Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Safety assessment of a single runway arrival procedure for aircraft equipped with a wake vortex detection, warning and avoidance system

Problem area
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. A potential improvement of wake vortex safety is through installation /use of a Wake Vortex Detection, Warning and Avoidance (WV DWA) system on-board aircraft.

Description of work
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. The I-Wake system is proposed as a safety net in support of ATC decided reduced separation. A single runway arrival procedure for aircraft equipped with a WV DWA system 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. This study has *quantified* wake vortex induced risk through the use of the WAVIR methodology, extended with an aircraft/pilot missed approach model and a causal model for the WV DWA system failure probability. The assessment of wake induced risk levels for the approach phase when reduced aircraft separation 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 WV DWA system capabilities.

Results and conclusions
The use of a WV DWA system 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. Therefore, WV DWA use would be most beneficial at low altitudes, where a rebounding wake might be present. Note that for wake vortex safety reasons initiation of a missed approach is not recommendable at low altitudes.

Applicability
Based on the above, the use of a WV DWA seems to have only minor impact on the wake vortex induced risk during single runway arrivals. A WV DWA system is mainly applicable as safety net in support of reduced separation.

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Safety assessment of a single runway arrival procedure for aircraft equipped with a wake vortex detection, warning and avoidance system

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Safety assessment of a single runway arrival procedure for aircraft equipped with a wake vortex detection, warning and avoidance system

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Summary

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. A potential improvement of wake vortex safety is through installation and use of a wake vortex detection, warning, and avoidance system on-board aircraft.

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. The I-Wake system is proposed as a safety net in support of ATC decided reduced separation, intended for protection along the glide path from ILS/GS intercept. A single runway arrival procedure that is designed for aircraft equipped with a WV DWA system 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. This study has *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 WV DWA system failure probability. The assessment of wake induced risk levels for the approach phase when reduced aircraft separation 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 WV DWA system capabilities (such as the horizontal and vertical scanning view, the angle of regard, the wake vortex detection range).

The use of a WV DWA 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. Therefore, WV DWA use would be most beneficial at low altitudes, where the probability of encountering a (rebounding) wake is highest. Note that for wake vortex safety reasons initiation of a missed approach is not recommendable at low altitudes. Based on the above, the operational use of a WV DWA seems to have only minor impact on the wake vortex induced risk during single runway arrivals. A WV DWA is mainly applicable as safety net in support of ATC decided reduced separation

Contents

Abbreviations

ATC	Air Traffic Control
ATC-WAKE	Integrated ATC Wake Vortex Safety and Capacity System (EU project)
COP	Climb Out Point
CRM	Collision Risk Manual
DH	Decision Height
DP	Deceleration Point
DWA	Detection, Warning, and Avoidance
EC	European Commission
EDR	Eddy Dissipation Rate
ERCR	Extended Roll Control Ratio
FAC	Follower Aircraft
FAP	Final Approach Point
FAS	Final Approach Speed
FHA	Functional Hazard Assessment
GS	Glide Slope
GUI	Graphical User Interface
ICAO	International Civil Aviation Organization
IF	Intermediate Fix
ILS	Instrument Landing System
I-WAKE	Instrumentation for on-board wake vortex DWA (EU project)
LAC	Leader Aircraft
LiDAR	Light Detection and Ranging
ND	Navigation Display
NLR	Netherlands National Aerospace Laboratory
NM	Nautical Mile
OM	Outer Marker
PFD	Primary Flight Display
RAPM	Reduced Aircraft Pilot Model
RDH	Reference Datum Height
TAS	True Air Speed
THR	Runway Threshold
UK MO	United Kingdom Meteorological Office
WAVIR	Wake Vortex Induced Risk assessment methodology
WV	Wake Vortex

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. 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. The I-Wake system is proposed as a safety net in support of ATC decided reduced separation, intended for protection along the glide path from ILS/GS intercept [10]. An I-Wake system could be useful as safety net in case reduced separation is applied, e.g. through use of ATC-Wake with reduced wake vortex separation in case of crosswind [8, 9, 10].

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. Although it is foreseen to use I-Wake as safety net in combination with ATC decided reduced separation [10], this study assumes that a WV DWA is used as a standalone system. A specific objective is to support the setting of requirements for the use of a WV DWA. Aspects to be considered are e.g. the time for caution and alert and WV DWA 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 a WV DWA single runway arrival procedure with reduced separation, there are three main issues to consider:

- If one or more WV DWA 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 WV DWA warning/alert is raised. Usually, the pilot will initiate a missed approach and/or turn away from the wake vortices detected by the WV DWA 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.

