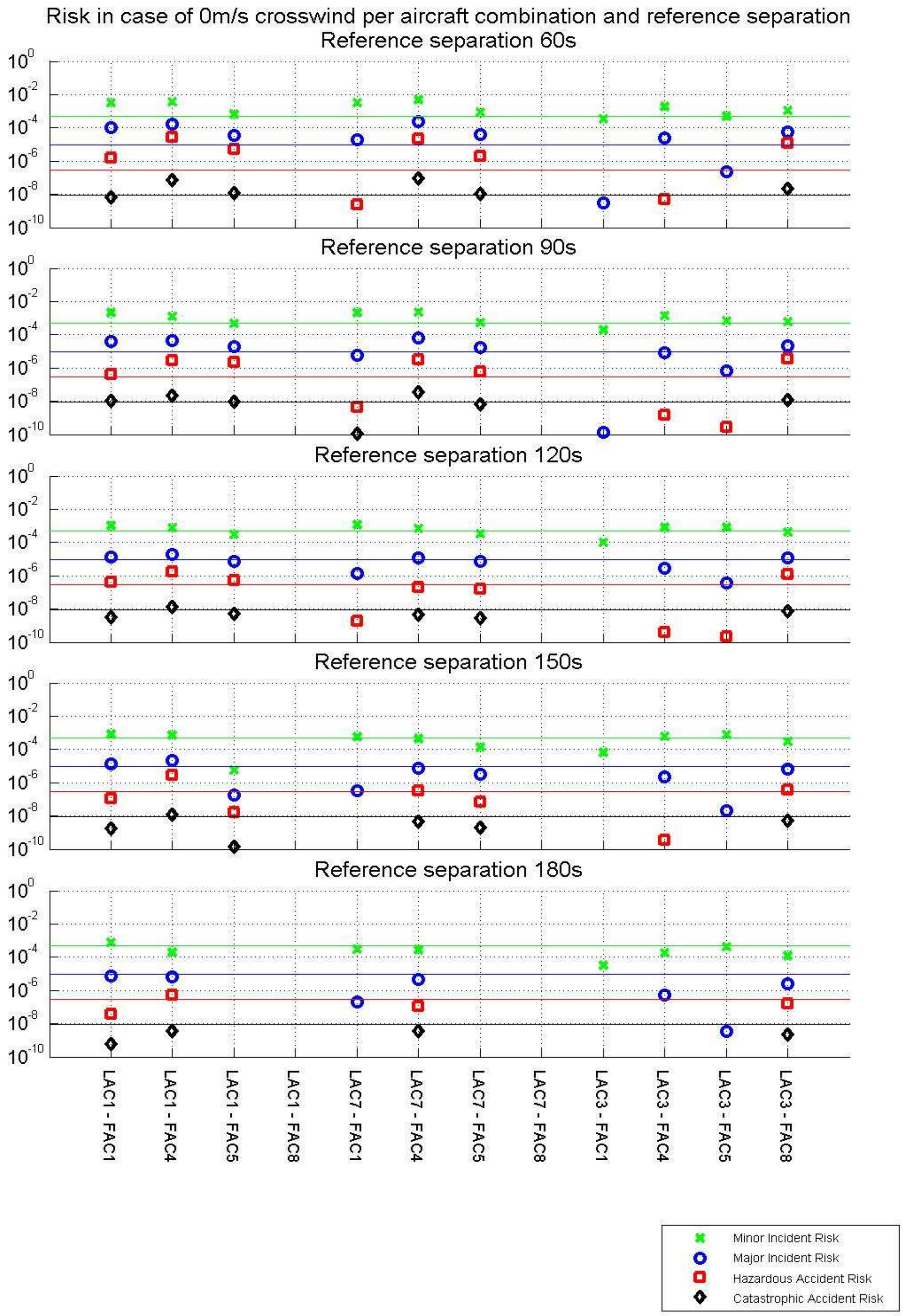

Figure 5-11 Overview of risk results in case of 0 m/s crosswind

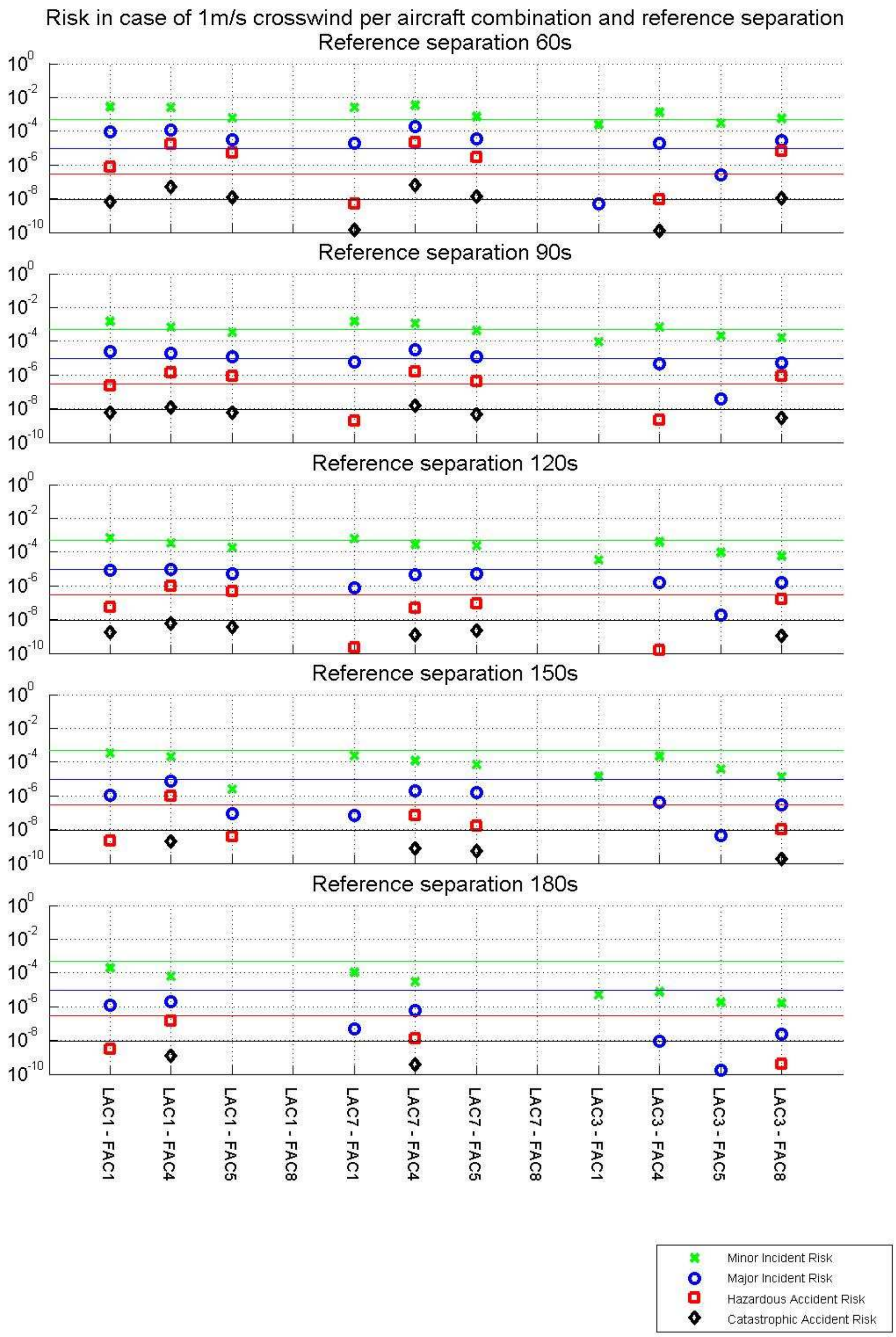

Figure 5-12 Overview of risk results in case of 1 m/s crosswind

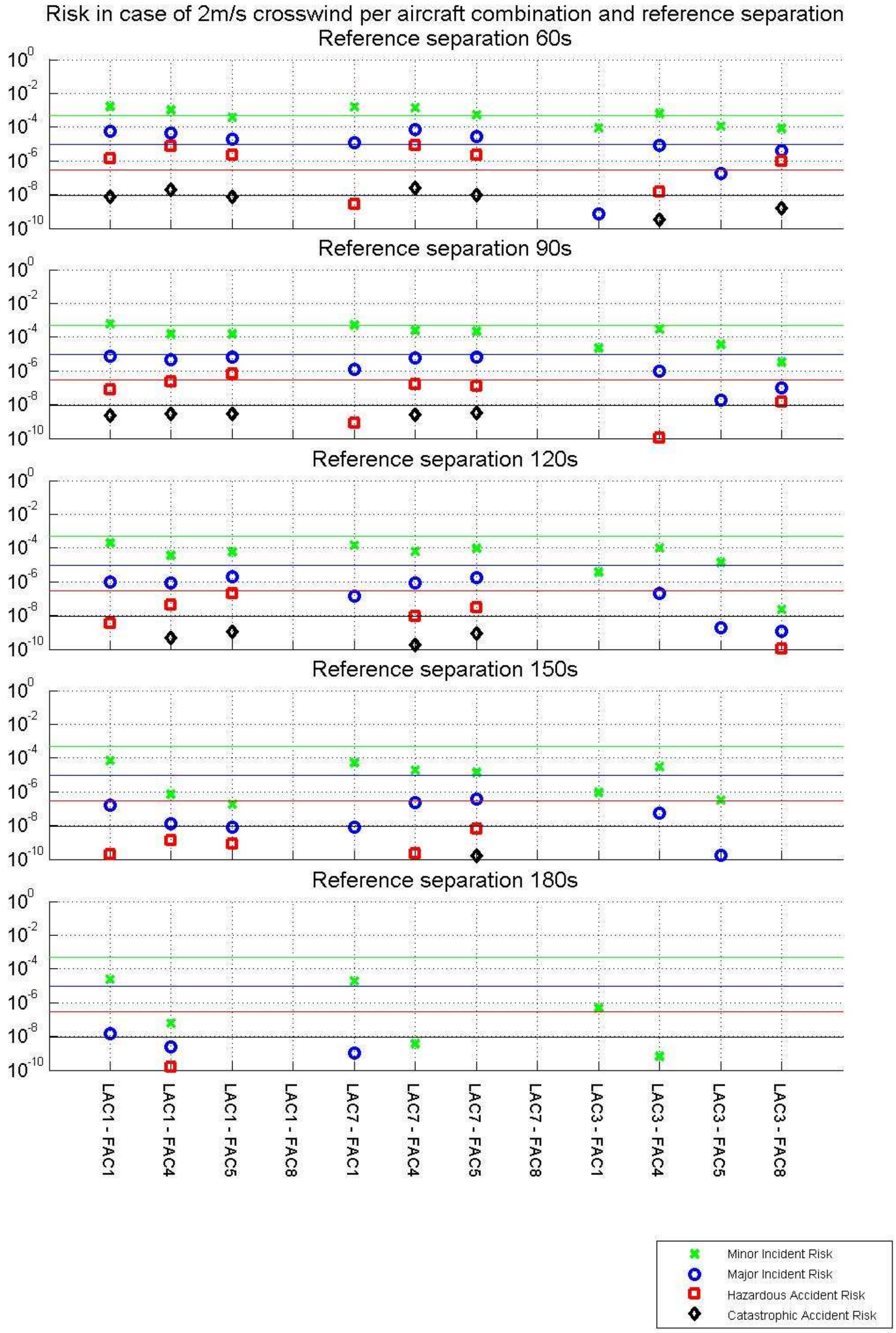

Figure 5-13 Overview of risk results in case of 2 m/s crosswind

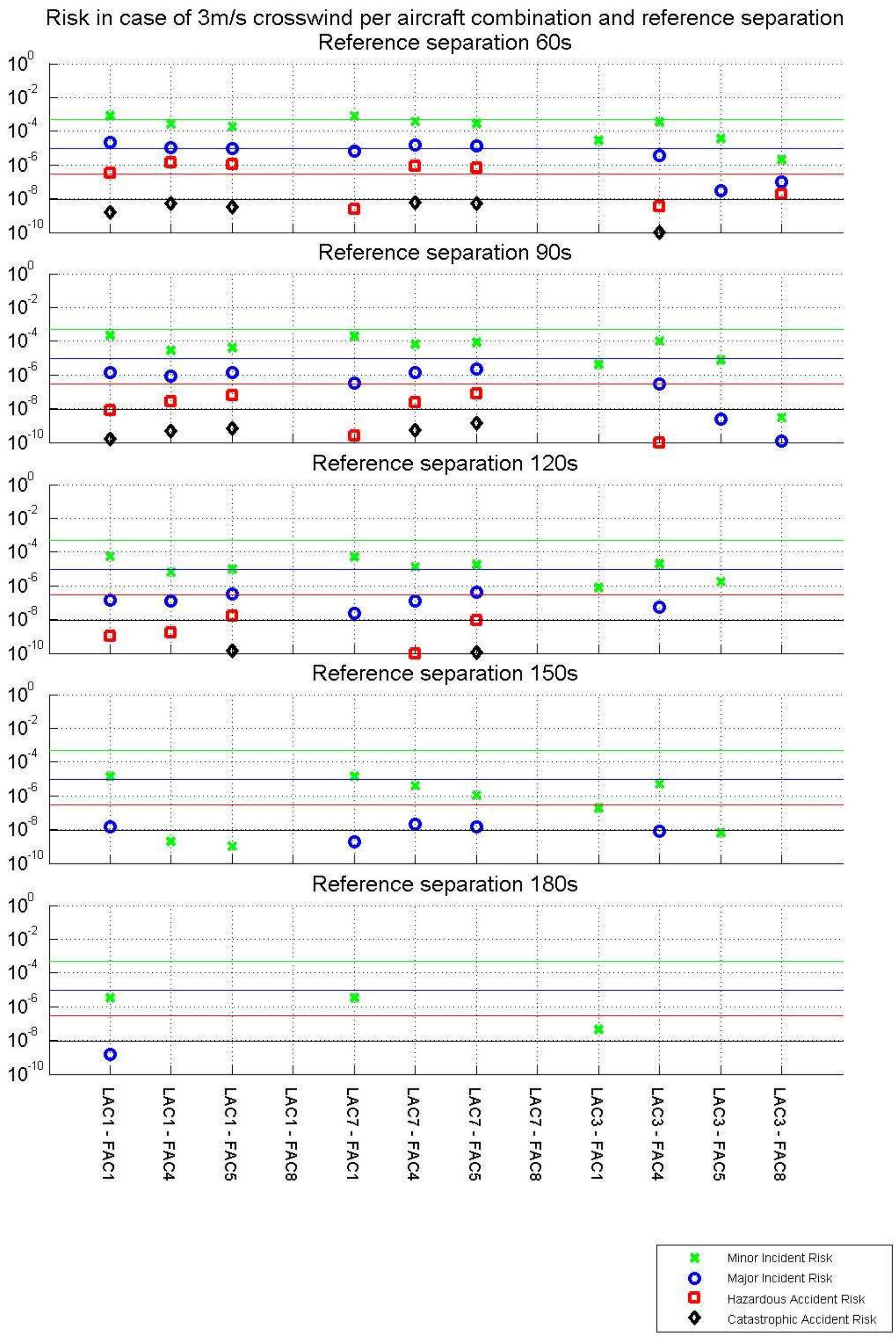

Figure 5-14 Overview of risk results in case of 3 m/s crosswind

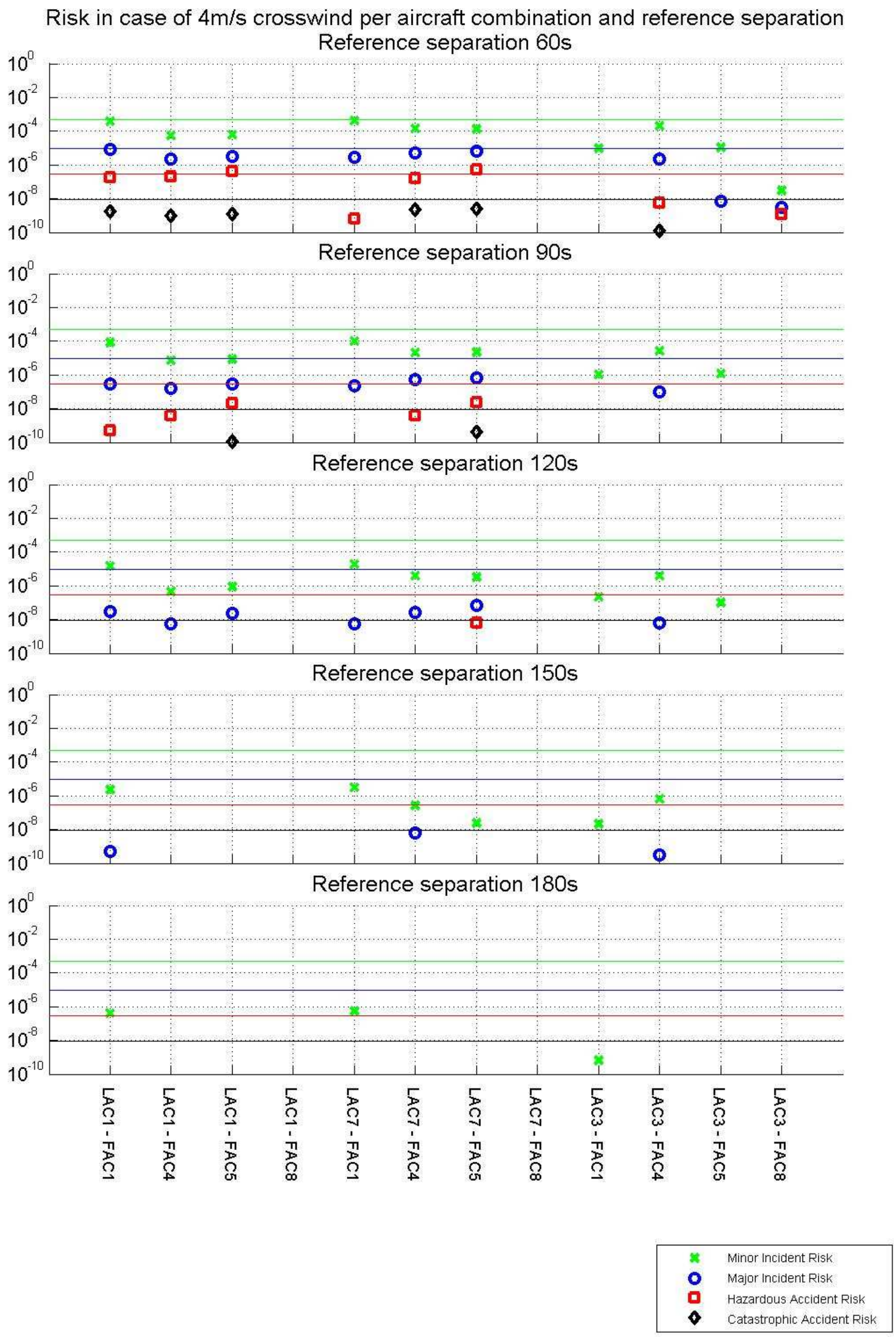

Figure 5-15 Overview of risk results in case of 4 m/s crosswind

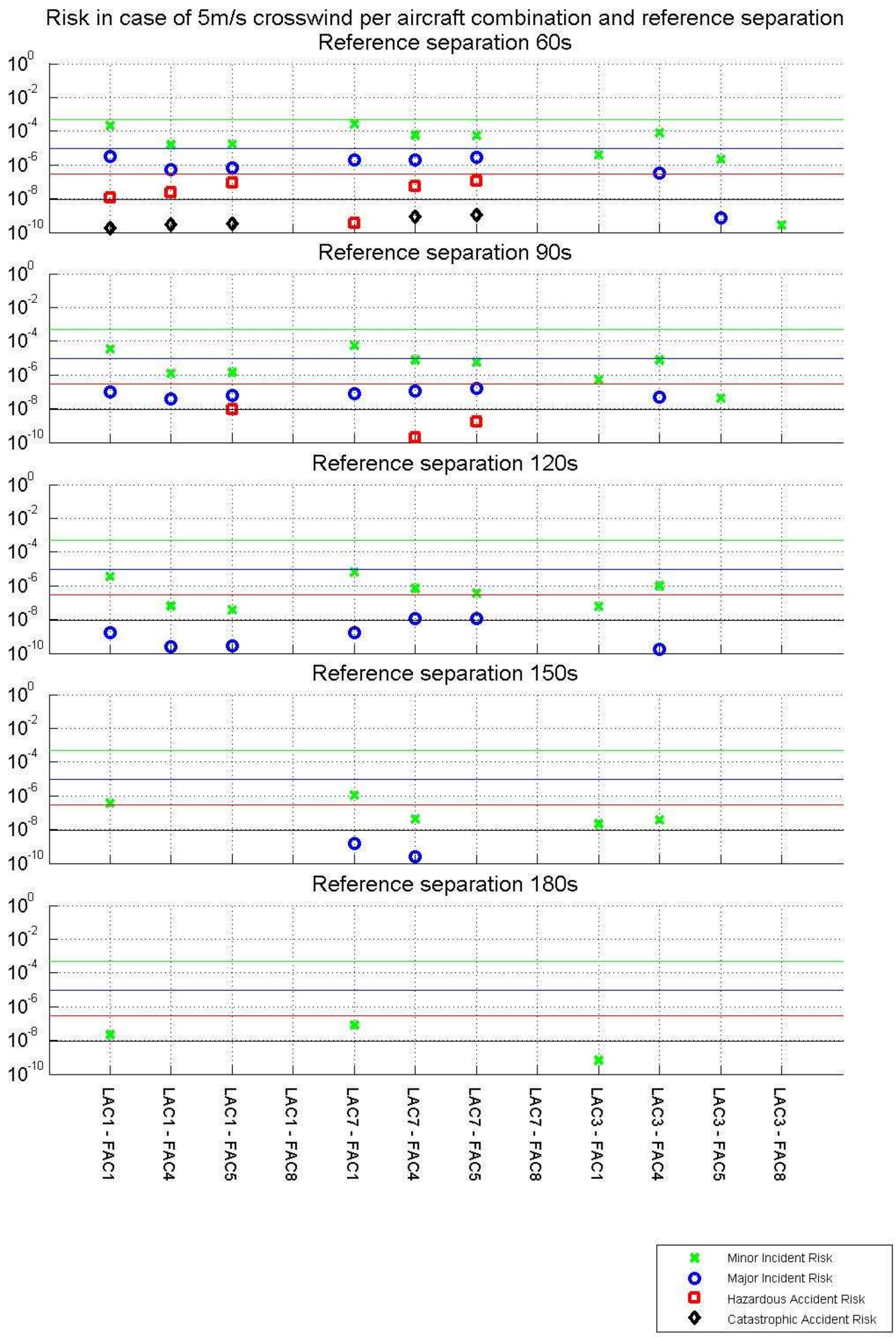

Figure 5-16 Overview of risk results in case of 5 m/s crosswind

5.6.2 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 5-17 on the basis of the risk assessment results sketched in Section 5.6.1.