Section 2 describes the WV DWA single runway arrival procedure, for which an assessment of wake vortex induced risk levels will be provided. Section 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 WV DWA system failure probability. The simulation scenarios are specified in Section 4. Risk assessment results are presented and discussed in Section 5. Finally, Section 6 provides the conclusions and recommendations.

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 2-1).

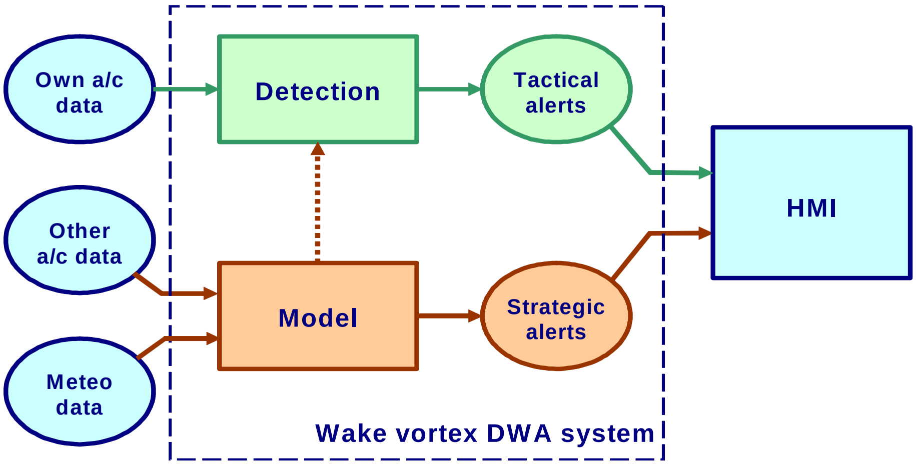

Figure 2-1 Schematic representation of the main functions of the WV DWA system

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

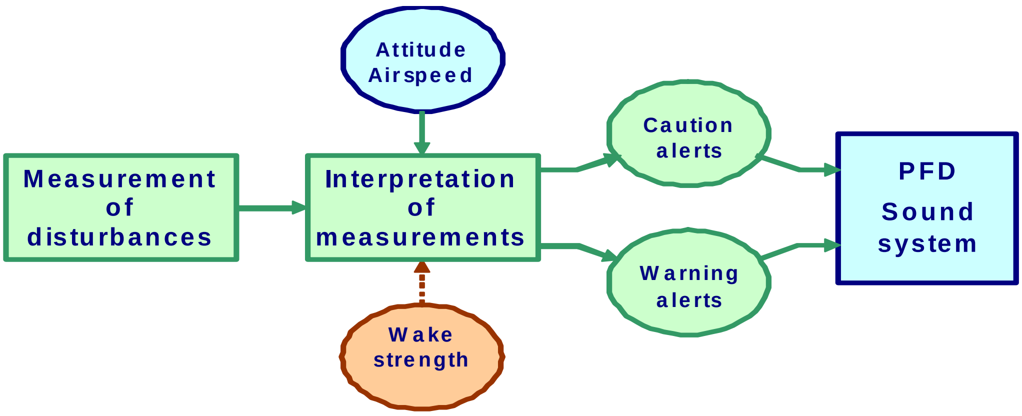

Figure 2-2 Schematic representation of the tactical wake vortex DWA function

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 2-3.

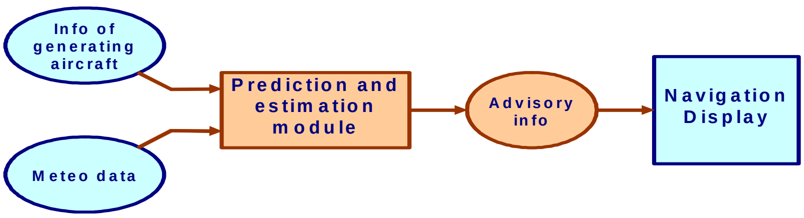

Figure 2-3 Schematic representation of the strategic wake vortex DWA function

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. I-Wake is foreseen as safety net in combination with ATC decided reduced separation [10].

3 Risk assessment methodology

3.1 General approach

This Section provides the risk assessment methodology for assessment of wake induced risk levels for the WV DWA 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 WV DWA single runway arrival operation with reduced separation, there are three main issues to consider:

- If one or more WV DWA 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 WV DWA warning/ alert is raised. Usually, the pilot will initiate a missed approach and/or turn away from the wake vortices detected by the WV DWA 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.

The risk assessment methodology will integrate the ‘classical’ WAVIR methodology with a missed approach model and a causal model for the WV DWA system failure probability. The 'classical' WAVIR methodology, which originates from S-Wake [1, 2, 7], 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.

3.2 Wake vortex detection, warning, and avoidance probability

De Jong et al. [3] provides a Functional Hazard Assessment (FHA) of the WV DWA system used in conjunction with a ground based ATC-Wake system [8, 9] during the approach phase of flight. The FHA revealed a number of possible consequences of (failures) of a DWA system:

- Unexpected encounter of a wake vortex;
- 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*" (the other events would either have no or minor immediate impact on safety. The "unexpected encounter of a wake vortex" will therefore be used as basis for the construction of a causal model to assess the on-board WV DWA failure probability. The core of this causal model is based on a failure of one or more of the WV DWA system components, including the performance of the on-board LiDAR system itself (field of view, angle of regard, detection distance). The resulting causal model, explaining the dependencies between the main influencing factors, is sketched in Figure 3-1.

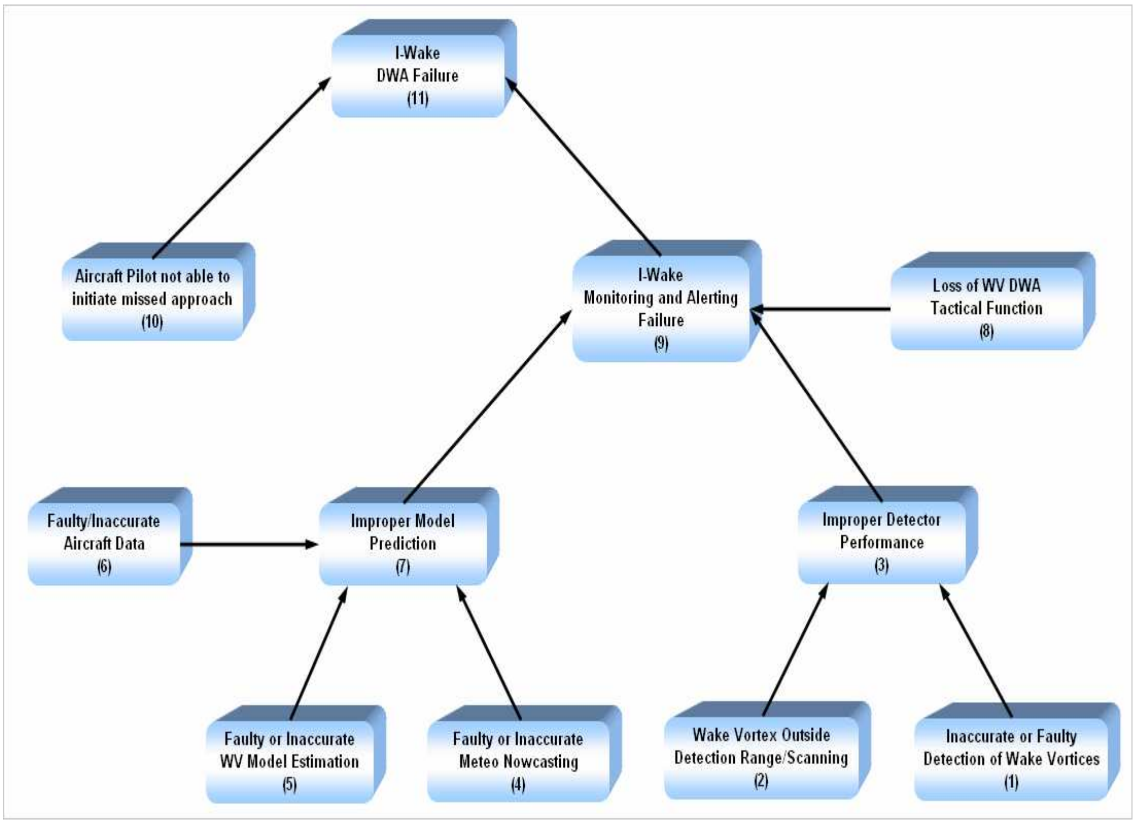

Figure 3-1 Causal model for the I-Wake system/operation

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.