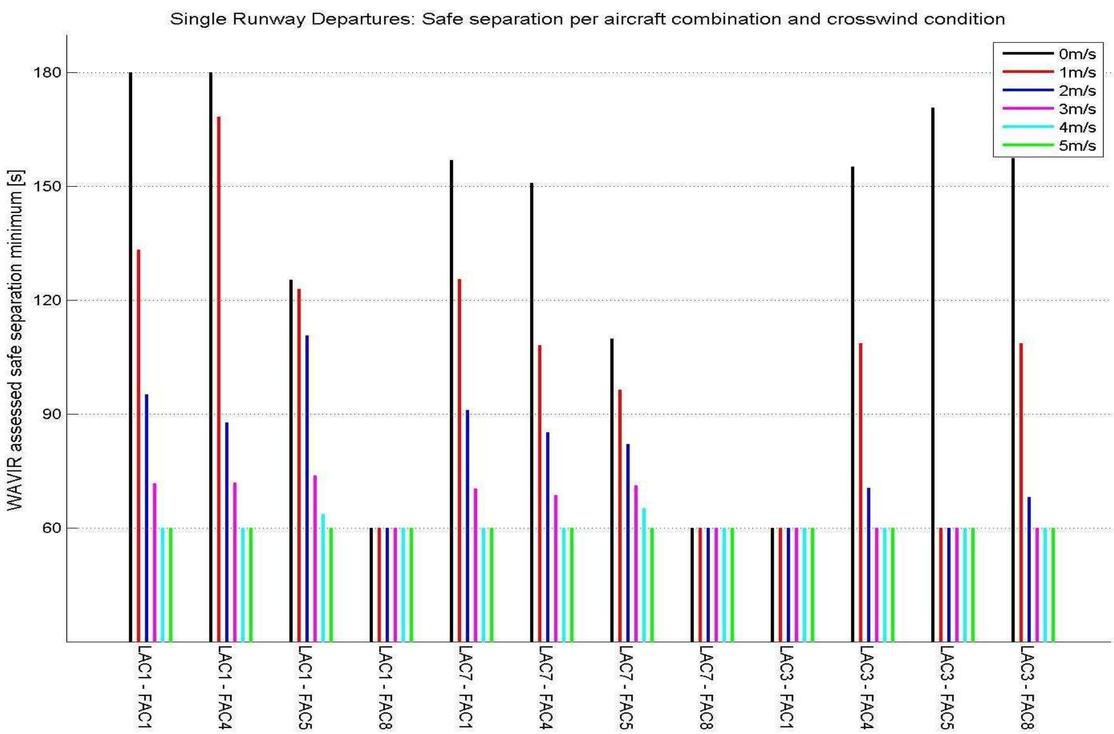

Figure 5-17 Overview of WAVIR assessed safe separation minima for the SRD operation

Taking into consideration that ATC-Wake Mode should be applied to all aircraft combinations, Table 5-10 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 components meet performance requirements that follow from Table 5-9. 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 5-10 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

5.7 Capacity improvements

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. Table 5-11 shows departure throughput in case of ICAO separation and in case of ATC-Wake separation.

Table 5-11 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 [10]	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.

5.8 Conclusions & 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 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.

[10] A crosswind climatology based on about 400,000 observations at about 10 m altitude at 3 large European airports is used [109]

Therefore, this study has quantified the possible safety improvements 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 [83]. 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 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 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 components was further investigated. This was done through a qualitative analysis of the effect of failures of ATC-Wake system components. 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. 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 [86, 87].

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 envisaged around 2010 at the earliest. 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
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6 Safety assessment of the I-Wake single runway arrival operation with reduced separation

6.1 Introduction

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. 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 in time. The EC project *I-Wake* has designed an on-board wake vortex detection, warning and avoidance system for the flight crew, which helps to minimize the probability that an aircraft encounters a wake vortex. An I-Wake system could be useful as safety net in case reduced separation is applied, e.g. through use of an ATC-Wake system with reduced wake vortex separation in case of crosswind.

The main objective of this study is to provide the I-Wake system with an assessment of wake induced risk levels for the approach phase when reduced aircraft separation (2.0 or 2.5 NM between all aircraft) is applied. Such analysis will be performed for different aircraft types and various wind conditions for reduced separation. A specific objective is to support the setting of requirements for the use of I-Wake. Aspects to be considered are e.g. the time for caution and alert and the I-Wake system capabilities (such as the horizontal and vertical scanning view, the angle of regard, the wake vortex detection range) and the initiation of a missed approach.

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

- If one or more I-WAKE system components provide a wrong or erroneous advice, there will be a higher risk on the presence of (severe) wake vortices. The consequences might be CATASTROPHIC, in case reduced aircraft separation (e.g. 2.0. or 2.5 NM) is applied.
- The pilot has to initiate a wake vortex avoidance manoeuvre, in case an I-Wake warning/alert is raised. Usually, the pilot will initiate a missed approach and/or turn away from the wake vortices detected by the I-Wake system on-board the aircraft.
- The separation distance between leader and follower varies along the approach, and after missed approach initiation the vertical distance between leader and follower increases. However, a missed approach will not be feasible at very low altitudes (below 200 ft).

Section 6.2 describes the I-Wake single runway arrival operation, for which an assessment of wake vortex induced risk levels will be provided. Section 6.3 describes the risk assessment methodology, which is based on integration of the ‘classical’ WAVIR methodology with a missed approach model and a causal model for the I-Wake system failure probability. The simulation scenarios are specified in Section 6.4. Risk assessment results are presented and discussed in Section 6.5. Finally, Section 6.6 provides the conclusions and recommendations.

6.2 I-Wake system and main functionalities

The primary purpose of the I-Wake system is to minimise the probability that an aircraft encounters a wake vortex. The system has a tactical and a strategic function. The tactical Wake Vortex Detection, Warning and Avoidance (WV DWA) function is to provide a caution and/or alert to the flight crew for impending encounters (e.g. within 30 seconds) with hazardous wakes. This is achieved by recognising atmospheric disturbance patterns for wake vortices using onboard sensors. The crew is alerted by both visual and aural cues when a wake hazard is detected. The strategic WV DWA function is to increase the flight crew's situational awareness of local wake hazards. Hazards are predicted and their severity estimated with a mathematical model on-board aircraft. This model uses current weather data, actual aircraft positions and aircraft characteristics such as weight and wingspan of surrounding aircraft. Information about possible wake hazards is displayed on the navigation display in the cockpit (see Figure 6-1).

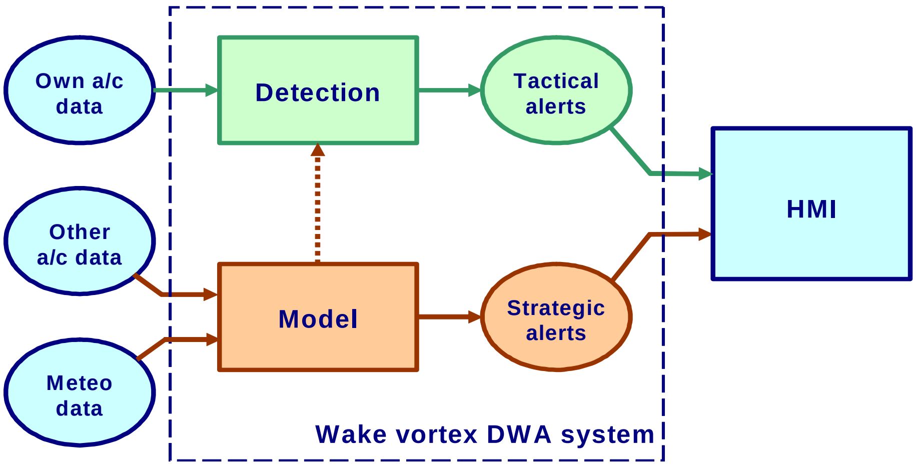

Figure 6-1 Schematic representation of the main functions of the WV DWA system

A schematic representation of the *tactical WV DWA function* is shown in Figure 6-2.

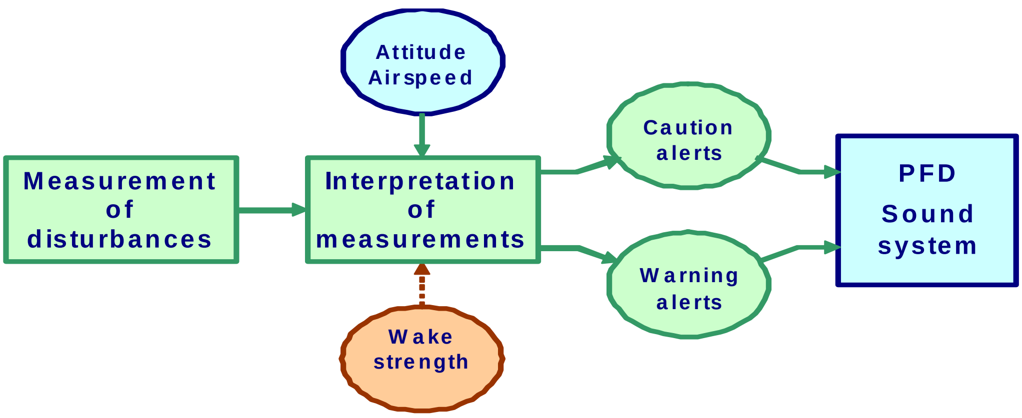

Figure 6-2 Schematic representation of the tactical wake vortex DWA function

The fundamental part of the wake vortex detection within the tactical function is a sensor that physically and independently measures disturbances in the atmosphere. The sensor for wake vortex detection will be a pulsed Light Detection and Ranging (LiDAR) system, fixed to the lower part of the fuselage at the front of the aircraft. The initial I-Wake system design proposes a LiDAR detection range for wake vortex induced atmospheric disturbances between 800 and 2400 meters. The LiDAR will scan a volume of air in front of the aircraft with an adjustable angle of regard. The field of view of the scanning is proposed to be about 6° wide and about 1.5° high. The signals received from the sensor are processed to determine if there is a possible wake vortex within the scanning volume. This process uses attitude and airspeed information from the own aircraft. The strength of a wake vortex will be estimated. Fifteen seconds or less prior to encountering a severe wake (i.e. a wake that exceeds the predetermined warning severity threshold) the flight crew will receive a visual and an aural WARNING alert. The visual warning will be displayed on the Primary Flight Display (PFD). The initial I-Wake system design proposes that a CAUTION alert will be provided between 15 and 30 seconds before encountering a wake vortex that has an estimated strength that is in excess of a predetermined caution threshold. CAUTION alerts are also given both visually (on the PFD) and aurally by a synthetic voice. Alerts can be cancelled or inhibited on the master warning panel. A schematic representation of the *strategic WV DWA function* is shown in Figure 6-3.

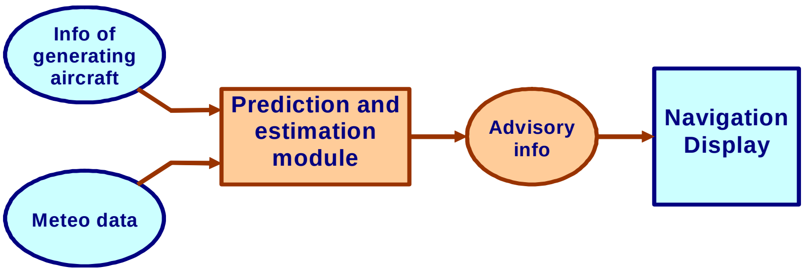

Figure 6-3 Schematic representation of the strategic wake vortex DWA function

The strategic wake vortex DWA function is based on a wake vortex model, which is contained in the prediction and estimation module. The wake vortex model requires information about the wake generating aircraft, such as position, trajectory, airspeed, weight and wingspan. It also requires meteorological data to determine transport and decay characteristics of the wake vortex. Both aircraft data and meteorological data need to be data-linked to the aircraft. In principle all wake hazards that are relevant to the aircraft are made available on the Navigation Display (ND) in the cockpit. Information that can be retrieved is the calculated location of the wake, and the estimated wake severity. The time-to-threat of the wake vortex is displayed on the PFD. The system shall indicate its operational state. In particular, the Wake Vortex DWA system will show if it is switched on or switched off. It will also indicate known system failures, at least those of the detection unit.

6.3 Risk assessment methodology

6.3.1 General approach

This Section provides the risk assessment methodology for assessment of wake induced risk levels for the I-wake single runway arrival operation with reduced aircraft separation (2.0 or 2.5 NM between all aircraft) is applied. Such analysis will be performed for different aircraft types and various wind conditions for reduced separation. A further objective is to support the setting of requirements for the I-Wake system Aspects to be considered are e.g. the time for caution and alert, the horizontal and vertical scanning view, the angle of regard, the wake vortex detection range and the minimum wake vortex severity threshold for initiation of a missed approach.

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

- If one or more I-Wake system components provide a wrong or erroneous advice, there will be a higher risk on the presence of (severe) wake vortices. The consequences might be CATASTROPHIC, in case reduced aircraft separation (e.g. 2.0. or 2.5 NM) is applied.
- The pilot has to initiate a wake vortex avoidance manoeuvre, in case an I-Wake warning/ alert is raised. Usually, the pilot will initiate a missed approach and/or turn away from the wake vortices detected by the I-Wake system on-board the aircraft.
- The separation distance between leader and follower varies along the approach, and after missed approach initiation the vertical distance between leader and follower increases. However, a missed approach will not be feasible at very low altitudes (below 200 ft).

The risk assessment methodology will integrate the ‘classical’ WAVIR methodology (see also Appendix A) with a missed approach model and a causal model for the I-Wake system failure probability. The 'classical' WAVIR methodology, which originates from S-Wake [9, 10], is used to assess wake vortex induced risk in the case of a failure of one or more of the I-Wake system components. In this case, no wake vortex avoidance manoeuvre is performed by the aircraft/pilot and a ‘worst case’ assessment of the incident/accident risk is obtained.

6.3.2 Wake vortex detection, warning, and avoidance probability

De Jong et al. [88] provides a Functional Hazard Assessment (FHA) of the I-Wake system used in conjunction with a ground based ATC-Wake system during the approach phase of flight. The FHA revealed a number of possible consequences of (failures) of the I-Wake system:

- Unexpected encounter of a wake vortex;
- Inappropriate ATC-Wake separation mode;
- Attempt to operate at the edge of safety;
- Crew confusion;

- Initiation of an unnecessary evasive action;
- Incorrect crew awareness of wake vortex hazards;
- Crew disregarding the wake vortex DWA system.

Of these possible consequences, the only event classified as MAJOR (with a potentially even more severe consequence in case of a very small aircraft flying at low altitude behind a large aircraft) is the "*unexpected encounter of a wake vortex*". This event will be used as basis for the construction of a causal model to assess the on-board I-Wake failure probability. The core of this causal model is based on a failure of one or more of the I-Wake system components. In addition to the failure probabilities of the I-Wake system components, the performance of the on-board LiDAR system itself is incorporated. The resulting causal model, explaining the dependencies between the main influencing factors, is sketched in Figure 6-4.

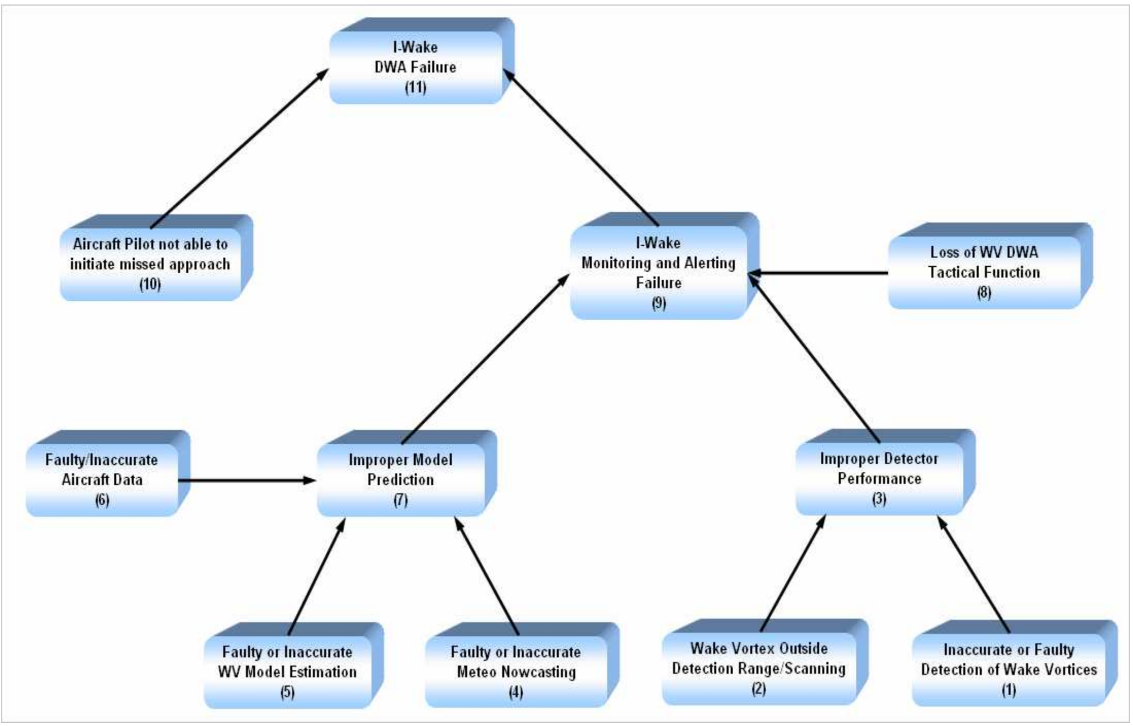

Figure 6-4 Causal model for the I-Wake system/operation

The nodes in this causal model have the following explanation:

- *I-Wake DWA Failure (11):* represents the probability distribution of aircraft/pilot not able to perform the I-Wake detection, warning and avoidance manoeuvre when required.
- *Aircraft/Pilot not able to initiate missed approach (10):* represents the probability of an aircraft/pilot not able to initiate an evasive action (missed approach) when needed.
- *I-Wake Monitoring and Alerting Failure (9):* represents the probability of not providing a timely warning to the flight crew when one should be given. As a result, no evasive action is possible and the pilot reacts later to a wake encounter when one should occur.

- *Loss of WV DWA Tactical Function (8):* represents the probability of loss of the WV DWA tactical function. There are 2 possibilities: 1) detected loss: crew is aware (there is a clear indication of DWA function loss) and the pilot will likely increase separation, and 2) undetected loss: crew is not aware (there is no clear indication of DWA function loss).
- *Improper Model Prediction (7):* represents the probability that the predictions of Wake Vortex locations and strength, as used in the I-Wake system, are inaccurate/wrong.
- *Faulty/Inaccurate Aircraft Data (6):* represents the probability that the aircraft data, as used in the I-Wake system, is inaccurate/wrong. As a result, incorrect information is used, causing improper functioning of the I-Wake system.
- *Inaccurate or Faulty WV Model Estimation (5):* represents the probability that the WV model locations and/or strengths predictions, as used in the I-Wake system, are wrong/ inaccurate. As a result, incorrect information is used, causing improper functioning.
- *Inaccurate or Faulty Meteo Nowcasting (4):* represents the probability that the meteorological nowcasting data, as used in the I-Wake system, is inaccurate or wrong. As a result, incorrect information is used, causing improper functioning of the I-Wake system.
- *Improper Detector Performance (3):* represents the probability that the on-board WV detection system (LiDAR) performs significantly less than the flight crew expects (while they are not aware of the inaccuracies). As a result wrong (or even no) alerts are given.
- *Wake Vortex Outside Detection Range/Scanning Volume (2):* represents the probability that the on-board WV detection system (LiDAR) does not detect the wake vortices of the leading aircraft, because these are outside the scanning volume of air ahead of the aircraft.
- *Inaccurate or Faulty Detection of Wake Vortices (1):* represents the probability that the on-board WV detection system (LiDAR) does not detect wake vortices of the leading aircraft, when these are inside the planned scanning volume of air ahead of the aircraft.

6.3.3 Aircraft flight trajectory model

The aircraft intercept their localizer at the Intermediate Fix (IF). From the IF, the aircraft are expected to fly along runway direction. During intermediate approach the flight trajectory is kept horizontal. From the Final Approach Point (FAP), an aircraft descends with a glide path angle of about 3°. Several reasons may cause an aircraft to initiate a missed approach at any altitude between the FAP and Decision Height (DH). The I-Wake single runway arrival operation assumes that prior to encountering a severe wake, the flight crew will receive an I-Wake warning/alert, after which the pilot may decide to initiate a missed approach. The purpose of such manoeuvre is to increase the vertical distance between (severe) wake vortices generated by the leader aircraft and the follower, thereby minimizing the probability that an aircraft encounters a wake vortex. The missed approach path consists of a curved part and a climb out part. From the Climb Out Point (COP), the aircraft climb under a constant climb out gradient. Important are the determination of the (maximum) altitude loss during the curved part of a missed approach and the time needed from initiation of a missed approach to the COP.

Initiation of the missed approach involves execution of several tasks by the crew, during which the aircraft first loses height and then as a consequence of adjustments of the flight controls attains an ascending trajectory. The height loss (and gained) during a missed approach is determined with a model based on the dynamic relation between the flight path angle γ and the pitch angle θ. This dynamic relation can be expressed as the following transfer function [110]:

$$\frac{\gamma(s)}{\theta(s)} = \frac{g/_{v}\, n_\alpha}{s + g/_{v}\, n_\alpha} \tag{6-1}$$

where g is the gravitational acceleration and ν is the True Air Speed (TAS) of the aircraft. The normal acceleration sensitivity, n_α , is defined as the "steady state normal acceleration change per unit change in angle-of-attack at constant air speed" [110]. It can be approximated by:

$$n_\alpha = \frac{C_{L_\alpha}}{C_L} \tag{6-2}$$

where $C_{L\alpha}$ is the lift curve slope and C_L is the lift coefficient. During rectalinear flight, the latter is equal to:

$$C_L = \frac{mg}{\frac{1}{2}\rho v^2 S} \tag{6-3}$$

where ρ is the air density, m is the mass, and S is the wing area of the aircraft.

The pitch angle θ depends on the elevator deflection δ_e , according to the following transfer function (constant speed, short period approximation) [111]:

$$\frac{\theta(s)}{\delta_e(s)} = K_Q \frac{\omega^2}{s^2 + 2\,\zeta\,\omega s + \omega^2} \quad \text{, with} \quad \omega = \sqrt{\frac{M_S C_{L_\alpha} g}{C_L I_R^2 \bar{c}}} \tag{6-4}$$

where ω and ζ are the short period frequency and the damping coefficient in the dynamic missed approach model respectively. Other new parameters are the pilot (pitch) gain (K_Q), static margin (M_S), dimensionless inertial radius (I_R), and the mean aerodynamic chord ($\bar{c}$).

The time needed to adapt the initial pitch angle (θ_{MAP}) to final pitch angle (θ_{COP}) is estimated by

$$T_{MA\ curve} = \frac{\theta_{COP} - \theta_{MAP}}{q} \tag{6-5}$$

where the commanded pitch rate (q) is assumed constant during the full curved part of the missed approach. This formula can also be used to estimate the distance flown until the COP.

6.3.4 Risk assessment model and toolset

Define t_{alert} and $t_{caution}$ as the time of alert and the time of caution for a potential wake vortex hazard respectively. The associated positions along the flight track are denoted by x_{alert} and $x_{caution}$. The LiDAR detection distance is specified by $[x_{\min}^{DET}, x_{\max}^{DET}]$, where $x_{\min}^{DET}$ denotes the minimum detection distance and $x_{\max}^{DET}$ denotes the maximum detection distance. Define the I-Wake system detection capabilities further via the following three parameters:

y_{FOV} LiDAR horizontal field of view;
z_{FOV} LiDAR vertical field of view;
Z_{AOR} LiDAR angle of regard.

In the detection phase, where $[x_t^i \in x_{\min}^{DET}, x_{\max}^{DET}]$ and an alert may be provided on the basis of wake detection information, the *'scan window'* is determined via the position of the aircraft and the I-Wake system detection capabilities. In the prediction phase, where a caution may need to be provided, there is some uncertainty because no actual wake vortex detection information is available. It is assumed that this uncertainty is dealt with by defining a *'caution bounding box'* as a percentage (larger than 100%) of the size of the scan window at $t = t_{alert}$.

Due to potential failure conditions of the I-Wake system components, it can not be assumed that the I-Wake system will always be functioning. Define the failure probabilities for the I-Wake subsystem components as constants, which are specified by setting requirements for the maximum allowable failure probabilities to be verified during the I-Wake system life cycle.

P_{FAD} Failure probability for I-Wake inaccurate (or faulty) aircraft data
P_{FWV} Failure probability for I-Wake inaccurate (or faulty) wake vortex model estimation
P_{FNC} Failure probability for I-Wake inaccurate (or faulty) meteorological now-casting data
P_{FD} Failure probability for I-Wake inaccurate (or faulty) detection of wake vortices
P_{LTF} Failure probability for loss of the overall wake vortex DWA tactical function

Assume now that the caution procedure is operational in case:

- The Correct Aircraft Data is used (i.e. $P_{FAD} = 0$);
- The Wake Vortex Model Estimation is correct (i.e. $P_{FWV} = 0$);
- The Meteorological Now-casting system is working correctly (i.e. $P_{FNC} = 0$).