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 WV DWA 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 [4]:

$$\frac{\gamma(s)}{\theta(s)} = \frac{g/_{v}\, n_{\alpha}}{s + g/_{v}\, n_{\alpha}} \qquad (3\text{-}1)$$

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" [4]. It can be approximated by:

$$n_{\alpha} = \frac{C_{L_{\alpha}}}{C_L} \qquad (3\text{-}2)$$

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

$$C_L = \frac{mg}{\frac{1}{2}\rho v^2 S} \qquad (3\text{-}3)$$

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) [5]:

$$\frac{\theta(s)}{\delta_e(s)} = K_Q \frac{\omega^2}{s^2 + 2\zeta\,\omega s + \omega^2} \quad \text{, with} \quad \omega = \sqrt{\frac{M_S C_{L_{\alpha}} g}{C_L I_R^2\, \bar{c}}} \qquad (3\text{-}4)$$

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

$$T_{MA\ curve} = \frac{\theta_{COP} - \theta_{MAP}}{q} \qquad (3\text{-}5)$$

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.

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 $[\, x_{\min}^{DET}, \mathrm{x}_{\max}^{DET}\,]$, where $x_{\min}^{DET}$ denotes the minimum detection distance and $\mathrm{x}_{\max}^{DET}$ 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 $[\, \mathrm{x}_{\mathrm{t}}^{\mathrm{i}} \in x_{\min}^{DET}, \mathrm{x}_{\max}^{DET}\,]$ 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 WV DWA 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 3.3.

The risk assessment model is integrated within the NLR WAke Vortex Induced Risk assessment (WAVIR) toolset. Figure 3-2 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.

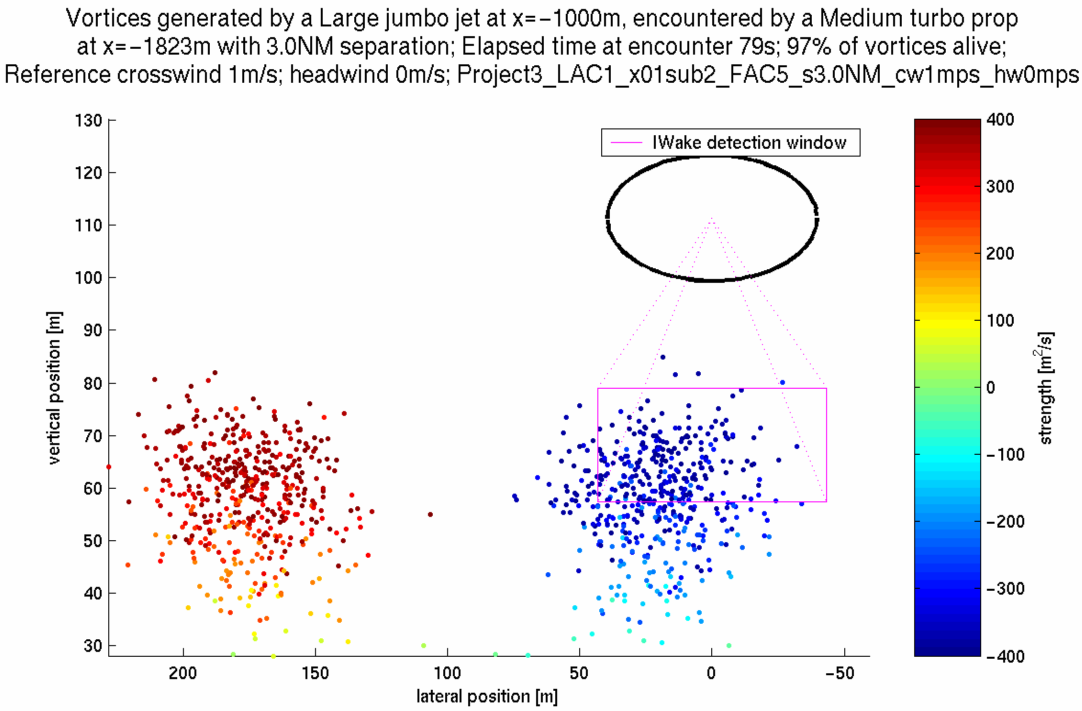

Figure 3-2 Simulated wake vortex positions and strengths, 90 % confidence interval about the aircraft position (circle) and scanning window at the gate where alert should be given

Figure 3-3 shows the WAVIR Graphical User Interface (GUI) dedicated to the specification of the parameters for the assessment of the WV DWA 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 study (an up-to-date WAVIR User Manual is available via NLR).

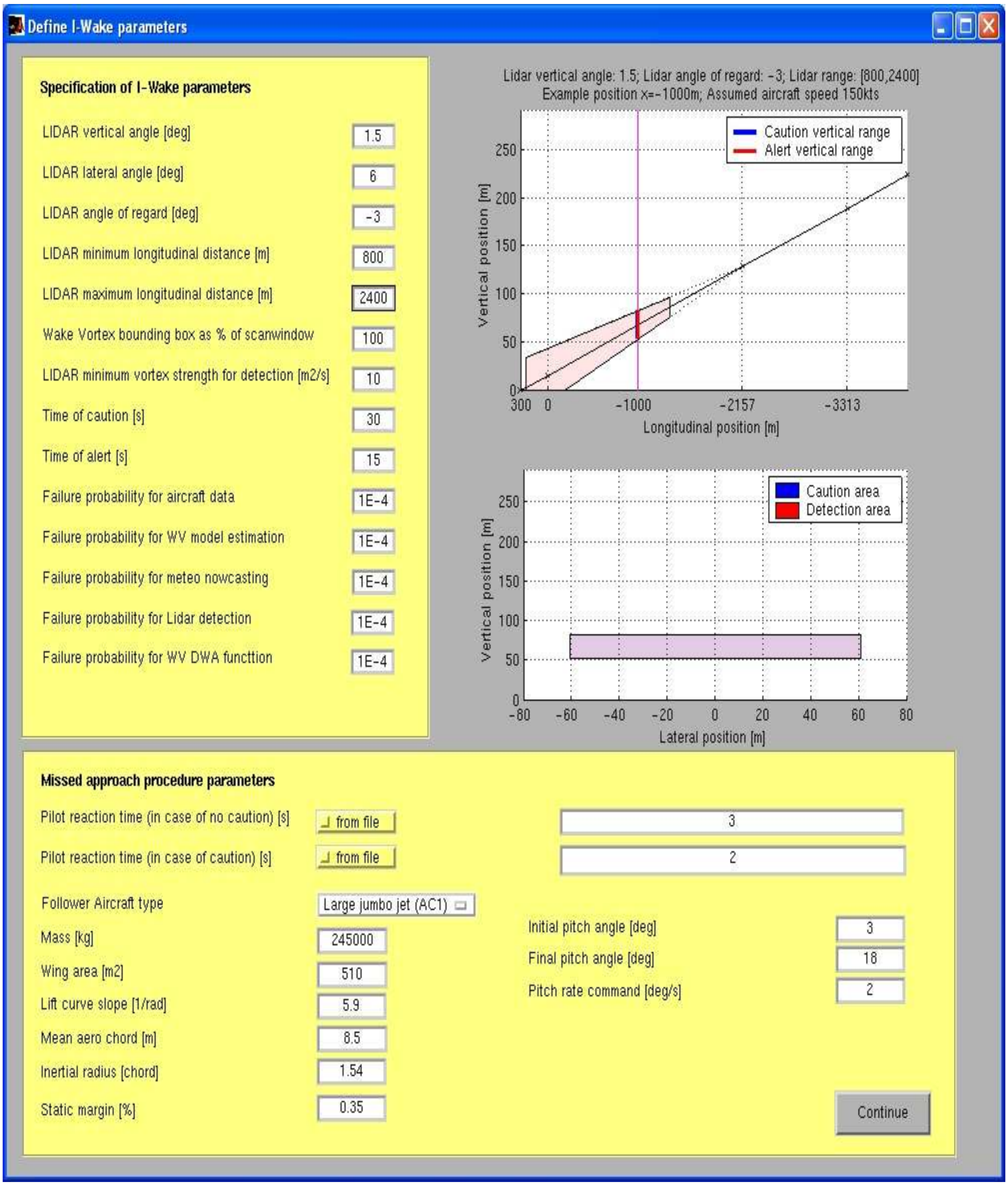

Figure 3-3 WAVIR Graphical User Interface for the specification of I-Wake parameters

4 Description of scenarios

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 WV DWA 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.

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 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 4-1. 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 3.3).

Table 4-1 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 4-1):

- 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.