Assume furthermore that the alerting procedure is operational in case:

- The on-board LiDAR detection system is working correctly (i.e. $P_{FD} = 0$);
- There is no loss of the overall wake vortex DWA function (i.e. $P_{LTF} = 0$);
- The wake vortex is inside the scanning volume of the on-board LiDAR system.

It is assumed that the pilot reaction time, in case of an alert, depends on the fact whether or not a caution has been given. In case of a previous caution, the pilot will react quicker to an alert. After an alert, the pilot may decide to initiate a missed approach, but only in case the actual height of the aircraft is above the Decision Height (DH). The pilot may also decide not to initiate a missed approach depending on e.g. the prediction of the wake vortex strength.

The I-Wake single runway arrival operation to be followed implies the following:

1. If the follower aircraft position is predicted to be within the wake vortex bounding box of (at least one of) the vortices *and* the caution procedure is operational, a caution is given.
2. If the follower aircraft detects a wake vortex (i.e. at least one of the vortices is within the LiDAR scanning volume) *and* the alerting procedure is operational, an alert is given.
3. If an alert is given and the aircraft is above DH, a missed approach may be initiated. The reaction time of the pilot depends on the fact whether or not a caution has been given.
4. If a missed approach is initiated, the aircraft first loses height and then as a consequence of adjustments of the flight controls attains an ascending trajectory. The height loss (and gained) is determined with the missed approach model described in detail in section 6.3.3.

The risk assessment model is integrated within the NLR WAke Vortex Induced Risk assessment (WAVIR) toolset. Figure 6-5 provides a result from the execution of the VORTICES module. The scanning window is used to estimate the probability of an alert and a missed approach.

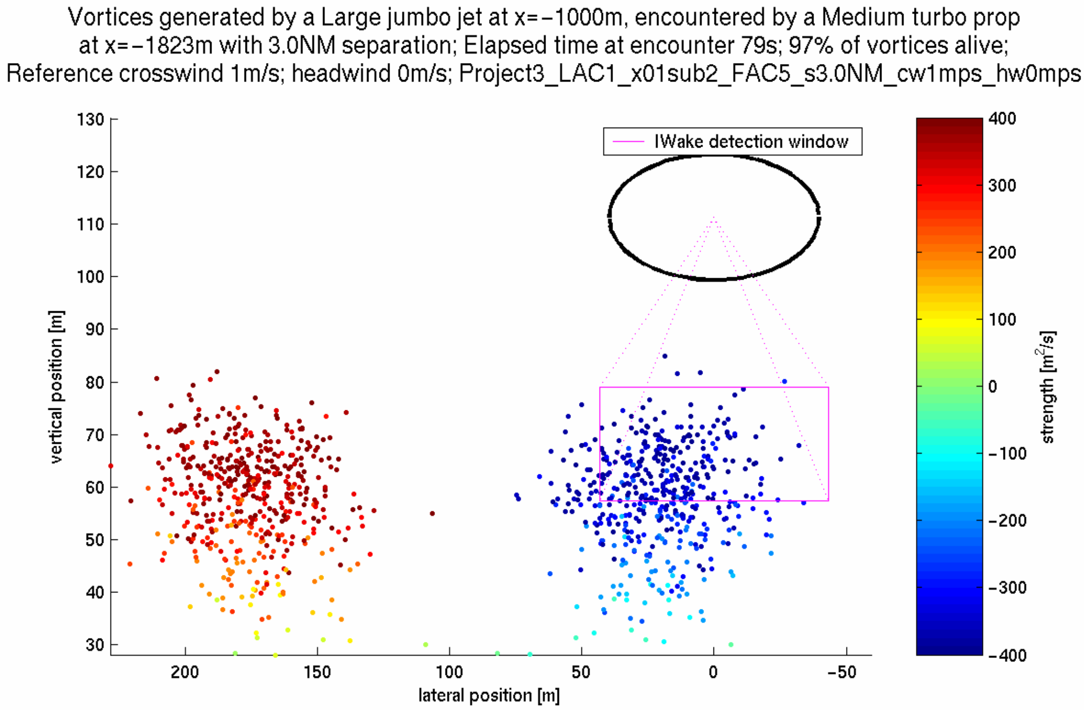

Figure 6-5 Simulated wake vortex positions and strengths, 90 % confidence interval about the aircraft position (circle) and scanning window at the gate where alert should be given

Figure 6-6 shows the WAVIR Graphical User Interface (GUI) dedicated to the specification of the parameters for the assessment of the I-Wake single runway arrival operation. The LiDAR detection system parameter setting (and the continuous update thereof) is shown in the Figure in the top-right of the GUI. Note that other parameter settings (e.g. for the VORTICES, the ENCOUNTER, and the RISK PREDICTION modules) are specified in other GUIs, which are not described in detail this thesis (an up-to-date WAVIR User Manual is available via NLR).

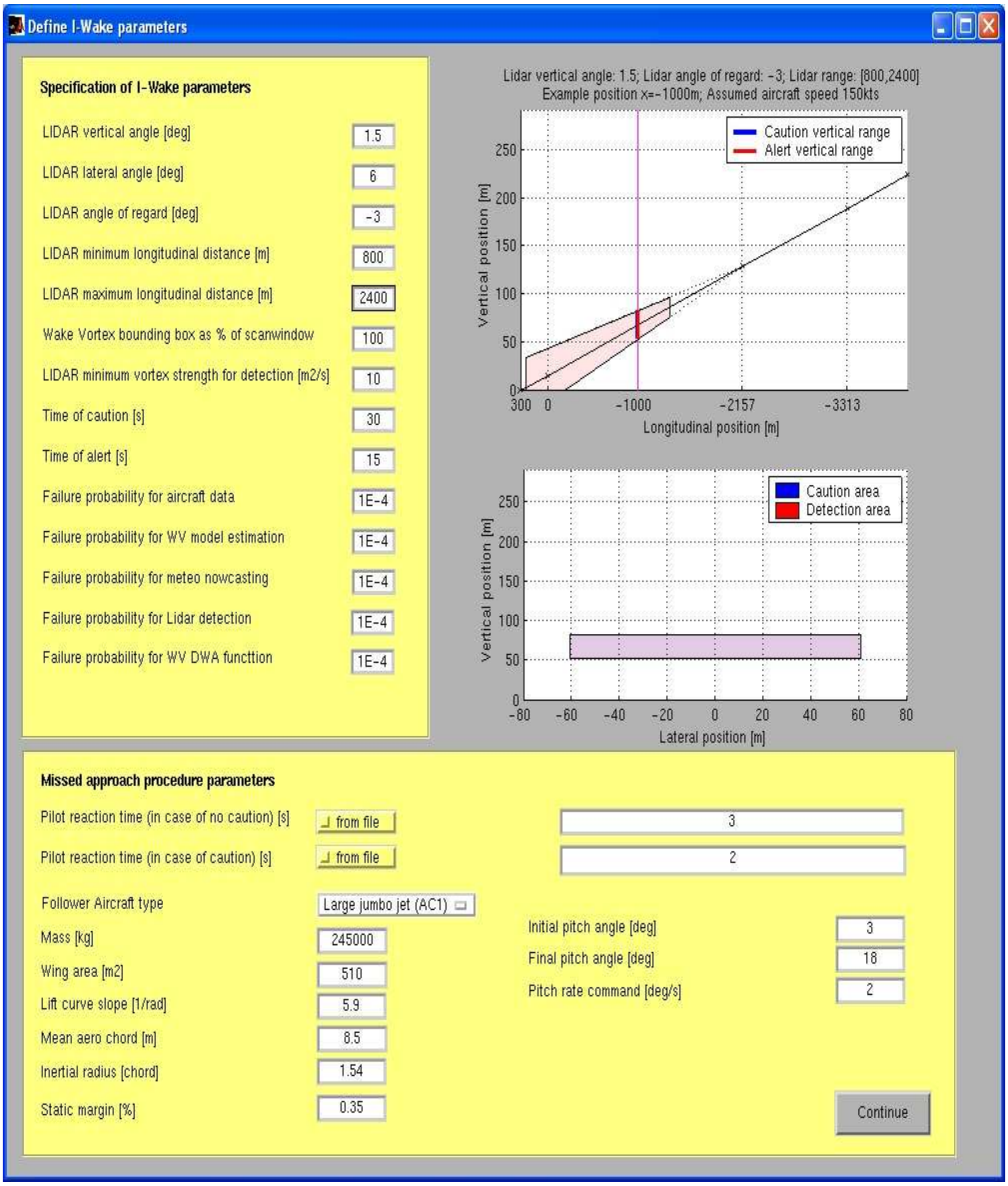

Figure 6-6 WAVIR Graphical User Interface for the specification of I-Wake parameters

6.4 Description of scenarios

6.4.1 General description

I-Wake aims at final approach operations with separation distances below current ICAO wake turbulence radar separation minima in favourable weather conditions. It is an aim of the current study to determine conditions under which reduced wake vortex separation of 2.5 NM (or even 2.0 NM) is feasible in terms of acceptable wake vortex risk and acceptable missed approach rate. These conditions imply the setting of requirements for the I-Wake system and operation. This will be done on the basis of final approach scenarios for the combination of a large jumbo jet followed by a medium jet, regional jet, and a medium turbo prop. The identification of conditions under which 2.5 NM (or even 2.0 NM) minimum separation may be feasible is based on a sensitivity analysis for selected assessment parameters in the model of the I-Wake single runway arrival operation. 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). A missed approach is only initiated after the I-Wake system detects a potentially dangerous wake vortex, and can be initiated at any height above 200 ft.

6.4.2 Set up of the simulation scenarios

The set up and results of the quantitative risk assessment of the I-Wake operation are obtained using the quantitative risk assessment methodology described in Section 6.3. The assessments have been performed for the situation without the use of an I-Wake system, and also for the proposed I-Wake operation. Basically, the focus is on the setting of the requirements for the I-Wake system. Therefore, the scenarios differ in the 'assessment parameters' listed in Table 6.1. In total, 24 scenarios have been assessed. Three different follower aircraft are considered: a Medium Jet (FAC 3), a Regional Jet (FAC 4), and a Medium Turbo Prop (FAC 5). A Large Jumbo Jet (LAC 1) is simulated as wake vortex generator aircraft. Separation distances of 2.0, 2.5, 3.0, and 4.0 NM (between all aircraft) have been considered. The crosswind is varied between values of 0, 1, 2, 3, and 4 m/s (measured at 10 m altitude with no head- or tailwind).

The aircraft are assumed to follow a 3 degrees glide path from ILS glide path intercept to touchdown. The glide path intercepts the runway 300 m beyond the runway threshold (corresponding to a Reference Datum Height (RDH) of 52 ft). From previous quantitative studies for single runway arrivals, it appeared that the risk is highest close to the runway threshold, i.e. close to the ground. It is expected that this will also be the case for the I-Wake operation and it is therefore that the safety assessment will focus on the last 4 NM of the approach. A simulation scenario is further defined by all the parameters and variables in the WAVIR toolset (including the extension with the missed approach model from Section 6.3.2).

Table 6-1 Assessment Parameter Matrix (1)

Scenario	LAC	FAC	Vert. Angle	Lat. Angle	Angle of Regard	Detection distance	Time of Alert	Failure probabilities	Bounding box
1	1	3	1.5	6.0	-1.5	800 - 2400	15	0.001	100
2	1	3	3.0	6.0	0	400 - 2400	10	0.001	100
3	1	3	1.5	3.0	-1.5	200 - 2400	7	0.001	100
4	1	3	1.5	6.0	-1.5	800 - 3200	20	0.001	100
5	1	3	3.0	3.0	-3.0	800 - 2400	15	0.001	100
6	1	3	1.5	6.0	-3.0	800 - 2400	15	0.001	100
7	1	3	3.0	6.0	-1.5	200 - 3200	7	0.001	100
8	1	3	1.5	6.0	-3.0	800 - 2400	20	0.001	100
9	1	3	1.5	6.0	-1.5	800 - 2400	15	0.001	150
10	1	3	1.5	6.0	-1.5	800 - 2400	15	0.001	200
11	1	3	1.5	6.0	-1.5	800 - 2400	15	Nil	100
12	1	3	3.0	12.0	-3.0	800 - 4800	15	Nil	100
13	1	4	1.5	6.0	-1.5	800 - 2400	15	0.001	100
14	1	4	1.5	6.0	-3.0	200 - 2400	7	0.001	100
15	1	4	1.5	6.0	-3.0	800 - 2400	15	0.001	100
16	1	4	3.0	12.0	-3.0	800 - 4800	15	0.001	150
17	1	4	3.0	12.0	-3.0	200 - 2400	7	0.01	150
18	1	4	1.5	6.0	-1.5	800 - 2400	15	0.1	100
19	1	5	1.5	6.0	-1.5	800 - 2400	15	0.001	100
20	1	5	1.5	6.0	-3.0	200 - 2400	7	0.001	100
21	1	5	1.5	6.0	-3.0	800 - 2400	15	0.001	100
22	1	5	3.0	12.0	-3.0	800 - 4800	15	0.001	150
23	1	5	3.0	12.0	-3.0	200 - 2400	7	0.01	150
24	1	5	1.5	6.0	-1.5	800 - 2400	15	0.1	100

As mentioned before, the aircraft are planned 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 (see Figure 6-7):

- 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.

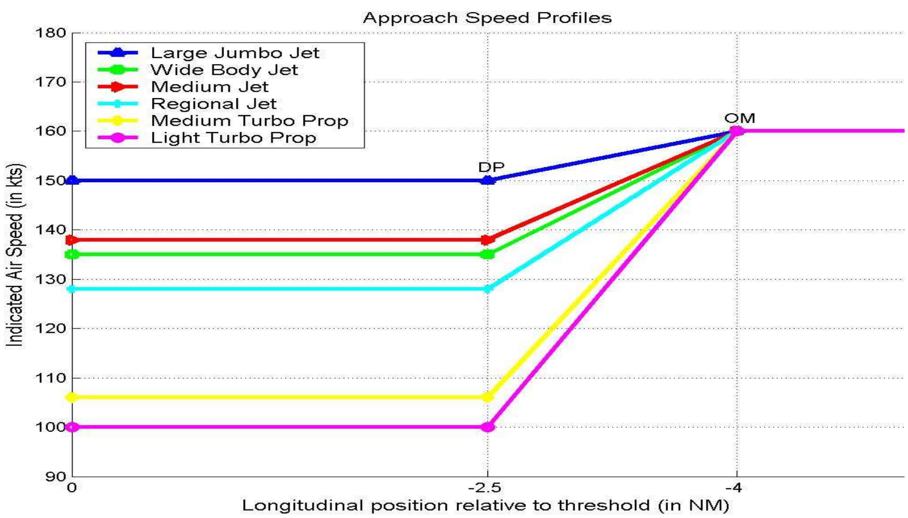

Figure 6-7 Nominal approach speed profiles

Analysis of wake vortex induced risk is done in the longitudinal positions listed in Table 6-2.

Table 6-2 Longitudinal and corresponding vertical nominal positions for arrivals

			Longitudinal positions for the arrival operation									
			x1	x2	x3	x4	x5	x6	x7	x8	x9	x10
x	[m]		0	-300	-900	-2000	-3000	-4000	-5000	-6000	-7408	-10000
	[NM]		0,0	-0,2	-0,5	-1,1	-1,6	-2,2	-2,7	-3,2	-4,0	-5,4
			Vertical positions for the arrival operation									
z	[m]		16	31	63	121	173	225	278	330	404	540
	[ft]		52	103	206	395	567	739	911	1083	1325	1771

Initiation and execution of a missed approach

The I-Wake operation is based on the initiation of a missed approach in case an I-Wake warning/alert is raised. After missed approach initiation the vertical distance between leader and follower increases (note that a missed approach is not feasible at altitudes below 200 ft).

Table 6-3 Aircraft and missed approach parameters

	Light Turbo Prop	Medium Turbo Prop	Regional Jet	Medium Jet	Wide Body Jet	Large Jumbo Jet
Mass	4000	20000	34000	60000	130000	245000
Wingspan	16	30	30	36	45	60
Root chord	3.70	3.40	5.00	6.50	11.40	17.00
Tip chord	0	0	0	0	2.70	0
Wing Area	29.60	51	75	117	317.25	510
Mean Aero Chord	1.85	1.70	2.50	3.25	7.05	8.50
Initial pitch angle	-1	-1	0	2	2	3
Final pitch angle	15	15	15	18	18	18
Pitch rate	2	2	2	2	2	2
Lift curve slope	5.5	6	5.7	5.7	5.0	5.9
Static margin	0.35	0.35	0.35	0.35	0.35	0.35
Inertial pitching moment	24000	330000	1700000	3000000	10530000	42000000
Inertial radius	1.324	2.389	2.828	2.176	1.277	1.540

Pilot reaction time

It is assumed that the pilot initiates a missed approach after receiving a WARNING alert from the I-Wake system. No action will be taken by the pilot after receiving a CAUTION alert. The reaction time of the pilot on a WARNING alert, leading to initiation of a missed approach, is 2 seconds in case a prior CAUTION was given and 3 seconds in case no CAUTION is given.

Fixed and actual separation

The separation is assumed to be fixed at the runway threshold. Separation distances of 2.0, 2.5, 3.0, and 4.0 NM will be evaluated (this separation applies to all aircraft combinations). Due to differences in speed profiles, actual separation along the flight path will vary.

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
- 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 $0.6 \times b_0$ will be used, where b_0 $(= d_y^i)$ is the wingspan of aircraft i. The strength of the secondary vortex is a fraction of the strength of the primary vortex. This fraction is drawn from a uniform distribution between 0.3 and 0.7.

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 UK Meteorological Office (UK MO).

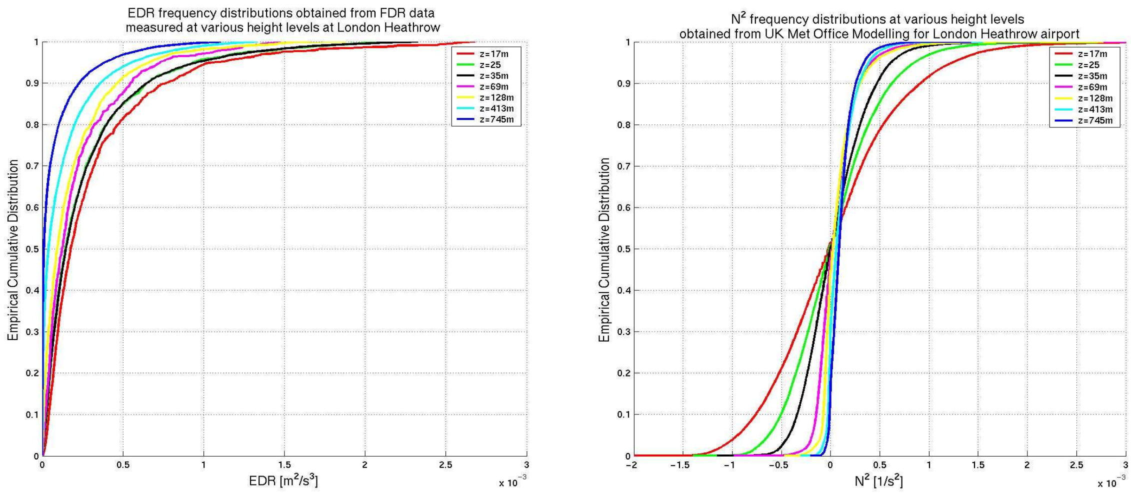

Figure 6-8 Frequency distributions for the London Heathrow climatology

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).

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 0.03 m which is representative for an airport environment. The wind value is specified at 10 m altitude. In this study , it is assumed that there is no head- or tailwind (i.e. only the crosswind velocity is specified).

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.

WV DWA causal model parameters

The following failure probabilities for the nodes in causal model are to be specified:

– Inaccurate or faulty aircraft data
– Inaccurate or faulty wake vortex model estimation
– Inaccurate or faulty meteorological now-casting data
– Inaccurate or faulty detection of wake vortices
– Loss of overall wake vortex DWA tactical function

In this study, it is mostly assumed that all the failure probabilities are equal to 10^{-4}, though values like 10^{-2} or even 10^{-1} are also considered. A more detailed analysis of the impact of these failure probabilities on the overall I-Wake Detection, Warning, and Avoidance probability is provided in Angeles Morales [107].

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).

6.5 Risk assessment

6.5.1 Overview of the risk assessment results

The next sub-sections present the risk assessment results for each of the 24 scenarios defined in Table 6-1. To analyse the impact of the assessment parameters and to assess the lowest possible risk achievable for the I-Wake single runway arrival operation, it is firstly assumed that missed approaches may be initiated at any height after an alert is provided by the I-Wake system.

Risk assessment results for a Medium Jet landing behind a Large Jumbo Jet under crosswind conditions of 0, 1, 2, and 3 m/s (with no head- or tailwind) are provided in Figures 6-9 until 6-12. Separation distances of 2, 2.5, 3, and 4 NM, with different crosswind conditions, are evaluated. Results without the I-Wake system are provided in grey, whereas the colours provide the incident/accident risk estimates in case the I-Wake system is used. Note that the scenario (in accordance with Table 6-1) is indicated on the horizontal axis.

Figures 6-13 and 6-14 provide the incident/accident risk estimates, under different crosswind conditions, for a Medium Jet behind a Large Jumbo Jet with 2 and 2.5 NM separation distance respectively. The incident/accident risk estimates for a Regional Jet (scenarios 13 – 18) and a Medium Turbo Prop (scenarios 19 – 24), both approaching and landing with 2 and 2.5 NM separation behind a Large Jumbo Jet, are provided in Figures 6-15 and 6-16 respectively.

An initial estimate for the minimum required separation distances for a Medium Jet landing behind a Large Jumbo Jet is given in Figure 6-17. An initial estimate for the minimum required separation distances for a Regional Jet (scenarios 13 – 18) and a Medium Turbo Prop (scenarios 19 – 24), both landing behind a Large Jumbo Jet, is given in Figure 6-18. Note that the coloured bars denote the crosswind (at 10 m altitude).

The intermediate results of the above incident/accident risk assessments are discussed in Section 6.5.5. It is important to realize that after timely detection of a dangerous wake vortex, the pilot may initiate a missed approach. However, one should realize that a missed approach is usually not appreciated from a capacity point of view as the aircraft will have to approach the airport once more. Therefore, a requirement might need to be set on the maximum allowable missed approach rate (e.g. 0.01 or 0.001), for example by only initiating a missed approach in case the vortex strength exceeds a certain threshold. Such threshold can be placed on e.g. the vortex strength, the roll control ratio, or the maximum attained bank angle. The relation between these factors is estimated using the Extended Roll Control Ratio (ERCR) model, see Appendix A. The impact of not initiating a missed approach below the Decision Height (usually 200 ft) on the lowest achievable wake vortex induced incident/accident risk is analysed also in section 6.5.5.

6.5.2 Wake vortex induced risk for different crosswind conditions

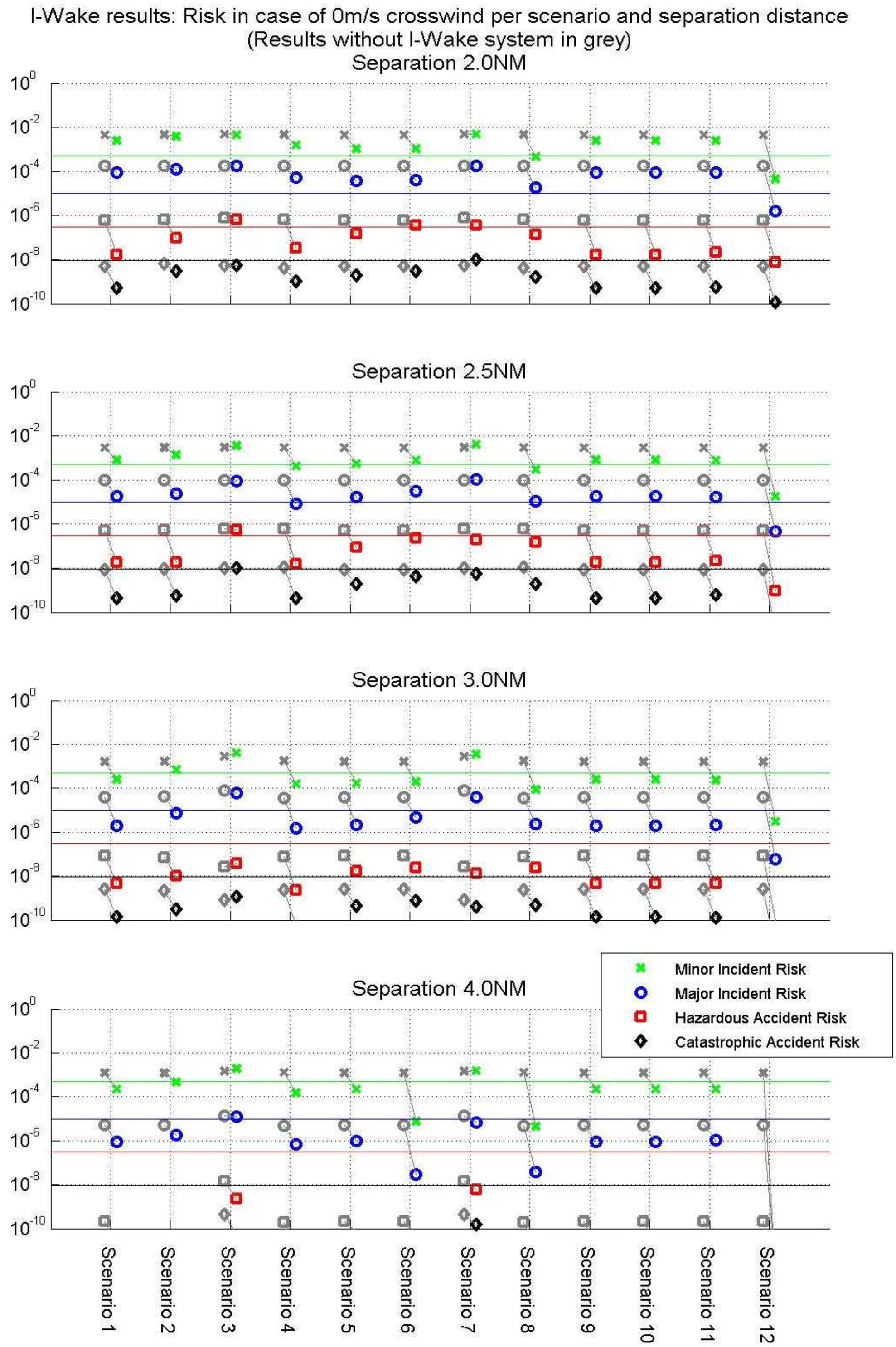

Figure 6-9 Risk in case of 0 m/s crosswind for scenarios 1-12

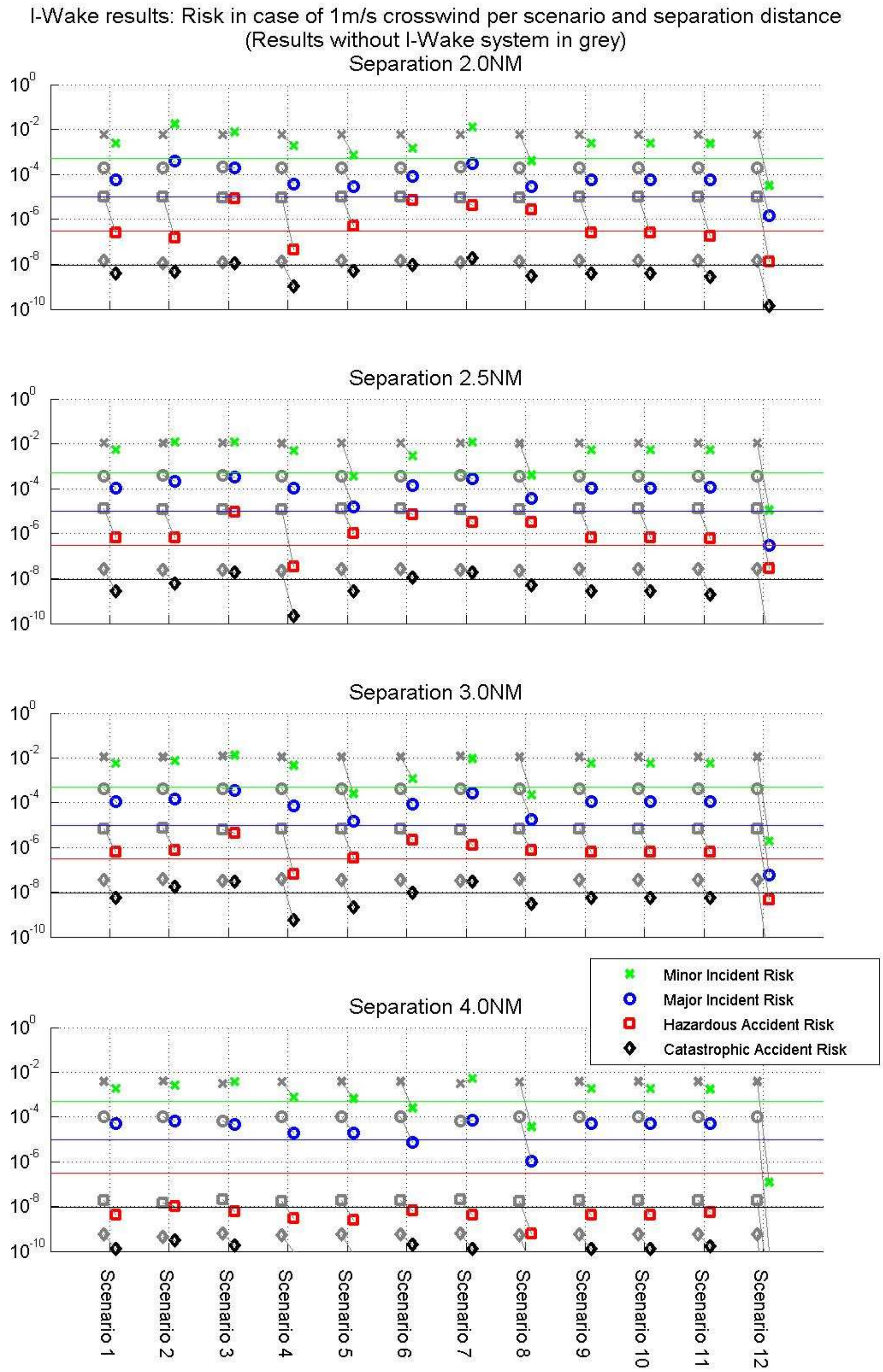

Figure 6-10 Risk in case of 1 m/s crosswind for scenarios 1 - 12

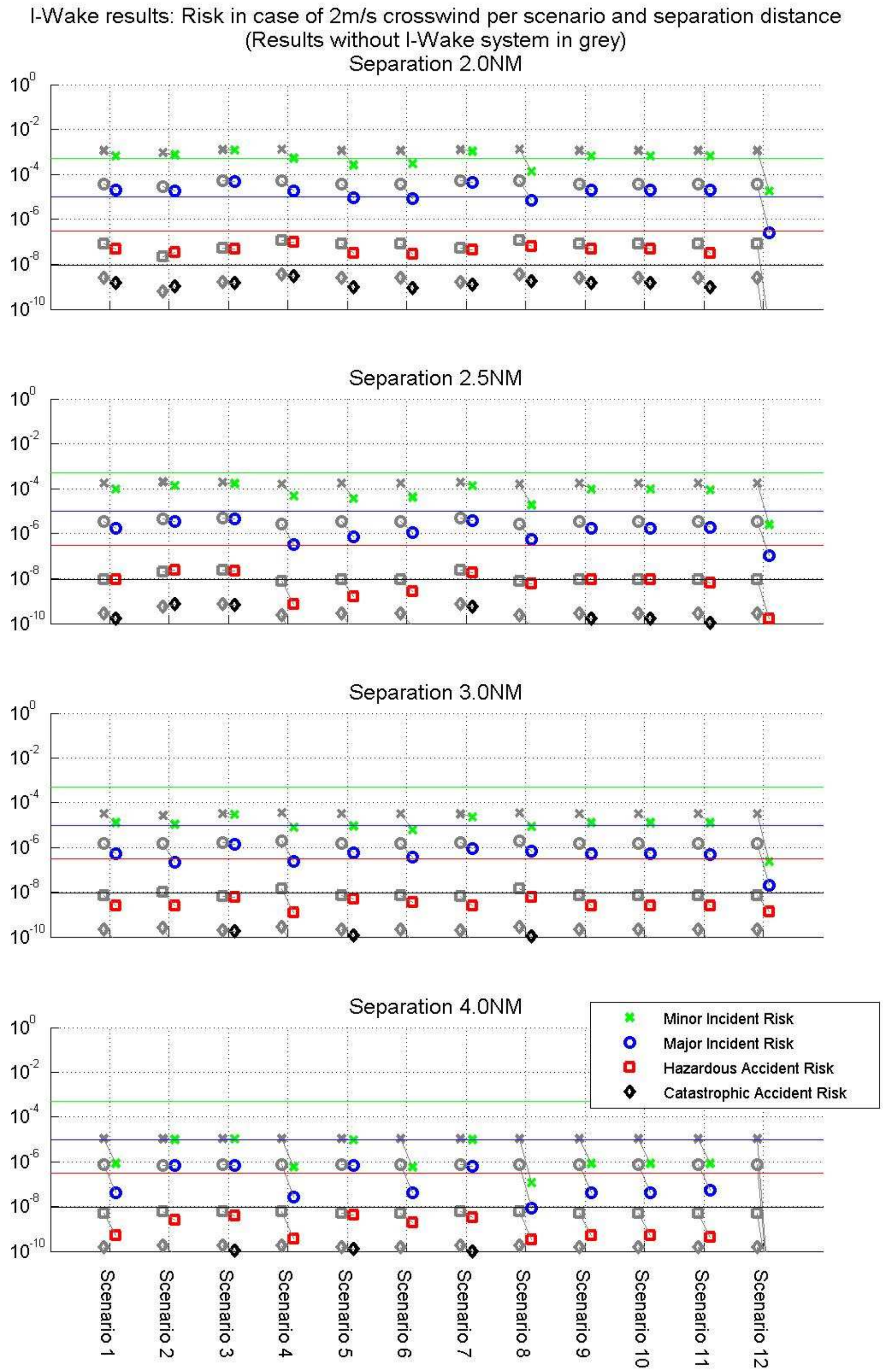

Figure 6-11 Risk in case of 2 m/s crosswind for scenarios 1 - 12

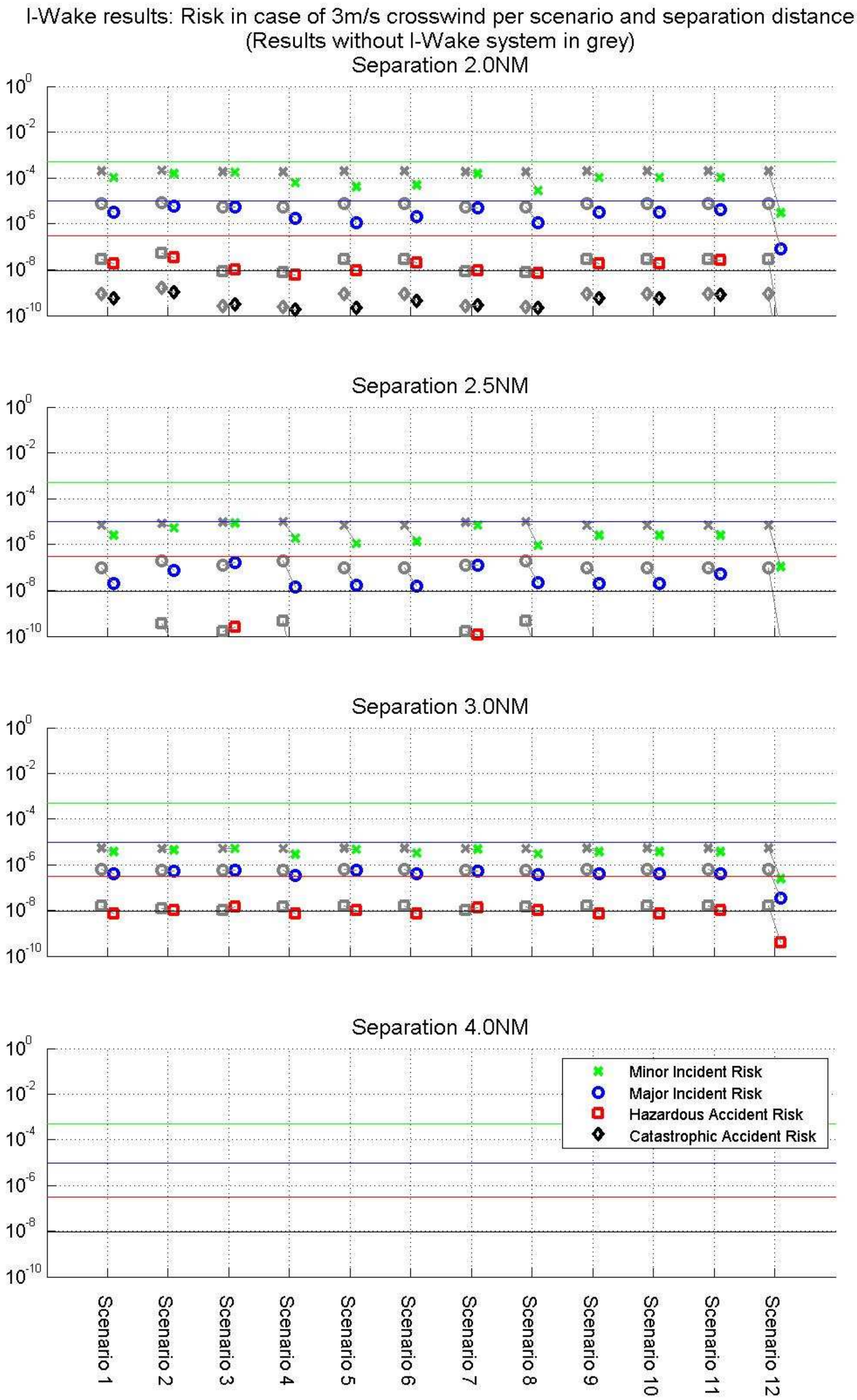

Figure 6-12 Risk in case of 3 m/s crosswind for scenarios 1 - 12

6.5.3 Wake vortex induced risk with reduced aircraft separation

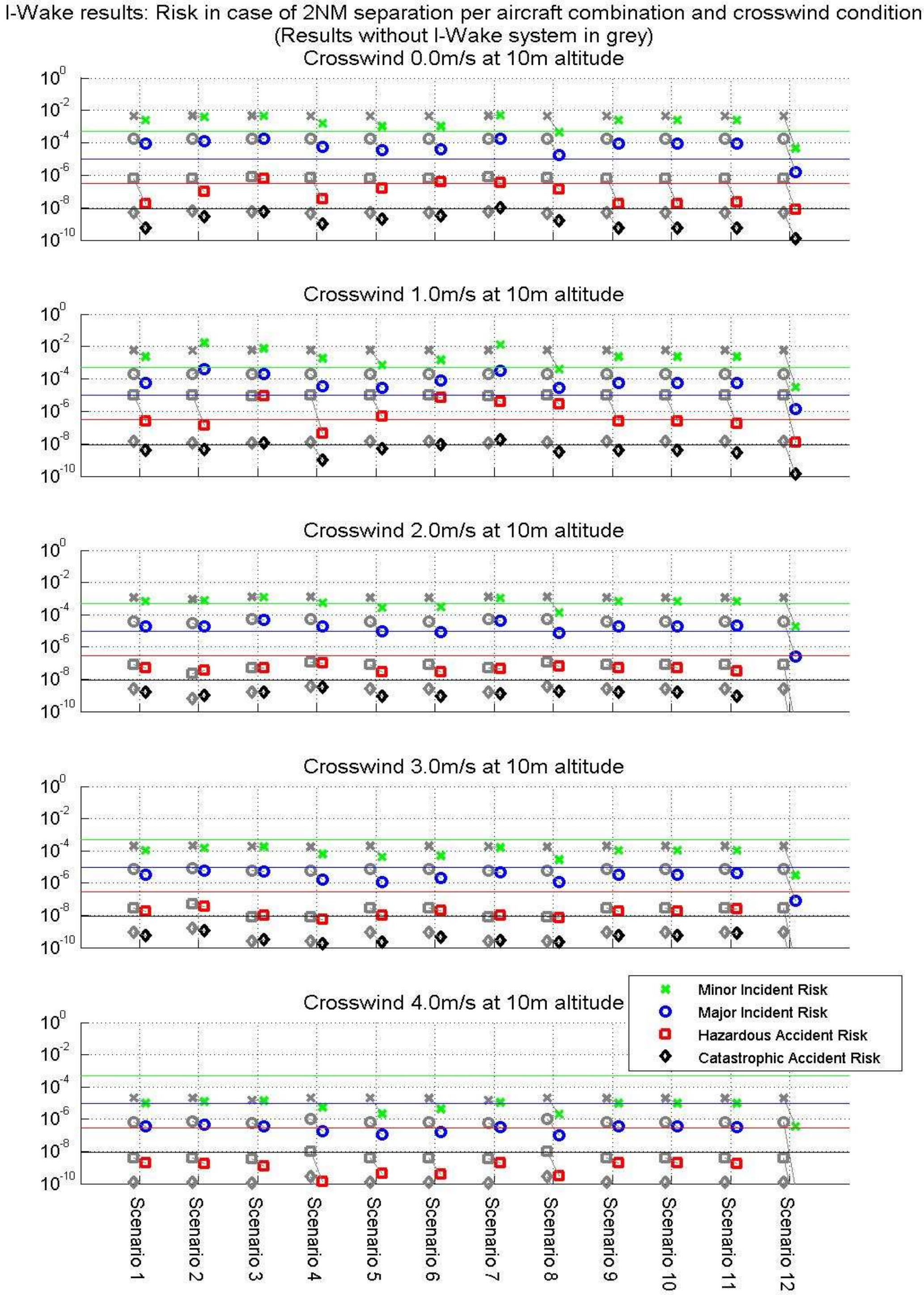

Figure 6-13 Risk in case of 2 NM separation for scenarios 1 - 12

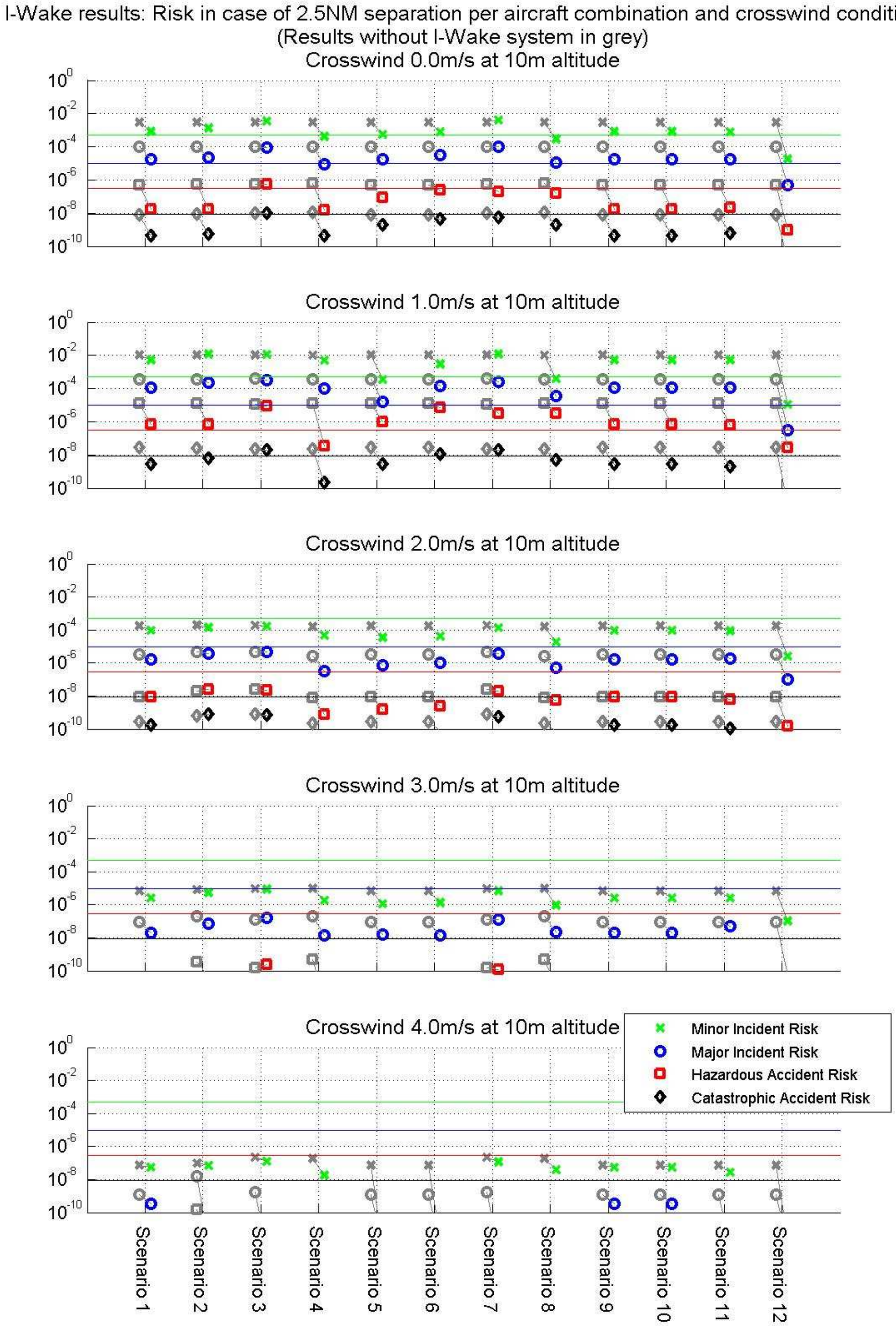

Figure 6-14 Risk in case of 2.5 NM separation for scenarios 1 - 12

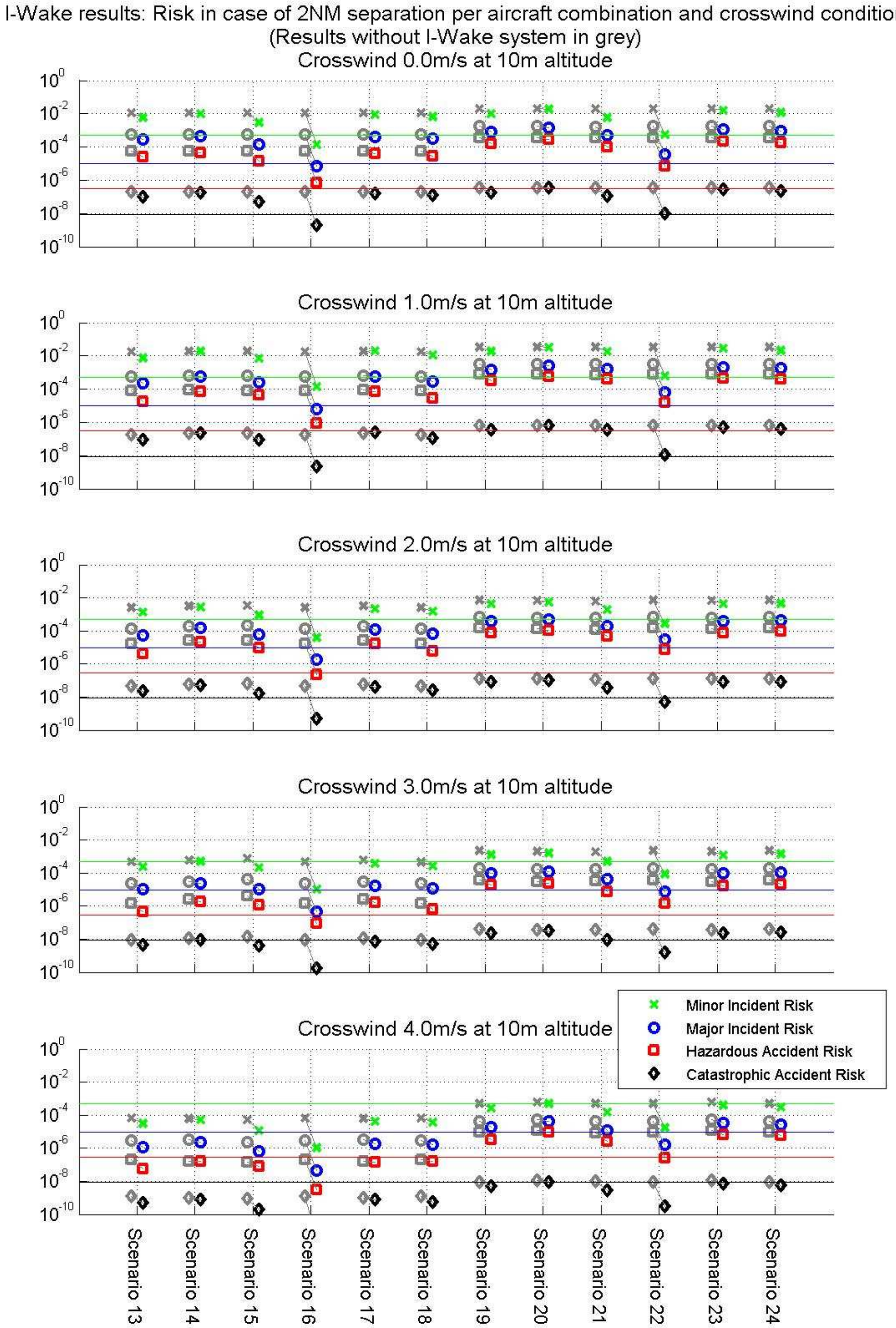

Figure 6-15 Risk in case of 2 NM separation for scenarios 13 - 24

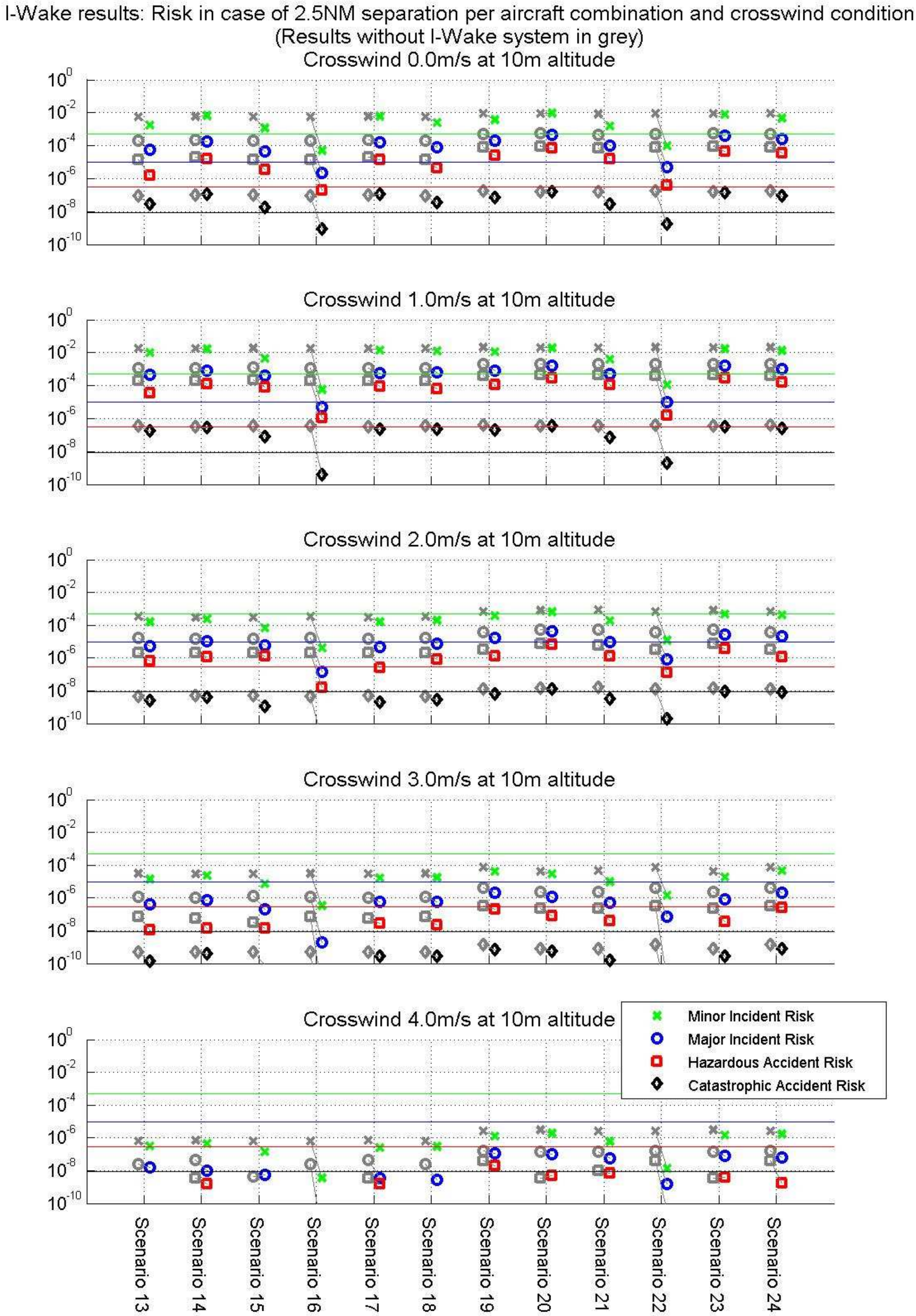

Figure 6-16 Risk in case of 2.5 NM separation for scenarios 13 - 24

6.5.4 Initial estimate of the minimum required aircraft separation distances

An initial estimate for the minimum required separation distances for a Medium Jet landing behind a Large Jumbo Jet is given in Figure 6-17. An initial estimate for the minimum required separation distances for a Regional Jet (scenarios 13 – 18) and a Medium Turbo Prop (scenarios 19 – 24), both landing behind a Large Jumbo Jet, is given in Figure 6-18.Note that the coloured bars denote the crosswind (at 10 m altitude). Results without I-Wake are provided in grey.

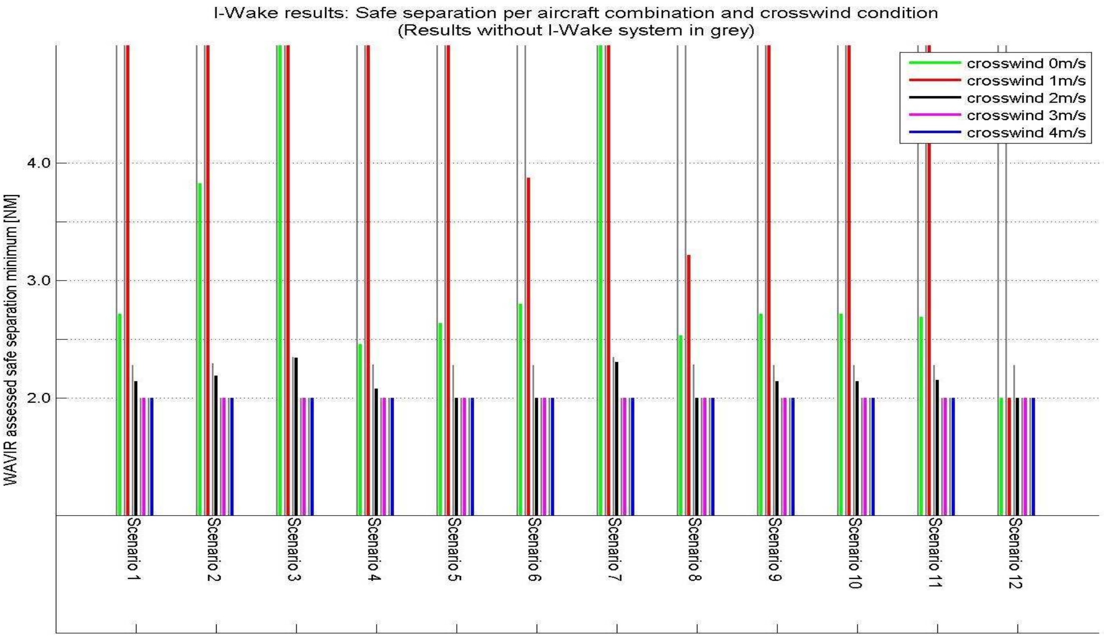

Figure 6-17 Minimum required separation distances with I-Wake (scenarios 1 - 12)

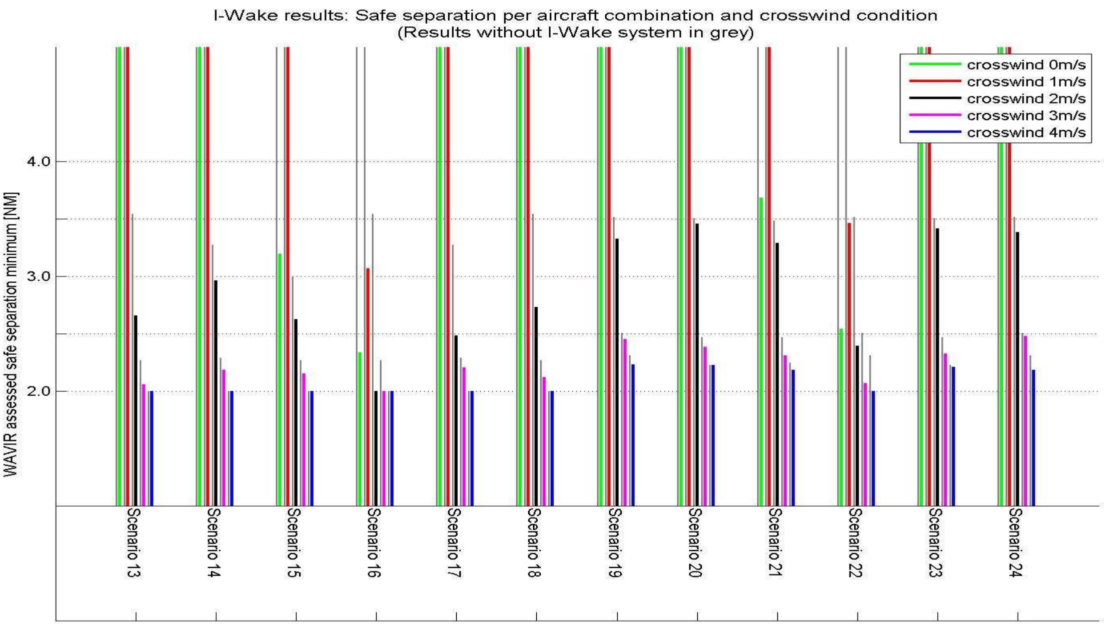

Figure 6-18 Minimum required separation distances with I-Wake (scenarios 13 - 24)

6.5.5 Discussion of the results

The incident/accident risk assessment results provided in the previous sub-sections lead to the following observations:

- There is almost no decrease in risk in scenarios 3 and 7, due to small alerting time of 7 seconds. This implies that about 15 seconds is indeed preferred as I-Wake time of alert.
- There is a large decrease in scenario 12 risk, due to the large lateral angle of the I-Wake detection system. This implies that a wide lateral angular view is very beneficial.
- Reducing the failure probabilities of the I-Wake system components further than 10^{-4} (e.g. compare scenario 11 with scenario 1) has almost no effect. Apparently it suffices to design the I-Wake system components such that a maximum failure probability of 10^{-4} is achieved.
- When comparing scenarios 13 - 18, the largest risk decrease occurs in scenario 16. Again this is most likely due to the large lateral angle. Note that the same angle is used in scenario 17, but here in combination with an alerting time of 7 seconds, which – apparently – is too low for timely wake avoidance. The same holds for scenario 23 as compared to scenario 22.
- The detection probabilities are relatively high near the threshold and lower further away from the threshold. Note that high detection probabilities will certainly imply high missed approach frequencies which are unacceptable from an airport efficiency point of view.
- Scenarios 1 to 12 (Medium Jet landing behind a Large Jumbo Jet) would need to provide the same results, when looking at the results without using the I-Wake system. The variation in the grey symbols therefore represents the uncertainty inherent to WAVIR calculations.

WAVIR assessed safe separation distances when using I-Wake system never exceed the results without using I-Wake. The largest reduction is observed in:

- Scenario 6. This is probably due to the combination of angle of regard (-3 degrees) and lateral angle (6 degrees) resulting in a risk reduction also further away from the threshold.
- Scenario 8. This is probably due to the combination of angle of regard (-3 degrees) and lateral angle (6 degrees) resulting in a risk reduction also further away from the threshold as well as a alerting time of 20 seconds which provides more time to avoid the vortices.
- Scenario 12. This is due to the large lateral detection angle (12 degrees).
- Scenario 16. This is due to the large lateral detection angle (12 degrees).
- Scenario 22. This is due to the large lateral detection angle (12 degrees).

Aspects to be considered for the setting of requirements for the I-Wake single runway arrival operation are, besides the minimum crosswind for reduced separation, e.g. the time for caution and alert, the horizontal and vertical scanning view, angle of regard, wake vortex detection range and the minimum wake vortex severity threshold for initiation of a missed approach. However, before these aspects can be dealt with, a second assessment is made in order to analyse the impact of not initiating a missed approach below the Decision Height (i.e. 200 ft).

Table 6-4 Assessment parameter matrix (2)

Scenario	LAC	FAC	Vert. Angle	Lat. Angle	Angle of Regard	Detection distance	Time of Alert	Failure probabilities	Bounding box	Vortex threshold
25	1	3	1.5	12.0	-3.0	800 - 2400	15	0.001	100	70
26	1	4	1.5	12.0	-3.0	800 - 2400	15	0.001	100	40
27	1	5	1.5	12.0	-3.0	800 - 2400	15	0.001	100	30

The parameters in Table 6-4 have been chosen such that the I-Wake system capabilities provide the lowest risk reduction without setting un-realistic and non-achievable requirements on the I-Wake system development. Figure 6-19 presents an initial estimate for the minimum required separation distances for a Medium Jet, Regional Jet, and a Medium Turbo Prop (all landing behind a Large Jumbo Jet), in case this optimal I-Wake setting is used. Note again that the coloured bars denote the crosswind (at 10 m altitude). Results with I-Wake are provided in grey.

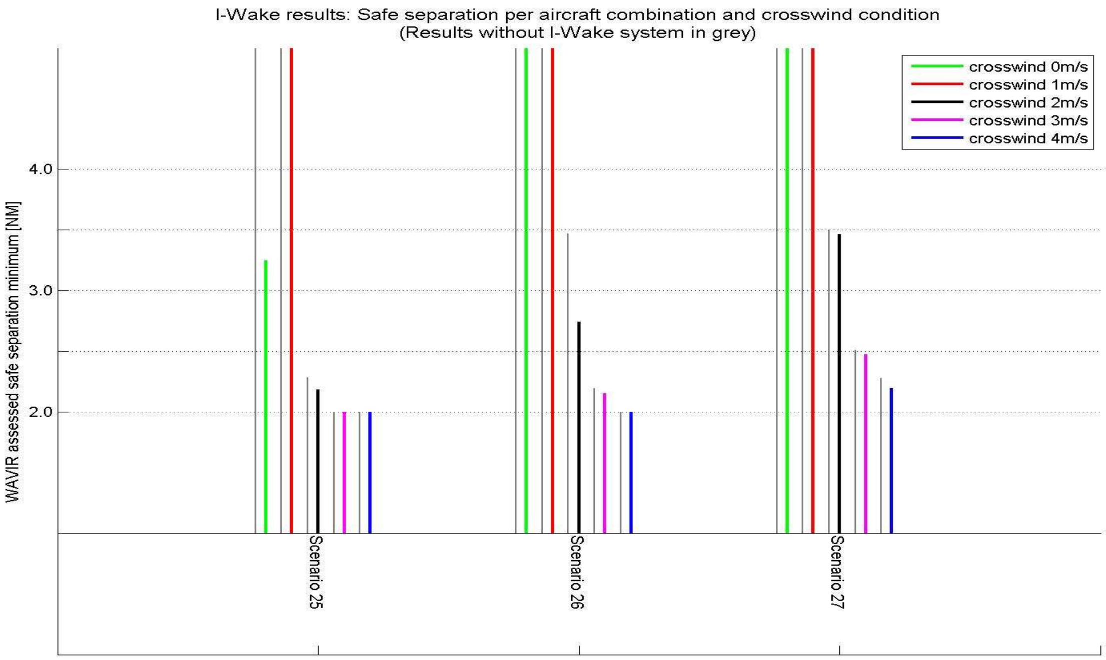

Figure 6-19 Minimum required separation distances with optimal I-Wake system setting

Figure 6-19 shows the major impact of not initiating a missed approach below the Decision height of 200 ft. In fact, the use of I-Wake seems to reduce the wake vortex induced risk only slightly as compared to the current practice. The main reason for this is the fact that the largest risk during single runway arrivals occurs near the runway threshold (see Section 4). Therefore, the use of I-Wake would be most beneficial at very low altitudes, where the probability of encountering a (rebounding) wake vortex is highest. Unfortunately, at altitudes below 200 ft it is also more difficult to initiate a missed approach. Therefore, the operational use of I-Wake seems to have only minor impact on the wake vortex induced risk during single runway arrivals (and, as a consequence, I-Wake use provides low potential for reduction of the separation minima).

6.6 Conclusions and recommendations

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. The EC project *I-Wake* has designed an on-board wake vortex detection, warning and avoidance system for the flight crew, which helps to minimize the probability that an aircraft encounters a wake vortex. An I-Wake system could be very useful as a ‘safety net’ in case reduced wake vortex separation is applied in the airport environment. The I-Wake single runway arrival operation assumes that a missed approach is initiated after the flight crew receives an alert indicating that the aircraft will likely encounter a severe wake vortex. Wake vortex induced risk related to the I-Wake operation with reduced separation has been assessed qualitatively through a Functional Hazard Analysis (FHA) [88]. This study has now also *quantified* the wake vortex induced incident/ accident risk through the use of the WAVIR methodology, extended with an aircraft/pilot missed approach model and a causal model for the I-Wake system failure probability.

The assessment of wake induced risk levels for the approach phase when reduced aircraft separation (2.0 or 2.5 NM between all aircraft) is applied has been performed for different aircraft types and various wind conditions. Aspects considered are e.g. the time for caution and alert and the I-Wake system capabilities (such as the horizontal and vertical scanning view, the angle of regard, the wake vortex detection range). Further main factors considered are:

- If one or more I-WAKE system components provide a wrong or erroneous advice, there will be a higher risk on the presence of (severe) wake vortices. The consequences might be CATASTROPHIC, in case reduced aircraft separation (e.g. 2.0. or 2.5 NM) is applied.
- The pilot has to initiate a wake vortex avoidance manoeuvre, in case an I-Wake warning/alert is raised. Usually, the pilot will initiate a missed approach and/or turn away from the wake vortices detected by the I-Wake system on-board the aircraft.
- The separation distance between leader and follower varies along the approach, and after missed approach initiation the vertical distance between leader and follower increases. However, a missed approach will not be feasible at very low altitudes (below 200 ft).

The use of I-Wake seems to reduce the wake vortex induced risk only slightly as compared to the current practice. The main reason for this is the fact that the largest risk during single runway arrivals occurs near the runway threshold (see Section 4). Therefore, the use of I-Wake would be most beneficial at very low altitudes, where the probability of encountering a (rebounding) wake vortex is highest. Unfortunately, at altitudes below 200 ft it is also more difficult to initiate a missed approach. Therefore, the operational use of I-Wake seems to have only minor impact on the wake vortex induced risk during single runway arrivals (and, as a consequence, I-Wake use provides low potential for reduction of the separation minima).

7 Conclusions

7.1 General overview

With the steady increase in air traffic, the aviation system is under continuous pressure to increase aircraft handling capacity. The introduction of Reduced Vertical Separation Minima (RVSM) above ‘Flight Level 290’ implied that the capacity bottleneck within the air transport system has changed from en-route towards the Terminal Manoeuvring Area (TMA) around busy airports. The diversity of airport operations (departures, approaches, missed approaches) and risk events (e.g. collision risk, wake turbulence risk, third party risk, runway incursion) implies that the safety assessment of newly proposed ATM systems and flight procedures in the airport environment is quite complex. New safety assessment methods are needed to assess safety. In this respect, the two most capacity limiting risk events, addressed in this Doctoral thesis, are *wake vortex encounters* and the *collision risk between aircraft*.

Various new ATM systems and flight procedures have been proposed to increase airport capacity while maintaining the same (required) level of safety. Newly proposed systems to cope with wake turbulence and allow a reduction of wake vortex separation minima include the ground based ATC-Wake system (for air traffic controllers) and the on-board I-Wake system (for pilots). An increase in runway capacity may also be achieved by using parallel runways more effectively or by designing new and advanced flight procedures. For all the new air traffic operations evaluated in this Doctoral thesis, ICAO standards and best practices do not exist and new safety assessment methodologies, incorporating the roles of the Air Traffic Controllers and pilots, are developed and applied. Introducing and/or planning changes to the air transport system cannot be done without showing that minimum safety requirements will be satisfied. This thesis therefore not only deals with the safety assessment process itself, but also with the setting of risk requirements for the newly proposed ATM systems and flight procedures.

The approach taken was to apply risk based decision making to support the introduction of new air traffic operations and systems for reduced aircraft separation in the airport environment. As worldwide quantitative risk requirements for the newly proposed air traffic operations have not yet been established, the question arises how to assess the level of risk which may be considered acceptable. Evidently, a zero incident/accident risk can not be realized and therefore risk criteria have been developed. There are several fundamental questions that have been resolved:

- What is the safety level of the current air traffic operations?
- Are the separation minima for the current air traffic operations overly conservative?
- Can the current separation minima safely be reduced?
- What are the requirements for the newly proposed air traffic operations and systems?

These questions require more comprehensive risk assessment models and risk criteria than currently available. Therefore, to answer these questions, several methodologies for the setting of risk criteria are developed and applied to the following safety studies:

- Collision risk analysis of the usage of parallel runways for landing;
- Collision risk analysis of simultaneous missed approaches on converging runways;
- Wake vortex safety assessment of single runway approaches;
- Safety assessment of ATC-Wake single runway departures;
- Safety assessment of the I-Wake single runway operation with reduced separation.

7.2 Main contribution to knowledge

The main focus has been the development of safety assessment methodologies with the aim to reduce aircraft separation minima. Historically, such methods are based on experimental flight tests and operational data analysis. This doctoral thesis has contributed with new methods based on mathematical modelling and risk based decision support, where the risk criteria for the risk events have been expressed in suitable incident/accident risk metrics based on historical data.

Collision risk analysis studies

To increase airport capacity, the FAA has proposed use of the Precision Runway Monitor (PRM) system during independent parallel approaches [27, 28, 39]. Although safety analyses of the PRM system have provided operational recommendations and requirements, collision risk during a double missed approach was not previously quantified or assessed. To fill this gap, this thesis has developed and applied new collision risk assessment models. It has been shown that the collision risk between aircraft conducting a simultaneous missed approach can indeed be considerable, and needs to be addressed to ensure that safety is not jeopardized. A limitation of the modelling approach is that the possibility of intervention when blunders occur was not taken into account. Therefore, to be able to also cope with such human factors issues (e.g. ATC monitoring and instructions and pilot reactions), the TOPAZ methodology has been extended and applied for analysis of the collision risk during simultaneous missed approaches to Amsterdam Airport Schiphol converging runways 19R (now indicated as 18C) and 22.

Collision risk analysis of the usage of parallel runways for landing

An increase in runway capacity may be achieved by using existing parallel runways more effectively or by building additional parallel runways. In order to evaluate the risks related to independent parallel approaches, insight into the collision risk during all approach flight phases, including intermediate approach, final approach, and missed approach, is necessary. Section 2 describes a probabilistic risk analysis of the collision risk between aircraft conducting independent parallel approaches under Instrument Meteorological Conditions (IMC), thereby using Instrument Landing System (ILS) procedures. A suitable risk metric and a Target Level of

Safety have been adopted. Various scenarios with varying runway spacing and different operational conditions have been evaluated. The main conclusions from the risk analysis are:

- The collision risk probability can be considerable and unacceptable under certain conditions, especially near turn on to the localizer and during a dual missed approach.
- Technological improvements and operational procedures *focusing on increased safety during final approach* only *do not significantly lower the overall collision risk* between aircraft conducting independent parallel approaches.

Independent parallel runway approaches may be judged acceptably safe if the runway spacing is greater than 1270 m and unsafe if the spacing is less than 930 m, provided that there is:

- At least 20 to 30 degrees angle of divergence between the nominal missed approach tracks, with turns to be executed ‘as soon as practicable’ and not above 500 ft;
- Some longitudinal distance between the parallel runway thresholds, where the aircraft with the highest Final Approach Point approaches the runway located ‘farthest away’.

Collision risk analysis of simultaneous missed approaches on converging runways
Section 3 concerns a risk analysis of simultaneous missed approaches on Amsterdam Schiphol converging runways 19R and 22, where the Obstacle Clearance Altitude (OCA) of runway 22 was proposed to be reduced from 350 ft to 200 ft. This allows the use of runway 22 during actual Category I weather conditions, and supports optimization of the arrival scheduling. A collision risk model has been developed for assessment of various missed approach procedures on runway 22, with possibly a left turn after completion of the initial missed approach phase.

Numerical evaluations show that the collision risk may attain an unacceptably high level under certain conditions, especially when approaching aircraft on runways 19R and 22 both make a straight missed approach, and ATC does not intervene. For trying to maintain the collision risk at a low and acceptable level, some risk reducing measures are identified. In particular, ATC monitoring and instructing – turn right! or climb to! – to aircraft conducting a missed approach on runway 19R in case of a previous straight missed approach on runway 22 is required. Provided that these identified measures are applied, the proposed reduction of the OCA of runway 22 to 200 ft is risk neutral within a broad spectrum of missed approach procedural aspects, and may be judged adequately safe. This conclusion is also valid for the possible future situation, where the final missed approach altitude is raised from 2000 to 3000 ft.

Wake vortex risk analysis studies
Wake vortex research has generally focused on analysis of wake vortex behaviour in different weather conditions and on analysis of the impact on wake encountering aircraft. Wake vortex safety related to proposed operations for reduced separation was not previously quantified or assessed in terms of incident/accident risk probabilities. To fill this gap, a Wake Vortex Induced Risk assessment (WAVIR) methodology was developed and applied. WAVIR has received

significant interest worldwide, and other organisations have followed with similar methods. The Airspace Simulation and Analysis for Terminal Instrument Procedures (ASAT) tool, which is used by the FAA, has been extended to assess the probability of a wake encounter behind a variety of leader aircraft and under different weather conditions. Airbus has now developed a Vortex Encounter Severity Assessment (VESA) tool, which allows assessment and comparison of aircraft reactions and effects of vortex encounters behind various aircraft. DLR has established the WakeScene (Wake Vortex Scenarios Simulation) Package to assess the relative encounter probability behind different wake vortex generating aircraft. However, so far, the WAVIR methodology is still the only method that enables explicit modelling of the role of both pilots and air traffic controllers working with new systems for reduced aircraft separation.

Wake vortex safety assessment of single runway approaches

Both in Europe and in the United States, the feasibility of increasing runway capacity through reduced wake vortex separation distances between aircraft in the arrival and departure flows is being investigated. Traditionally three methods have been used to determine safe wake vortex separation distances: (i) flight test experiments, (ii) historic operational data, and (iii) analytical models. Section 4 describes the development the Wake Vortex Induced Risk assessment (WAVIR) methodology and its application, within S-Wake, to assess the safety of single runway wake vortex separation distances. The main results of the S-Wake project show that an increase in runway throughput might be achieved through exploiting favorable wind conditions (sufficiently strong crosswind and/or strong headwind). It is further motivated that this can only be achieved through the use of new and advanced concepts of operations with appropriate decision making tools for air traffic controllers and pilots. Both in Europe and the United States, such proposed Concept of Operations for reduced wake vortex separation depends 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. This has therefore led to the design of the ground based ATC-Wake system and the on-board I-Wake system, the topics of Sections 5 and 6 of this doctoral thesis respectively.

Safety assessment of ATC-Wake single runway departures

One potential approach to reduce the wake vortex separation distance between aircraft at take-off is by utilizing the ATC-Wake system and operational concept designed to allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. Section 5 has quantified the possible safety improvements to be obtained by installation of ATC-Wake and use during the departure phase of flight. This includes an assessment, with the WAVIR tool-set, of required crosswind values for which reduced aircraft separation can be applied. For the ATC-Wake departure operation with reduced separation, two more issues have been considered: 1) the air traffic controller will warn the pilot about a potential wake vortex encounter in case an ATC-Wake alert is raised, and 2) if an ATC-Wake system component provides wrong advice, there is a higher risk on the presence of severe wake vortices. Consequences might be catastrophic in case of a light aircraft following a heavy aircraft.

For airports with ATC-Wake in use, Section 5 indicates that the present separation of two to three minutes between aircraft departing at the same runway might be reduced to 120, 90, or even 60 seconds for all aircraft types in the presence of sufficient crosswind. As these indicative separation minima, dependent on crosswind conditions, do not yet account for crosswind uncertainty, the setting of requirements for the ATC-Wake system components was further investigated. This was done through a qualitative analysis of the effect of failures of ATC-Wake system components, assuming that failure conditions with severe consequences must be extremely improbable and minor failure conditions may be probable. 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.

Safety assessment of the I-Wake single runway operation with reduced separation
Another potential improvement of wake vortex safety in the airport environment is through installation and use of a wake vortex detection, warning, and avoidance system on-board aircraft. The fundamental part is a pulsed Light Detection and Ranging (LiDAR) sensor system that measures disturbances in the atmosphere and enables real-time forewarning of turbulent conditions. Section 6 presents an investigation of wake vortex safety under *reduced separation* (2.0 or 2.5 NM between all aircraft) during the approach and landing phases of flight when using such I-Wake system on-board aircraft.

The I-Wake operation assumes that a missed approach is initiated, after the flight crew receives an alert indicating that the aircraft will likely encounter a severe wake vortex. Wake vortex induced risk related to the I-Wake operation with reduced separation has been assessed qualitatively through a Functional Hazard Analysis (FHA) [88]. This study has now also *quantified* the wake vortex induced incident/ accident risk through the use of the WAVIR methodology, extended with an aircraft/pilot missed approach model and a causal model for the I-Wake system failure probability. The assessment of wake induced risk levels for the approach phase when reduced aircraft separation (2.0 or 2.5 NM between all aircraft) is applied has been performed for different aircraft types and various wind conditions. Aspects that have been considered are e.g. the time for caution and alert and the I-Wake system capabilities (such as the horizontal and vertical scanning view, the angle of regard, and the wake vortex detection range).

The use of I-Wake seems to reduce the wake vortex induced risk only slightly as compared to the current practice. The main reason for this is the fact that the largest risk during single runway arrivals occurs near the runway threshold (following S-Wake). Therefore, the use of I-Wake would be most beneficial at very low altitudes, where the probability of encountering a (rebounding) wake vortex is highest. Unfortunately, at altitudes below 200 ft it is also more difficult to initiate a missed approach. Therefore, the operational use of I-Wake seems to have only minor impact on the wake vortex induced risk during single runway arrivals (and, as a consequence, I-Wake use provides low potential for reduction of the separation minima)

7.3 Impact of the main results

The new mathematical methods all support two common rationales for acceptance of a newly proposed air traffic operation, namely by showing that the number of risk events does not exceed some pre-defined, and agreed upon, risk requirement and furthermore also does not increase with the introduction of the new operation. The developed risk assessment models are based on risk metrics in terms of incident/accident probabilities per movement, with risk requirements derived on the basis of historical incident/accident data. It has been shown that the current wake vortex aircraft separation minima, which depend on the aircraft weight, are indeed overly conservative under certain conditions. Introduction of variable wind dependent aircraft separation rules will enable increase of airport capacity, while maintaining safety. Aircraft separation can be reduced safely, provided that new wake vortex prediction, detection and avoidance systems - such as ATC-Wake (for air traffic controllers) and I-Wake (for pilots) - are implemented for operational use. It has been shown that specific missed approach procedures, which take into account local airport runway layout, will lead to an increase of airport capacity.

The safety assessments have built sufficient confidence in the operational use of the new proposed ATM systems and flight procedures for the application of reduced aircraft separation in the airport environment. The results from the collision risk analysis studies have been used directly by the Dutch Civil Aviation authority and Air Traffic Control Centre, and were brought forward successfully to the ICAO Obstacle Clearance Panel. The results from the wake vortex risk analysis studies have been used directly for the design and the setting of requirements for the ATC-Wake and I-Wake systems and their associated concepts of operation. It has been shown that both are promising concepts for increasing aircraft handling capacity in the airport environment. As a result of the wake vortex safety studies, new concepts of operations for reduced wake vortex separations are now being validated in Europe (under co-ordination of EUROCONTROL) and the United States (under co-ordination of the FAA and NASA). Trials at European airports are foreseen as the ideal way forward for gathering the required data to complete the local Safety Cases realize the reduction of the wake vortex separation minima.

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Appendix A WAke Vortex Induced Risk assessment (WAVIR)

A.1 Introduction

To determine the probability of occurrence of each of the defined wake vortex induced risk events (see Section 4.4.1), a safety assessment model is required. In view of the uncertainties and the difficulties in understanding of the wake vortex phenomena, it is proposed to follow a probabilistic approach. This probabilistic method should enable evaluation of wake vortex safety under various operational and weather conditions. It should also be possible to evaluate the current practice as well as promising new concepts, such as new operational improvements, aerodynamic aircraft designs, or weather related separation minima. The approach should be able to handle both single runway and dual or closely spaced parallel runways. Considering these requirements, three probabilistic sub models are integrated within a stochastic framework:

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

For the evaluation of wake vortex induced risk, it is necessary to develop a mathematical model to characterise wake vortex induced incident/accident probabilities. This is done as follows. In section A.2, an overview is given of the safety modelling relations and dependencies. Section A.3 introduces the main notations. In subsection A.4, a stochastic model for the wake vortex severity prediction is presented. Subsequently, in subsection A.5, this model is extended with a stochastic wake encounter model to predict the roll and loss of height of the following aircraft, resulting in an assessment of encounter severity (see Section A.6). Section A.7 presents a stochastic dynamical incident/accident prediction model to assess the selected risk metrics.

A.2 Overview of the modelling relations and dependencies

The incident/accident risk, in terms of minor incident, major incident, hazardous accident, and catastrophic accident probability, provides the information necessary for regulatory authorities to judge the acceptability of risk. However, pilots/crew and passengers will have a different perception of safety (in relation to actual encounters with wake vortices). Therefore, to also support the acceptability of risk assessment results by pilots/crew and passengers, the concept of encounter severity is introduced. Clearly, the more “severe” the encounter, the larger the incident/accident risk. The issue of appropriate encounter severity metrics (or hazard criteria) has been studied for many years [9, 64, 65, 85, 94, 98, 99]. The following two metrics have been chosen to classify individual encounters:

- Maximum attained bank angle;
- Encounter altitude.

To assess the numerical values of the selected risk metrics (in terms of risk event probabilities per aircraft movement (e.g. per approach or per departure), an incident/accident prediction model is proposed (see Section A.7). It describes and characterises the probabilistic relation between individual (simulated) encounters and the risk of an incident or accident. The relations and dependencies between the different sub-models are visualised in Figure A-1.

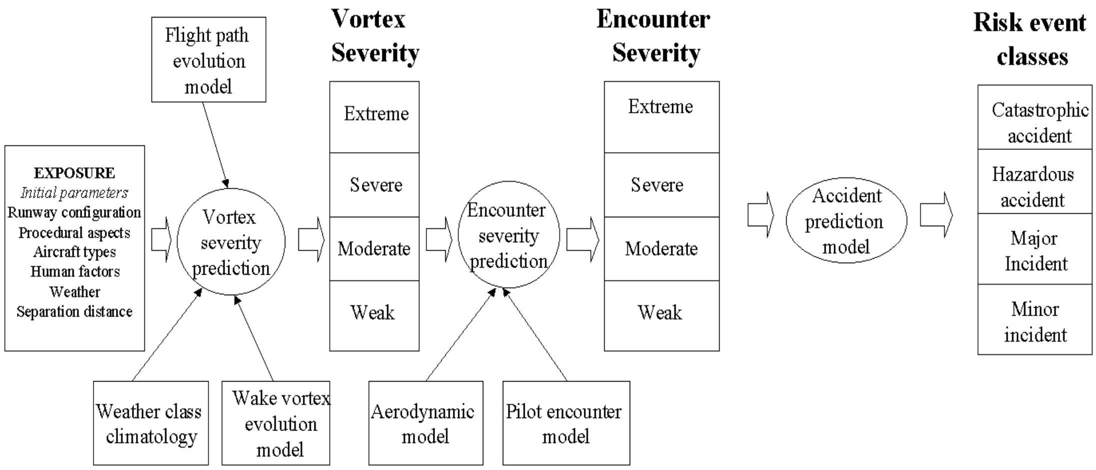

Figure A-1 Overview of modelling relations and dependencies

A.3 Notations

A situation of a sequence of aircraft, which fly toward an airport, is assumed. For the position and velocity components of aircraft *i*, there is a process $\left(x_t^i,\, y_t^i,\, z_t^i,\, \dot{x}_t^i,\, \dot{y}_t^i,\, \dot{z}_t^i\right)$. In addition, there are processes $\left(w_{x,t}^i,\, w_{y,t}^i,\, w_{z,t}^i\right)$ for the wind speed components, and also for the other main meteorological components (including atmospheric turbulence and stratification effects) together defining the ambient weather conditions acting locally on aircraft.

A.4 Wake vortex severity prediction

The left and right centres of the vortex at moment *s* which are generated by aircraft *j* at moment *t*, are represented by two fields $\delta^{j-}(t,s)$ and $\delta^{j+}(t,s)$, with $s \geq 0$, each of which assumes (y,z) values in $\mathbb{R}^2$. At moment $t+s$, the strengths of the left and right vortices that are generated by aircraft *j* at moment *t* are represented by the two fields $\Gamma^{j-}(t,s)$ and $\Gamma^{j+}(t,s)$, each of which assumes strength values in $\mathbb{R}$. At moment $t+s$, the core radius of the left and right vortices that are generated by aircraft *j* at moment *t* are represented by two fields $r_{core}^{j-}(t,s)$ and $r_{core}^{j+}(t,s)$, each of which assumes values in $\mathbb{R}$. Note that it is assumed that the x co-ordinate follows from the flight path evolution model (using the relations with t, s, and aircraft speed profiles). To shorten the notation, the components are placed into a joint $\mathbb{R}^8$ -valued field $\chi^j(t,s)$:

$$\chi^{j}(t,s) \overset{\Delta}{=} \text{column}\left\{\delta^{j-}(t,s),\ \delta^{j+}(t,s),\ \Gamma^{j-}(t,s),\ \Gamma^{j+}(t,s), r_{core}^{j-}(t,s), r_{core}^{j+}(t,s)\right\} \quad \text{(A-1)}$$

Research is ongoing for many years to improve differential equations for the motion and decay of the components of the joint field $\chi^{j}(t,s)$. Widely known equations in current literature are the ones given by Corjon & Poinsot [76, 77, 95], which are largely based on those of Greene [90] and Liu [91]. Recent European research activities include work on the validation of different decay models and the simulation of probabilistic wake vortex behaviour under different weather and wind conditions [3, 4, 7, 10, 11, 96]. When adding an extension for the wind velocity in *z* direction, these equations are of the form:

$$\frac{d\,\chi^{j}(t,s)}{d\,s} = f\left(\chi^{j}(t,s), \wp^{j}(s)\right) \quad \text{(A-2)}$$

where $\wp^{j}(s)$ denotes local external influences such as the local wind $\left\{w_{x,t}^{j},\ w_{y,t}^{j},\ w_{z,t}^{j}\right\}$ at moment *t*, the local Brünt-Väissällä frequency $N^{j}(t+s)$, the Turbulent Kinetic Energy (which depends on the Root Mean Square (RMS) velocity of atmospheric turbulence $q_{rms}{}^{j}(t+s)$) and/or the Eddy Dissipation Rate $\varepsilon^{j}(t+s)$.

To define the solution of the differential equation for $s \geq 0$, the components of $\chi^{j}(t,0)$ (the initial boundary conditions) have to be characterized. It is known that [77, 98]:

$$\begin{aligned}
\delta_{y}^{j\pm}(t,0) &= y_{t}^{j} \pm \tfrac{1}{2} b_{0}^{j} \\
\delta_{z}^{j\pm}(t,0) &= z_{t}^{j} \\
\Gamma^{j\pm}(t,0) &= \pm\Gamma_{t,0}^{j} \equiv \pm \frac{m^{j} g}{b_{0}^{j} \rho_{t}^{j}} \left(\dot{x}_{t}^{j} - w_{x,t}^{j}\right)^{-1}
\end{aligned} \quad \text{(A-3)}$$

with b^{j}_{0} the initial spacing between the primary vortex centres, m^{j} the mass of aircraft *j*, *g* the gravitational acceleration, and ρ^{j}_{t} the local air density.

Next, the moment in time that (the longitudinal position of) an aircraft *i* reaches the wake generated at longitudinal position *x* (by aircraft *j*) is characterised. To do so, it is assumed that the longitudinal wind speed component is height dependent and constant at a certain height, and denoted by $w_{x,t}^{i}(z)$. Then that moment in time is a stopping time, defined by [3]:

$$\tau_{x}^{ij} = \tau_{x}^{j} + \inf_{s,z}\left\{s > 0, z > 0 \,\middle|\, x_{\tau_{x}^{j}+s}^{i} = x + s\, w_{x,\tau_{x}^{j}}^{j}(z)\right\} \quad \text{(A-4)}$$

with

$$\tau_{x}^{j} \equiv \inf_{t}\left\{t \,\middle|\, x_{t}^{j} = x\right\} \quad \text{(A-5)}$$

It is furthermore assumed that the airspeeds of both aircraft in x direction are bounded and either both strictly positive or both strictly negative. In view of this, this equation means that $\{\tau^{ij}_x\}$ is a monotonous process. Hence, an $\mathbb{R}^8$-valued stochastic process $\{\chi^{ij}_t\}$, which represents the properties (of the vortices generated by aircraft j) that are used to characterise the risk imposed to aircraft i, can be defined as follows:

$$\chi^{ij}_{\tau^{ij}_x} \equiv \chi^j\left(\tau^j_x, \tau^{ij}_x - \tau^j_x\right) \tag{A-6}$$

The decay of the vortex circulation strength depends on the ambient atmospheric conditions such as e.g. stratification, turbulence, and wind shear. Several deterministic wake vortex decay models have been given in literature. Those of Greene [90], Donaldson & Bilanin [92], and Sarpkaya [80, 81, 82] have been implemented. All models use the same decay model for atmospheric stratification, but differ in the modelling of atmospheric turbulence effects. In the model of Greene an additional (weak) viscous decay term is employed. Table A-1 gives an overview of the decay terms of the wake vortices generated by aircraft j.

Table A-1 Wake vortex decay terms of the different models

Model	**Viscous Interaction**	**Stratification**	**Turbulence**
Donaldson & Bilanin	none		$\frac{d\Gamma}{dt} = -0.4 q^j_{rms}(t)\frac{\Gamma}{b_0}$
Sarpkaya	none	$\frac{d\Gamma}{dt} = \frac{A_s\,(\mathrm{N}^j)^2\,(\mathrm{z}_0 - z)}{b_0}$	$\frac{d\Gamma}{dt} = -\frac{C_S}{T_S}\Gamma_0 \exp\left[-\frac{C_S}{T_S}t\right]$
Greene	$\frac{d\Gamma}{dt} = -1.045\, w_{desc}\, \mathrm{C_D}$		$\frac{d\Gamma}{dt} = -0.41 q^j_{rms}(t)\frac{\Gamma}{b_0}$

Proper values for the model constants have been defined mainly on the basis of LiDAR wake data. Model constant A_S is defined as $A_s = \pi/4 * 1.73 * 2.09 * b_0^2 = 2.83976 * b_0^2$ and z_0 is the initial height of the vortex (the flying altitude of the wake generating aircraft), w_{desc} is the wake vortex descent speed and C_D the viscous drag coefficient (C_D= 0.2). The Brunt-Väissällä frequency N^j characterises the stability of the atmospheric boundary layer. It is directly related to the vertical temperature gradient:

$$N^j = \sqrt{\frac{g}{\overline{\theta}^j}\frac{d\overline{\theta}^j}{dz}} \tag{A-7}$$

Here $\overline{\theta}^j$ is the so-called potential temperature in the atmosphere acting on aircraft j. The root-mean-square velocity $q_{rms}{}^j(t+s))$ is equal to $\sqrt{2TKE}$, in which TKE is the Turbulent Kinetic

Energy. In Sarpkaya's model, the parameter C_S is a constant (it was taken equal to 0.45 as proposed by Sarpkaya) and T_S depends on the Eddy Dissipation Rate (ε^j or *EDR*). It should be noted that the decay rate due to stratification is zero initially ($z=z_0$) but then increases with time. On the other hand the decay rate due to turbulence is largest initially (for the Donaldson & Bilanin model the decay rate is proportional to Γ and therefore largest initially, for the Sarpkaya model the exponential term is equal to 1 initially and then decays). For the effect of crosswind on vortex decay, a simple model proposed by Cox et al. [93] can be used. The model assumes that the decay of the vortex with opposite-sign vorticity in comparison with the crosswind shear is accelerated by applying a couple in the opposite sense to the vortex circulation:

$$\frac{d\Gamma}{dt} = -\frac{2}{3} C_{DV} \sigma_c w_0 b_0 \tag{A-8}$$

where C_{DV} is the viscous coefficient caused by the crosswind and σ_c is the crosswind shear.

The following characterisation for the vortex core radius at the moment in time that the aircraft *i* reaches the vortices generated at longitudinal position *x* (by aircraft *j*) is adopted [76, 77]:

$$r^j_{core,\tau^{ij}_x} = \max\left\{ r^j_{core,0},\ \tfrac{1}{80}\sqrt{\Gamma^j_{0,\tau^j_x}\left(\tau^{ij}_x - \tau^j_x\right)}\right\} \tag{A-9}$$

with $r^j_{core,0}$ the initial radius of aircraft *j*'s vortex cores.

The vortex pair can be non-symmetric, with possible different intensities and radii, and can induce a non-zero bank angle. For a pair with given strengths and radii, the Burnham-Hallock profile of tangential velocity as a function of the distance d_{vc} to the vortex centre is:

$$V^j_{\theta,\tau^{ij}_x}(d_{vc}) = \frac{\Gamma^{j\pm}_{\tau^{ij}_x}}{2\pi}\left(\frac{d_{vc}}{(r^j_{core,\tau^{ij}_x})^2 + d_{vc}^2}\right) \tag{A-10}$$

Alternatively, a Lamb-Oseen tangential velocity profile can be used:

$$V^j_{\theta,\tau^{ij}_x}(d_{vc}) = \frac{\Gamma^{j\pm}_{\tau^{ij}_x}}{2\pi\, d_{vc}}\left[1 - \exp\left[-1.2564\left(\frac{d_{vc}}{(r^j_{core,\tau^{ij}_x})^2}\right)^2\right]\right] \tag{A-11}$$

The velocity field resulting from the pair is the vector sum of the velocity fields of each vortex, which consists of a side-wash and down-wash velocity component.

A.5 Wake encounter severity prediction

For computing a metric of the wake encounter severity a wake encounter model is to be used. In WAVIR two models of different complexity are available. A short description of the models and their assumptions and limitations is given in the next sub-sections. At the moment, the models only take into account the effect of the prime vortices. Extension of the models to also include the effects of the secondary and mirror vortices is to be further investigated.

A.5.1 The Extended Roll Control Ratio Model (ERCR)

The Extended Roll Control Ratio (ERCR) model computes for a given wake induced rolling moment an estimate of the maximum wake induced bank angle. It is based on the one Degree Of Freedom (1-DOF) roll model of Tatnall [85]. The roll-control ratio is 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. The wake induced rolling moment $C_{R,v}$ is computed with a simplified analytical model as defined by Tatnall. The wing span of the aircraft (d_y^i) and the wing planform (Taper Ratio ($\lambda_{TR}{}^i$) and Aspect Ratio ($A_R{}^i$))are taken into account, but aerodynamic effects on the fuselage and the tail surfaces are neglected. The vortex flow field is defined with a Burnham-Hallock type vortex pair: vortex circulation strength (Γ), vortex core radius (r_{core}) and the initial lateral distance between the vortices ($b^j_o = \pi / d_y{}^j$) are user controlled input parameters. The roll control power is computed from a simplified formula.

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 has therefore to be limited in order to prevent infinite roll. However, Tatnall derived a table of suitable (aircraft type dependent) wake encounter duration times T_v such that the 1-DOF model predicts equal maximum roll angles as with a more elaborate 3-DOF model. So the aircraft type dependent wake encounter duration time T_v implicitly accounts for the dynamic aspect of the encounter. In the WAVIR application these maximum duration times are also used. This is probably not fully justified, because not only the most severe (vortex centred) encounters (for which the model has been designed) but also weaker encounters (aircraft positions relatively far from vortex cores) play a role in the wake encounter severity metrics. Using the vortex encounter time T_v, a pilot response time T_R, and the aircraft roll characteristics (max roll control power, rolling moment of inertia), formulas are obtained for the roll rate p_t^i, the bank angle ϕ^i and the maximum bank angle $\Phi_{max,\,inf}$ (without control input). The maximum bank angle is the most important output of the Tatnall model [85], but the roll-control ratio (RCR) is an output too and can also be used to classify the encounter severity. The pertaining equations (A-12) are:

$$p_t^i = \frac{K_1}{K_2}\left[C_{R,v}(e^{K_2 t}-1) - H(t-T_V)(e^{K_2(t-T_V)}-1\right]$$
$$-C_{R,c,\max}\left[H(t-T_R)(e^{K_2(t-T_R)}-1) - H(t-T_F)(e^{K_2(t-T_V)}-1))\right]$$

$$\phi_t^i = \frac{K_1}{K_2}\left[C_{R,v}\left(\frac{e^{K_2 t}-1}{K_2}-t\right) - H(t-T_V)\left(\frac{e^{K_2(t-T_V)}-1}{K_2}-(t-T_V)\right)\right]$$
$$-C_{R,c,\max}\left[H(t-T_R)\left(\frac{e^{K_2(t-T_R)}-1}{K_2}-(t-T_R)\right) - H(t-T_F)\left(\frac{e^{K_2(t-T_F)}-1}{K_2}\right)-(t-T_F)\right] \quad \text{(A-12)}$$

$$\Phi_{\max,\inf} = -\frac{K_1 C_{R,v} T_V}{K_2}$$

Here K_1 and K_2 are aircraft dependent constants which, for aircraft i , are equal to:

$$K_1{}^i = \frac{\frac{1}{2}\rho_t^i (v_t^i)^2 (d_y^i)^3}{A_R^i I_{xx}{}^i}, \qquad K_2{}^i = K_1{}^i C_{l,\bar{p}}{}^i \frac{d_y^i}{2 v_t^i} \quad \text{(A-13)}$$

where v_t^i denotes the three dimensional velocity (airspeed), $C_{1,\bar{p}}{}^i$ is the roll damping coefficient of the aircraft (note that $C_{1,\bar{p}} < 0$), $A_R{}^i$ is the Aspect Ratio, I_{xx} the inertial rolling moment, and the roll control capability $C_{R,c,max}$ is assumed equal to $0.07\, C_{1,\bar{p}}$ [85]. This is based on a minimum requirement and therefore a conservative estimate: actual roll control power capability may be larger, leading to lower roll control ratio RCR in practice and smaller maximum bank angles. In the above equations sub-fix f denotes the following aircraft. *H* is the Heaviside step function:

$$H(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases} \quad \text{(A-14)}$$

The finish time T_F for the control input, i.e. when the bank angle has returned to 0, is given by:

$$T_F = T_R + \xi T_V \quad \text{(A-15)}$$

where ξ is the roll control ratio (RCR):

$$\xi = \frac{C_{R,v}}{C_{R,c,\max}} \quad \text{(A-16)}$$

Worst case conditions are assumed: the wake encountering aircraft is placed (instantaneously) in the centre of the (non-decayed) wake generating aircraft, assuming a rather small vortex core radius (0.025 $d_y{}^j$). The vortex induced rolling moment coefficient $C_{R,v}$ and the vortex encounter duration time T_v are taken according to Tatnall [85]. A rather conservative pilot reaction time T_R = 0.6 seconds is assumed. A summary of the Roll Control Ratios (RCRs) and maximum bank angles is given in Table A.2. The relation between the two wake encounter severity metrics is also visualised in Figure A-2. The higher the Roll Control Ratio (RCR), the less becomes the influence of the controls on computed maximum roll angle (compare Φ_{max} and $\Phi_{max,inf}$).

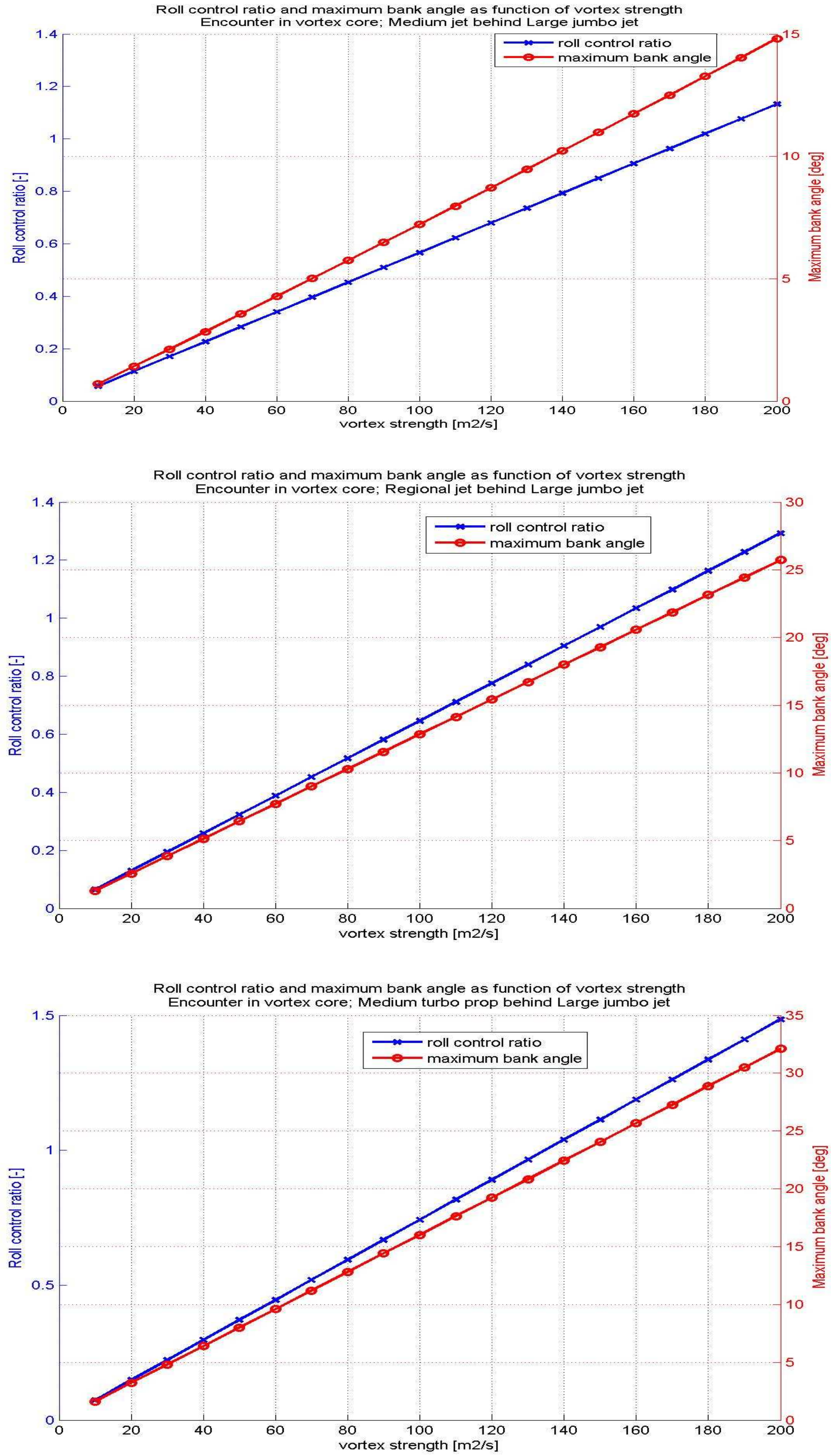

Figure A-2 Relation between roll control ratio and maximum bank angle

Table A-2 Summary of computed RCR and maximum bank angles with ERCR model

Follower	**Leader**							
	Medium Jet (Γ= 244.3)				**Large Jumbo Jet (Γ= 550.5)**			
	T_v	RCR	Φ_{max}	$\Phi_{max,inf}$	T_v	RCR	Φ_{max}	$\Phi_{max,inf}$
Light Turbo Prop	0.72	5.18	84.5	109.9	0.72	9.67	172.2	205.2
Regional Jet	0.89	2.42	25.2	37.9	0.95	4.72	60.5	78.9
Medium Jet	1.00	2.02	12.6	31.9	1.1	3.88	36.3	67.4
Large Jumbo Jet	1.08	1.76	8.0	19.7	1.78	2.81	27.8	51.6

A.5.2 The Reduced Aircraft/Pilot Model (RAPM)

For the characterisation of how the process $\{\chi^{ij}_t\}$ induces a roll and loss of height process $\{\vartheta^{ij}_t\}$ for aircraft *i*, the reduced aircraft/pilot model developed in S-Wake is used [89, 100, 101]. It consists of a flight dynamics model for the simulation of the aircraft response and a pilot model for simulation of the pilot behaviour during wake vortex encounters. The model provides:

- Vertical position (i.e. loss of height), vertical speed & acceleration;
- Lateral position (i.e. sideslip) and lateral acceleration;
- Bank angle, roll rate and roll acceleration;
- Pitch angle and pitch rate;
- Yaw angle (i.e. ILS localizer deviation), yaw rate and yaw acceleration.

Aircraft flight dynamics model

Let the bank angle, pitch angle, and yaw angle at moment s during the encounter which starts at moment t, be represented by the three fields $\phi^i(t,s)$, $\theta^i(t,s)$ and $\varsigma^i(t,s)$ (where s=0 denotes the beginning of the wake encounter). Let the body-axis roll rate (p_t^i), pitch rate (q_t^i) and yaw rate (r_t^i) now be defined by:

$$p_t^i = \frac{d\phi_t^i}{dt} \qquad q_t^i = \frac{d\theta_t^i}{dt} \qquad r_t^i = \frac{d\varsigma_t^i}{dt} \tag{A-17}$$

Also, let h_t^i denote the height of aircraft *i* during the encounter, i.e. $h_t^i \equiv z^i_{t+\tau_x^{ij}}$, where the encounter severity is evaluated from the moment τ^{ij}_x onwards. To shorten the notation, the above components are placed into the joint $\mathbb{R}^5$-valued field ϑ^{ij}(t,s), characterising the rolling process induced on aircraft *i*:

$$\vartheta^{ij}(t,s) \overset{\Delta}{=} \text{column}\left\{h^i(t,s),\ y^i(t,s),\ \phi^i(t,s),\ \theta^i(t,s), \varsigma^i(t,s)\right\} \tag{A-18}$$

Differential equations for the components of the joint field ϑ^{ij} (t,s) are given in Escande [101], and are of the form

$$\frac{d^2\vartheta^{ij}(t,s)}{ds}+\frac{d\vartheta^{ij}(t,s)}{ds}=g\left(\vartheta^{ij}(t,s),\varpi^i(s),\psi^i(s)\right) \quad \text{(A-19)}$$

with ϖ^i(s) denoting the local external influences such as the (auto)pilot response time, aircraft characteristics (e.g. airspeed, wingspan, aspect ratio of the wing, horizontal tail, vertical tail, mean aerodynamic chord, mass, moments of inertia, aerodynamic derivatives), glide path angle, angles of attack and sideslip, heading angle, rudder deflection, air density. The aileron deflection $\psi^i(s)$ is influenced by the pilot behaviour and allows to take into account the actual reactions from the pilot to the roll upsets experienced when encountering the vortices.

To define the solution for the above differential equation for s≥0, the components of ϑ^{ij} (t,0) and dϑ^{ij} (t,0)/dt (the initial boundary conditions) have to be characterised. It should be noted that the moment s=0 corresponds to the moment τ^{ij}_x that a wake generated at longitudinal position *x* by aircraft *j* will arrive at the longitudinal position of aircraft *i*.

It is known that the initial state of the aircraft can be represented by [101]:

$$\begin{aligned} h^i(t,0) &= z^i_{t+\tau^{ij}_x} \\ y^i(t,0) &= y^i_{t+\tau^{ij}_x} \\ \phi^i(t,0) &= 0 \\ \theta^i(t,0) &= \alpha^i_{t+\tau^{ij}_x} \\ \varsigma^i(t,0) &= \beta^i_{t+\tau^{ij}_x} \end{aligned} \quad \text{(A-20)}$$

with $\alpha^i_{t+\tau^{ij}_x}$ and $\beta^i_{t+\tau^{ij}_x}$ denoting angle of attack and angle of side slip at the time of encounter.

Pilot behaviour model

For the characterisation of the rolling process induced on aircraft *i*, an appropriate model of the pilot behaviour during wake vortex encounters is also required. The pilot behaviour and its effect on the aircraft is modelled through a so-called crossover model for the inceptor deflection or aileron deflection ψ^i_t [100]:

$$\psi^i_t = K_P\cdot\left[\left(\frac{1}{f}-\frac{c}{f^2}\right)\left(\frac{a}{f}-\frac{d\cdot c}{f^2}\right)\left(\frac{b}{f}-\frac{e\cdot c}{f^2}\right)\right]\cdot\begin{bmatrix} h^i_t \\ \dot{h}^i_t \\ \ddot{h}^i_t \end{bmatrix}+K_P\cdot\left[\frac{c}{f}\right]\cdot\Delta\phi^i_t \quad \text{(A-21)}$$

with the so-called pilot (roll rate) gain (K_P^i), pilot lead time (T_{lead}^i), aircraft lag time (T_{lag}^i), and equivalent time delay (τ_e^i) being the four tuning parameters representing the adaptation of the pilot model to the different dynamics (of aircraft *i*).

The six constants a, b, c, d, e and f are to be determined on the basis of the latter three tuning parameters (pilot lead time, aircraft lag time and equivalent time delay) [100, page 25]. Note that the pilot lead-time is determined through the use of a pilot activation time (representing the initial time with the pilot not responding) and an alert bank angle (allowing the pilot inactive / not responding as long as the bank angle excursion does not exceed a prescribed value).

The input of this model is the bank angle error $\Delta\phi_t^i$, which represents the difference between the commanded bank angle and the actual bank angle. Clearly, during an approach the pilot tries to establish wing levels, so that the commanded bank angle is zero. Hence: $\Delta\phi_t^i = \phi_t^i$. This pilot model can be integrated into the aircraft flight dynamics differential equation model.

A.5.3 Comparison of the ERCR and RAPM 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 A.3. The results are for a Regional Jet behind a Large Jumbo Jet configuration (wake circulation strength is equal to 300 m^2/s). The wake intercept angle was assumed equal to zero.

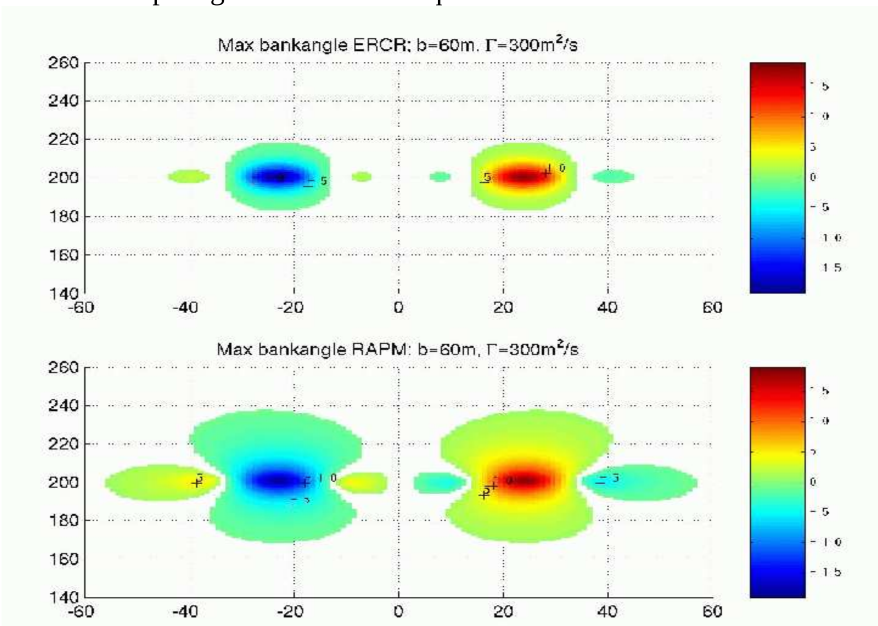

Figure A-3 Comparison between computed maximum roll angles for ERCR and RAPM models, as a function of (initial) aircraft position in the wake. Regional jet (wingspan 30m) in the wake of a 60m span aircraft having a wake circulation strength of 300 m^2/s

The difference between both results is relatively small. Note that simplifying assumptions are made on the initial aircraft attitudes, because the evaluations are made in gate planes at fixed longitudinal positions and, as a consequence, the vortex and aircraft positions are defined independently. Further improvements might be realised by developing a wake intercept model, which defines more realistic wake intercept routes.

A.6 Wake encounter severity classification

To support the acceptability of risk assessment results by pilots/crew and passengers, the concept of *encounter severity* has been introduced. The following two metrics have been chosen to classify individual encounters:

- Maximum attained bank angle excursion;
- Altitude at which the encounter occurs.

NASA determined encounter severity boundaries in terms of maximum bank angle, where the boundaries under IFR conditions remain constant for altitudes above 350 ft, but decrease with lower altitudes [94, 99]. It was e.g. noted that a maximum roll angle of more than 7 degrees is perceived by pilots as hazardous at altitudes of 200 ft or less, whereas roll angles as large as 15 – 20 degrees seem acceptable above 200 ft. For the analysis of incident reporting data, NATS have introduced three encounter severity categories [102]:

- Category A for a roll angle of more than 30 degrees;
- Category B for a roll angle of more than 10 degrees and less than 30 degrees;
- Category C for a roll angle of less than 10 degrees.

These classification schemes are now combined into a newly proposed categorization with four encounter severity classes as follows:

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

with the aim to establish some kind of probabilistic relation with the four defined risk events that are proposed for policy making of wake vortex induced risk. It is now assumed that the threshold boundaries are defined as functions of the maximum bank angle, and are dependent on the height at which the following aircraft *i* encounters the wake, i.e.

$$\bar{\phi}_{WeakEnc}(h) < \bar{\phi}_{ModEnc}(h) < \bar{\phi}_{SevEnc}(h) < \bar{\phi}_{ExtrEnc}(h) \qquad \text{(A-22)}$$

It is furthermore assumed that:

- The threshold boundaries of the four encounter severity categories are constant above a certain *critical crash-into-terrain height* h^i_{CCIT} (e.g. the height of 350 ft as determined for Instrument Flight Rules (IFR) conditions by NASA). From the above categorisation, it follows that $\bar{\phi}_{ModEnc}(h) \equiv 10°$ and $\bar{\phi}_{SevEnc}(h) \equiv 30°$ for $h > h^i_{CCIT}$.
- The lower threshold boundary of the *Weak Encounter Category* is constant and independent of the encounter height. The value is such that aircraft disturbances caused by regular air turbulence (i.e. small bank angle) are not classified as being related to a wake encounter.
- There is an increased probability of an *Extreme Encounter*, in case the encounter occurs below the critical crash-into-terrain height h^i_{CCIT}. Clearly, for such encounter heights, the threshold boundaries for the four encounter severity categories decrease with altitude.

Thus the four tests that lead to a classification of individual (simulated) wake encounters into the wake encounter severity classes are (A-23):

Weak Encounter: $\bar{\phi}_{WeakEnc}(h) < \left|\max_t\{\phi^i_t\}\right| < \bar{\phi}_{ModEnc}(h)$, $t \in [\tau^{ij}_x, \tau^{ij}_x + T_{enc}]$

Moderate Encounter $\bar{\phi}_{ModEnc}(h) < \left|\max_t\{\phi^i_t\}\right| < \bar{\phi}_{SevEnc}(h)$, $t \in [\tau^{ij}_x, \tau^{ij}_x + T_{enc}]$

Severe Encounter $\bar{\phi}_{SevEnc}(h) < \left|\max_t\{\phi^i_t\}\right| < \bar{\phi}_{ExtEnc}(h)$, $t \in [\tau^{ij}_x, \tau^{ij}_x + T_{enc}]$

Extreme Encounter $\bar{\phi}_{ExtEnc}(h) < \left|\max_t\{\phi^i_t\}\right|$, $t \in [\tau^{ij}_x, \tau^{ij}_x + T_{enc}]$

A.7 Incident/accident prediction

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

As an example, Table A-3 shows that *Weak encounter*s will most likely result in a *Minor Incident*, whereas *Severe Encounters* and *Extreme Encounters* may result in a *Hazardous Accident*. Appropriate values for the transition probabilities can be determined using encounter data from incident/accident data collection activities (such as being collected at Heathrow airport). Note that, in the following, it is also assumed that certain transition probabilities are zero (see also Table A-3). For example, Weak Encounters will never result in a Major Incident or Hazardous Accident and Extreme Encounters will never result in a Minor Incident. The values in Table A-3 are elicited through expert judgment [61]. Further study on appropriate values in the Table A-3 is recommended.

Table A-3 Transition Probability Matrix (individual elements are denoted by eg $P_{T\,(A \rightarrow B)}$)

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

The risk metrics to be characterized are:

1. Probability p^{ij}_{MinInc} of a minor incident of aircraft *i* (induced by the vortices of aircraft *j*).
2. Probability p^{ij}_{MajInc} of a major incident of aircraft *i* (induced by the vortices of aircraft *j*).
3. Probability p^{ij}_{HazAcc} of a hazardous accident of aircraft *i* (induced by vortices of aircraft *j*.)
4. Probability p^{ij}_{CatAcc} of a catastrophic accident of aircraft *i* (induced by vortices of aircraft *j*).

Let's start with the characterization of *catastrophic accident risk*. As long as the aircraft *i* encountering the vortices of aircraft *j* is able to maintain position above ground, there will be no reason for a catastrophic accident. Or, the maximum height loss of aircraft *i* shall be less than its initial encounter height. Let h^i_t denote the height of aircraft *i* during the encounter. Then

$$p^{ij}_{CatAcc} \equiv 1 - \Pr\left\{ h^i_t > 0, \forall t \right\} \tag{A-24}$$

The *instantaneous catastrophic accident risk* (in terms of probability at moment t) is defined as

$$p^{ij}_{CatAcc}\left(t\right) \equiv \Pr\left\{ h^{\mathrm{i}}_{\mathrm{t}} = 0 \right\} \tag{A-25}$$

Evaluation yields

$$p^{ij}_{CatAcc}\left(t\right) = 1 - \int_{h=0}^{\infty} p_{h^i_t}(\mathrm{h})\, dh \qquad \text{(A-26)}$$

where $p_{h^i_t}\left(h\right)$ denotes the density of $h^i{}_t$.

To evaluate *catastrophic accident risk* in terms of probability per movement, the instantaneous risk is integrated over the entire aircraft movement (e.g. approach or departure):

$$p^{ij}_{CatAcc} = \frac{1}{T_{mov}} \int_0^{T_{mov}} p^{ij}_{CatAcc}(t)\, dt \qquad \text{(A-27)}$$

where T_{mov} denotes the time-duration of the aircraft movement (e.g. approach or departure).

Alternatively, it is also possible to evaluate the catastrophic accident per movement through the use of the *maximum* instantaneous risk over the entire aircraft movement, i.e.

$$\bar{p}^{\,ij}_{CatAcc} = \max_t \; p^{ij}_{CatAcc}\left(t\right) \qquad \text{(A-28)}$$

The subsequent characterization for *minor incidents, major incidents,* and *hazardous accidents* follows a similar approach, but is however based on a two-dimensional requirement on the bank angle and the height loss of aircraft *i* during the encounter. Since these two stochastic variables are dependent, their joint probability density function is used. The encounter severity classification scheme defined in section A.6 is also used to assess the other three risk metrics.

Let's proceed with the characterization of *minor incident risk*. Provided that the aircraft is able to maintain position above the ground, it is now assumed that a *weak encounter* or a *moderate encounter* might lead to a *minor incident*. Let $\bar{\phi}_{WeakEnc}(h)$, $\bar{\phi}_{ModEnc}(h)$ and $\bar{\phi}_{SevEnc}(h)$ denote the height dependent threshold boundaries of the weak encounter class, then equation (A-29) is:

$$\begin{aligned} p^{ij}_{MinInc} \equiv\; & P_{T(WEAK\rightarrow MINOR)} \Pr\left\{ \exists\; t : \{ \bar{\phi}_{WeakEnc}(\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) < \left|\phi^i_t\right| < \bar{\phi}_{\mathrm{ModEnc}}(\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) \} \cap \{ \mathrm{h}^{\mathrm{i}}_{\mathrm{s}} > 0, \forall s \} \right\} \\ & + P_{T(MOD\rightarrow MINOR)} \Pr\left\{ \exists\; t : \{ \bar{\phi}_{ModEnc}(\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) < \left|\phi^i_t\right| < \bar{\phi}_{\mathrm{SevEnc}}(\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) \} \cap \{ \mathrm{h}^{\mathrm{i}}_{\mathrm{s}} > 0, \forall s \} \right\} \end{aligned}$$

The *instantaneous minor incident risk* (in terms of probability at moment t) is defined as (A-30):

$$p^{ij}_{MinInc}\ (t) \equiv P_{T(WEAK\rightarrow MINOR)}\ \Pr\left\{\{\bar{\phi}_{WeakEnc}(h^i_t) < \left|\phi^i_t\right| < \bar{\phi}_{ModEnc}(h^i_t)\} \cap \{h^i_s > 0, \forall s\}\right\} + P_{T(MOD\rightarrow MINOR)}\ \Pr\left\{\{\bar{\phi}_{ModEnc}(h^i_t) < \left|\phi^i_t\right| < \bar{\phi}_{SevEnc}(h^i_t)\ \} \cap \{h^i_s > 0, \forall s\}\ \right\}$$

Evaluation yields

$$p^{ij}_{MinInc}\ (t)\ = P_{T(WEAK\rightarrow MINOR)} \int_{h=0}^{\infty} \int_{\phi=\bar{\phi}_{WeakEnc}(h)}^{\bar{\phi}_{ModEnc}(h)} p_{h^i_t,\phi^t_i}(h,\phi)d\phi dh + P_{T(MOD\rightarrow MINOR)} \int_{h=0}^{\infty} \int_{\phi=\bar{\phi}_{ModkEnc}(h)}^{\bar{\phi}_{SevEnc}(h)} p_{h^i_t,\phi^t_i}(h,\phi)d\phi dh \tag{A-31}$$

where $p_{h^i_t,\phi^i_t}(h,\phi)$ denotes the joint density of *(h,ϕ)*, $p_{h^i_t}(h)$ denotes the marginal density function of the height $h^i{}_t$ and $p_{\phi^i_t}(\phi)$ denotes the marginal density function of bank angle $\phi^i{}_t$.

To evaluate *minor incident risk* in terms of probability per movement, the instantaneous risk is integrated over the entire aircraft movement (e.g. approach or departure):

$$p^{ij}_{MinInc} = \frac{1}{T_{mov}} \int_0^{T_{mov}} p^{ij}_{MinInc}(t)\, dt \tag{A-32}$$

where T_{mov} denotes the time-duration of the aircraft movement (e.g. approach or departure).

From a *minor incident* point of view, the critical moment in time and the associated point along the aircraft flight path are defined via:

$$\hat{t}^{ij}_{MinInc} = \arg\max_t\ p^{ij}_{MinInc}(t) \tag{A-33}$$

Let's proceed with the characterization of *major incident risk*. Provided that the aircraft is able to maintain position above the ground, it is now assumed that a *moderate, severe or extreme encounter* might lead to a *major incident*. Let $\bar{\phi}_{ModEnc}(h)$, $\bar{\phi}_{SevEnc}(h)$ and $\bar{\phi}_{ExtEnc}(h)$ denote the height dependent threshold boundaries of the associated encounter classes, then (A-34) is:

$$p^{ij}_{MajInc} \equiv P_{T(WEAK\rightarrow MAJOR)}\ \Pr\left\{\exists\ t\ :\{\bar{\phi}_{ModEnc}\ (\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) < \left|\phi^i_t\right| < \bar{\phi}_{\mathrm{SevEnc}}\ (\mathrm{h}^{\mathrm{i}}_{\mathrm{t}})\} \cap \{\mathrm{h}^{\mathrm{i}}_{\mathrm{s}} > 0, \forall s\}\ \right\} + P_{T(SEV\rightarrow MAJOR)}\ \Pr\left\{\exists\ t\ :\{\bar{\phi}_{SevEnc}\ (\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) < \left|\phi^i_t\right| < \bar{\phi}_{\mathrm{ExtEnc}}\ (\mathrm{h}^{\mathrm{i}}_{\mathrm{t}})\} \cap \{\mathrm{h}^{\mathrm{i}}_{\mathrm{s}} > 0, \forall s\}\right\} + P_{T(EXT\rightarrow MAJOR)}\ \Pr\left\{\exists\ t\ :\{\bar{\phi}_{ExtEnc}\ (\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) < \left|\phi^i_t\right|\} \cap \{\mathrm{h}^{\mathrm{i}}_{\mathrm{s}} > 0, \forall s\}\ \right\}$$

The *instantaneous major incident risk* (in terms of probability at moment t) is defined as (A-35):

$$\begin{aligned} p^{ij}_{MajInc}(t) \equiv\ & P_{T(MOD\rightarrow MAJOR)}\ \Pr\left\{\{\bar{\phi}_{ModEnc}(h^i_t) < \left|\phi^i_t\right| < \bar{\phi}_{SevEnc}(h^i_t)\} \cap \{h^i_s > 0, \forall s\}\right\} \\ & + P_{T(SEV\rightarrow MAJOR)}\ \Pr\left\{\{\bar{\phi}_{SevEnc}(h^i_t) < \left|\phi^i_t\right| < \bar{\phi}_{ExtEnc}(h^i_t)\} \cap \{h^i_s > 0, \forall s\}\right\} \\ & + P_{T(EXT\rightarrow MAJOR)}\ \Pr\left\{\{\bar{\phi}_{ExtEnc}(h^i_t) < \left|\phi^i_t\right|\ \} \cap \{h^i_s > 0, \forall s\}\right\} \end{aligned}$$

Evaluation yields

$$\begin{aligned} p^{ij}_{MajInc}(t) = & P_{T(MOD\rightarrow MAJOR)} \int_{h=0}^{\infty} \int_{\phi=\bar{\phi}_{ModEnc}(h)}^{\bar{\phi}_{SevEnc}(h)} p_{h^i_t,\phi^t_i}(h,\phi)\,d\phi\,dh \\ & + P_{T(SEV\rightarrow MAJOR)} \int_{h=0}^{\infty} \int_{\phi=\bar{\phi}_{SevEnc}(h)}^{\bar{\phi}_{ExtEnc}(h)} p_{h^i_t,\phi^t_i}(h,\phi)\,d\phi\,dh \\ & + P_{T(EXT\rightarrow MAJOR)} \int_{h=0}^{\infty} \int_{\phi=\bar{\phi}_{ExtEnc}(h)}^{\infty} p_{h^i_t,\phi^t_i}(h,\phi)\,d\phi\,dh \end{aligned} \qquad \text{(A-36)}$$

where $p_{h^i_t,\phi^i_t}(h,\phi)$ denotes the joint density of *(h,ϕ)*, $p_{h^i_t}(h)$ denotes the marginal density function of the height h^i_t and $p_{\phi^i_t}(\phi)$ denotes the marginal density function of bank angle ϕ^i_t.

To evaluate *major incident risk* in terms of probability per movement, the instantaneous risk is integrated over the entire aircraft movement (e.g. approach or departure):

$$p^{ij}_{MajInc} = \frac{1}{T_{mov}} \int_0^{T_{mov}} p^{ij}_{MajInc}(t)\,dt \qquad \text{(A-37)}$$

where T_{mov} denotes the time-duration of the aircraft movement (e.g. approach or departure).
From a *major incident* point of view, the critical moment in time and the associated point along the aircraft flight path are defined via:

$$\hat{t}^{ij}_{MajInc} = \arg\max_t\ p^{ij}_{MajInc}(t) \qquad \text{(A-38)}$$

Let’s proceed with the characterization of *hazardous accident risk*. Provided that the aircraft is able to maintain position above the ground, it is now assumed that a *severe* or *extreme encounter* might lead to a *hazardous accident*. Let $\bar{\phi}_{SevEnc}(h)$ and $\bar{\phi}_{ExtEnc}(h)$ denote the height dependent threshold boundaries of the associated encounter classes, then equation (A-39) is:

$$\begin{aligned} p^{ij}_{HazAcc} \equiv\ & P_{T(SEV \to HAZARDOUS)} \Pr\left\{ \exists\ t : \{ \bar{\phi}_{SevEnc}(\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) < \left|\phi^i_t\right| < \bar{\phi}_{\mathrm{ExtEnc}}(\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) \} \cap \{ \mathrm{h}^{\mathrm{i}}_{\mathrm{s}} > 0, \forall s \} \right\} \\ & + P_{T(EXT \to HAZARDOUS)} \Pr\left\{ \exists\ t : \{ \bar{\phi}_{ExtEnc}(\mathrm{h}^{\mathrm{i}}_{\mathrm{t}}) < \left|\phi^i_t\right| \} \cap \{ \mathrm{h}^{\mathrm{i}}_{\mathrm{s}} > 0, \forall s \} \right\} \end{aligned}$$

The *instantaneous hazardous accident risk* (in terms of probability at moment t) is defined as

$$\begin{aligned} p^{ij}_{HazAcc}(t) \equiv\ & P_{T(SEV \to HAZARDOUS)} \Pr\left\{ \{ \bar{\phi}_{SevEnc}(h^i_t) < \left|\phi^i_t\right| < \bar{\phi}_{ExtEnc}(h^i_t) \} \cap \{ h^i_s > 0, \forall s \} \right\} \\ & + P_{T(EXT \to HAZARDOUS)} \Pr\left\{ \{ \bar{\phi}_{ExtEnc}(h^i_t) < \left|\phi^i_t\right| \} \cap \{ h^i_s > 0, \forall s \} \right\} \end{aligned} \tag{A-40}$$

Evaluation yields

$$\begin{aligned} p^{ij}_{HazAcc}(t) = & P_{T(SEV \to HAZARDOUS)} \int_{h=0}^{\infty} \int_{\phi=\bar{\phi}_{SevEnc}(h)}^{\bar{\phi}_{ExtEnc}(h)} p_{h^i_t, \phi^t_i}(h,\phi)\, d\phi\, dh \\ & + P_{T(EXT \to HAZARDOUS)} \int_{h=0}^{\infty} \int_{\phi=\bar{\phi}_{ExtEnc}(h)}^{\infty} p_{h^i_t, \phi^t_i}(h,\phi)\, d\phi\, dh \end{aligned} \tag{A-41}$$

where $p_{h^i_t, \phi^i_t}(h,\phi)$ denotes the joint density of *(h,ϕ)*, $p_{h^i_t}(h)$ denotes the marginal density function of the height $h^i{}_t$ and $p_{\phi^i_t}(\phi)$ denotes the marginal density function of bank angle $\phi^i{}_t$.

To evaluate *hazardous accident risk* in terms of probability per movement, the instantaneous risk is integrated over the entire aircraft movement (e.g. approach or departure):

$$p^{ij}_{HazAcc} = \frac{1}{T_{mov}} \int_0^{T_{mov}} p^{ij}_{HazAcc}(t)\, dt \tag{A-42}$$

where T_{mov} denotes the time-duration of the aircraft movement (e.g. approach or departure). From a *hazardous accident* point of view, the critical moment in time and the associated point along the aircraft flight path are defined via:

$$\hat{t}^{ij}_{HazAcc} = \arg\max_t\, p^{ij}_{HazAcc}(t) \tag{A-43}$$

Acronyms and abbreviations

A320	Airbus A320
AGARD	Advisory Group for Aerospace Research and Development
AIAA	American Institute of Aeronautics and Astronautics
AIP	Aeronautical Information Publication
ALARP	As Low As Reasonably Practicable
AMAAI	Aircraft Models for Analysis of (ADS-B based) In-trail following
AMJ	Advisory Material Joint
ATC	Air Traffic Control
ATCO	Air Traffic COntroller
ATCOD	Air Traffic COntrol incident Database
ATC-WAKE	Air Traffic Control Wake Vortex Safety and Capacity System
ATFM	Air Traffic Flow Management
ATIO	Aviation Technology, Integration and Operations
ATM	Air Traffic Management
AOM	Aircraft Operational Manual
AVOSS	Aircraft Vortex Spacing System
AWOP	All Weather Operations Panel
B707	Boeing 707
B737	Boeing 737
B747	Boeing 747
BA	British Airways
BADA	Base of Aircraft Data
BKN	Altitude at which the clouds are broken
C172	Cessna 172
CV990	Convair 990
CAA	Civil Aviation Authorities
CBA	Cost Benefit Analysis
CAT	Category
CFIT	Controlled Flight Into Terrain
COP	Climb Out Point
CR	Contract Report
CRM	Collision Risk Model
CROSS	Control, Risk, Optimization, Stochastics and Systems
CRT	Collision Risk Tree
DA	Decision Altitude
DASC	Digital Avionics Systems Conference

DCIA	Dependent Converging Instrument Approaches
DCPN	Dynamically Coloured Petri Net
DH	Decision Height
DNV	Det Norske Veritas
DOT	U.S. Department of Transportation
DP	Deceleration Point
DTOP	Dual Threshold OPeration
DWA	Detection, Warning, and Avoidance
EC	European Commission
ECAC	European Civil Aviation Conference
EDR	Eddy Dissipation Rate
ERCR	Extended Roll Control Ratio
ESARR	EUROCONTROL Safety Regulatory Requirements
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
ETWIRL	European Turbulent Wake Reporting Log
EUROCONTROL	European Organisation for the Safety of Air Navigation
F50	Fokker 50
F86	North American F-86 Sabre
F100	Fokker 100
FAA	Federal Aviation Administration
FAC	Follower Aircraft
FANOMOS	Flight track and Aircraft Noise Monitoring System
FAP	Final Approach Point
FAR	Federal Aviation Regulations
FAS	Final Approach Speed
FCOM	Flight Crew Operational Manual
FDR	Flight Data Recorder
FHA	Functional Hazard Assessment
FL	Flight Level
FMAA	Final Missed Approach Altitudes
FMEA	Failure Mode and Effects Analysis
FMS	Flight Management System
FORTRAN	Formula Translation/Translator
FTA	Fault Tree Analysis
GND	Ground controller
GS	Glide Slope
HALS	High Approach Landing System

HDB	Heathrow Data Base
HMI	Human Machine Interface
IASC	International Aviation Safety Conference
ICAO	International Civil Aviation Organization
ICAS	International Congress of Aeronautical Sciences
IF	Intermediate Fix
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IST	Information Society Technologies
ISTaR	Information System for Safety and Risk analysis
I-WAKE	Instrumentation for on-board wake vortex DWA
JAA	Joint Aviation Authorities
JAR	Joint Aviation Requirements
KLM	Koninklijke Luchtvaart Maatschappij
LAC	Leader Aircraft
LiDAR	Light Detection And Ranging system
LOC	Localizer
LOP	Lift Off Point
LVNL	Lucht Verkeersleiding Nederland
MA	Missed Approach
MAG	Magnetometer Instrument
MAPt	Missed Approach Point
MTOW	Maximum Take Off Weight
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATS	National Air Traffic Services Ltd.
ND	Navigation Display
NM	Nautical Mile
NLR	National Aerospace Laboratory
NTZ	No Transgression Zone
NPA	Non Precision Approach
OCA	Obstacle Clearance Altitude
OCP	Obstacle Clearance Panel
OM	Outer Marker
PANS-ATM	Procedures for Air Navigation Services – Air Traffic Management
PANS-OPS	Procedures for Air Navigation Services – Operations
PFD	Primary Flight Display

PRM	Precision Runway Monitor
PSA	Probabilistic Safety Assessment
QSA	Qualitative Safety Assessment
R/T	Radio / Telephony
R&D	Research and Development
RAPM	Reduced Aircraft Pilot Model
RASMAR	Risk Analysis of Simultaneous MAs on converging Runways 19R/22
RCR	Roll Control Ratio
RDH	Reference Datum Height
RGCSP	Review of the General Concept of Separation Panel
RMS	Root Mean Square
ROT	Runway Occupancy Time
RVSM	Reduced Vertical Separation Minimum
RWY	Runway
SID	Standard Instrument Departure
SW II	Swearingen Metro II
SRC	Safety Regulatory Commission
SRD	Single Runway Departures
TAS	True Air Speed
TCAS	Traffic Collision Avoidance System
THR	Runway Threshold
TLS	Target Level of Safety
TMA	Terminal Manoeuvring Area
TOL	Take Off Length
TOP	Take Off Position
TOPAZ	Traffic Organization and Perturbation AnalyZer
TP	Turning Point
TWR	Tower Controller
UK	United Kingdom
USA	United States of America
VFR	Visual Flight Rules
WAVENC	Wake Vortex Evolution and Wake Vortex Encounter
WAVENDA	Wake Vortex ENcounter Detection Algorithm
WAVIR	WAke Vortex Induced Risk assessment
WV	Wake Vortex
WVBC	Wake Vortex Behavior Classes
WVE	Wake Vortex Encounter
WVV	Wake Vortex Vector

Articles and Conferences

All the work presented in the doctoral thesis of Mr. Speijker has been carried out under contract to and/or with key customers of National Aerospace Laboratory NLR. The results have been published and presented at various conferences in the field of aviation safety and risk analysis. The customers have all granted NLR permission to publish the results. The details and acknowledgements to the co-authors of the technical publications are provided in the following.

Section 2 has been carried out under contracts awarded by the Civil Aviation Authorities the Netherlands over the period 1995 – 1997. This study was published by NLR as TP-97183, entitled *"Collision risk related to the usage of parallel runways for landing"*, with authors *L.J.P. Speijker, M.J.H. Couwenberg, H.W. Kleingeld†* [2]. The study was presented by Mr. Speijker at the International Aviation Safety Conference (IASC 1997), Rotterdam, 27 - 29 August 1997.

Section 3 has been carried out under the RASMAR contract awarded by the Civil Aviation Authorities the Netherlands. This study was published by NLR as TP-2000-644, entitled *"Risk analysis of simultaneous missed approaches on Schiphol converging runways 19R and 22"*, with authors *L.J.P. Speijker, H.A.P. Blom, G.J. Bakker, A.K. Karwal, G.B. van Baren, M.B. Klompstra, E.A.C. Kruijsen* [2]. The study was presented by Mr. Speijker at the 6th International Conference on Probabilistic Safety Assessment and Management (PSAM6) [8].

Section 4 is based on work carried out under the S-Wake contract awarded by the European Commission (EC), contract number G4RD-CT-1999-00099. This study was also published by NLR as TP-2003-248, entitled *"S-Wake Final Report for Work Package 4, Probabilistic Safety Assessment"*, with author *L.J.P. Speijker* [10]. Part of the S-Wake study has also been presented at the 22nd International Congress of Aeronautical Sciences (ICAS 2000), in Harrogate, and the 23rd Digital Avionics Systems Conference (DASC 2004), Salt Lake City, Utah.

Section 5 is based on work carried out under the ATC-Wake contract awarded by the European Commission (EC), project number IST-2001-34729. A summary paper has been published by NLR as TP-2006-465 for the ESREL 2006 (in the Proceedings as *"Safety assessment of ATC-Wake single runway departures"*, with authors *L.J.P. Speijker, A. Vidal, and R.M. Cooke* [56]). The ATC-Wake results will also be published in the *Journal of Air Traffic Control*.

Section 6 results from work carried out as part of the NLR basic research programme, on the basis of the final results of the I-Wake contract awarded by the European Commission (EC), under contract number G4RD-CT-2002-00778. A summary paper has been published by NLR as TP-2006-532, entitled *"Safety assessment of the I-Wake single runway arrival operation with reduced separation"*, with authors *L.J.P. Speijker, G.B. van Baren, R.M. Cooke* [21].

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In my first five years of NLR, from 1996 onwards, I have started with the realization of the NLR Information System for SafeTy and Risk analysis (ISTaR), a software working environment for the quantitative safety assessment of newly proposed flight procedures. The full realization of ISTaR would however not have been possible without Gerben van Baren who, from 2000 onwards, has helped me with the implementation of the various mathematical risk assessment models. This enabled me to focus on the conceptual issues involved in the development of the risk assessments. Also, it made it possible for me to acquire and manage the ATC-Wake project, which was supported by some key project members, including Gerben van Baren, Theo Verhoogt, and Antoine Vidal. Geert Moek and Henk Blom have provided some very valuable insights into the mathematical details related to stochastic modeling of ATM operations. This work would also not have been possible without the NLR operational experts. Without the valuable comments and feedback of e.g. Marijn Giesberts, Henk Kleingeld, Arun Karwal, Peter van der Geest, and Gerard van Es, the conclusions and recommendations of the work contained in this doctoral thesis would have looked different. The numerous talks with Marijn Giesberts on the practical usefulness of research results have changed my view on R&D.

Also, I should mention that during the course of my activities at NLR, I have learned that there almost always seems to be a motivation and rationale for further improvements towards an even better validated model. The use of data gathered during measurement campaigns and through flight tests has an attractiveness that cannot be underestimated.

I would like to thank NLR, the Dutch government, European Commission, EUROCONTROL, NASA, and Delft University of Technology for helping me with this work, and for giving me the chance to perform safety research for several years. Last but not least, I am thankful to all my personal friends and family, who have always kept believe that the finalization of this Doctoral thesis would ‘at some point in time and space’ become reality. During the last couple of years, I have realized that a positive attitude towards life helps to survive even the highest barriers and mountains imaginable.

Curriculum Vitae

Lennaert Speijker was born on June 12th 1967 in Haarlem, Netherlands. He studied Mathematical Engineering at the Delft University of Technology, where he graduated in 1995 in the Faculty of Control Risk, Optimization, Stochastics and Systems theory (CROSS). His final Master of Science thesis on “Optimal maintenance decisions for dikes”, given risk requirements on the probability of flooding, was carried out at Delft Hydraulics under the supervision of Jan van Noortwijk and Roger Cooke [1]. The results were published in the Journal “Probability in the Engineering and Informational Sciences” [5]. This made him very clear that the field of risk analysis and safety was by far the most interesting. He then joined National Aerospace Laboratory NLR, where he started to work on the development and application of mathematical models to assess the safety of civil aviation. Under supervision of Roger Cooke, he has completed this doctoral thesis with the aim to provide the aviation community with evidence and argumentation to support the safe introduction of reduced aircraft separation in the airport environment. In recent years, following the ‘9/11’ terrorist attacks on the New York Twin Towers, he has focused on air transport security research and development. In this area, he has worked on regulatory issues, threat assessments, and validation of new security systems and concepts to improve in-flight security [18, 19]. At present, he is working as a Senior R&D Manager in the NLR Air Transport Safety Institute.

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