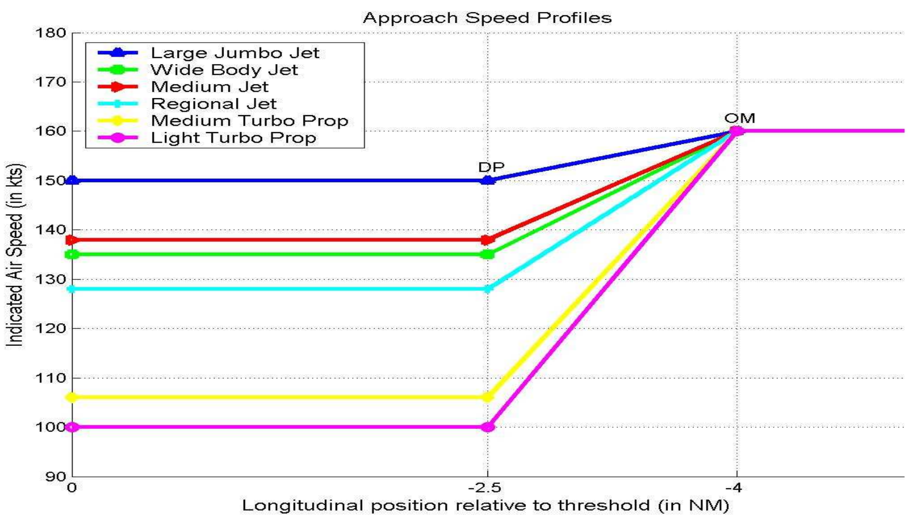

Figure 4-1 Nominal approach speed profiles

Analysis of wake vortex induced risk is done in the longitudinal positions listed in Table 4-2.

Table 4-2 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 4-3 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).

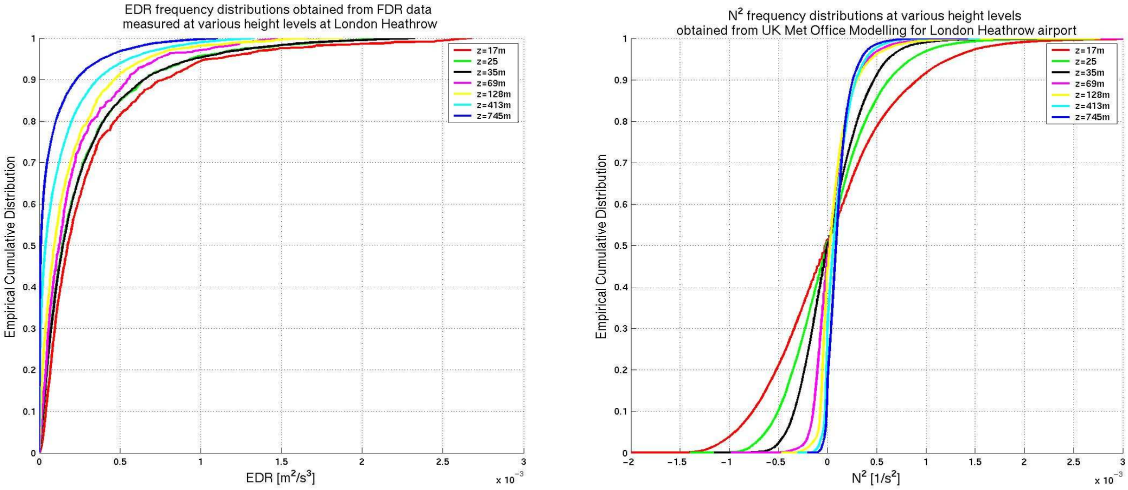

Figure 4-2 Frequency distributions for the London Heathrow climatology

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) [7]. 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 [6].

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).

5 Risk assessment

5.1 Overview of the risk assessment results

Sections 5-2 - 5.5 present the risk assessment results for each of the 24 scenarios defined in Table 4-1. To analyse the impact of the assessment parameters and to assess the lowest possible risk achievable for a WV DWA single runway arrival operation, it is firstly assumed that missed approaches may be initiated at any height. This provides a best possible estimate for the lowest risk achievable with a WV DWA system. Results for the case where missed approaches are not initiated below 200 ft are discussed later on in section 5.6.

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 5-1 until 5-4. Separation distances of 2, 2.5, 3, and 4 NM, with different crosswind conditions, are evaluated. Results without a WV DWA system are provided in grey, whereas the colours provide the incident/accident risk estimates in case a WV DWA system is used. Note that the scenario (in accordance with Table 4-1) is indicated on the horizontal axis. Figures 5-5 and 5-6 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 5-7 and 5-8 respectively.

The intermediate results of the above incident/accident risk assessments (for the case where missed approaches are initiated at any height) are discussed in Section 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 issuing a warning 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.

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 5.5. This provide a more realistic and achievable estimate for the achievable lowest risk, as it is also clear that for wake vortex safety reasons a missed approach initiation is not recommendable at low altitudes.

5.2 Wake vortex induced risk for different crosswind conditions

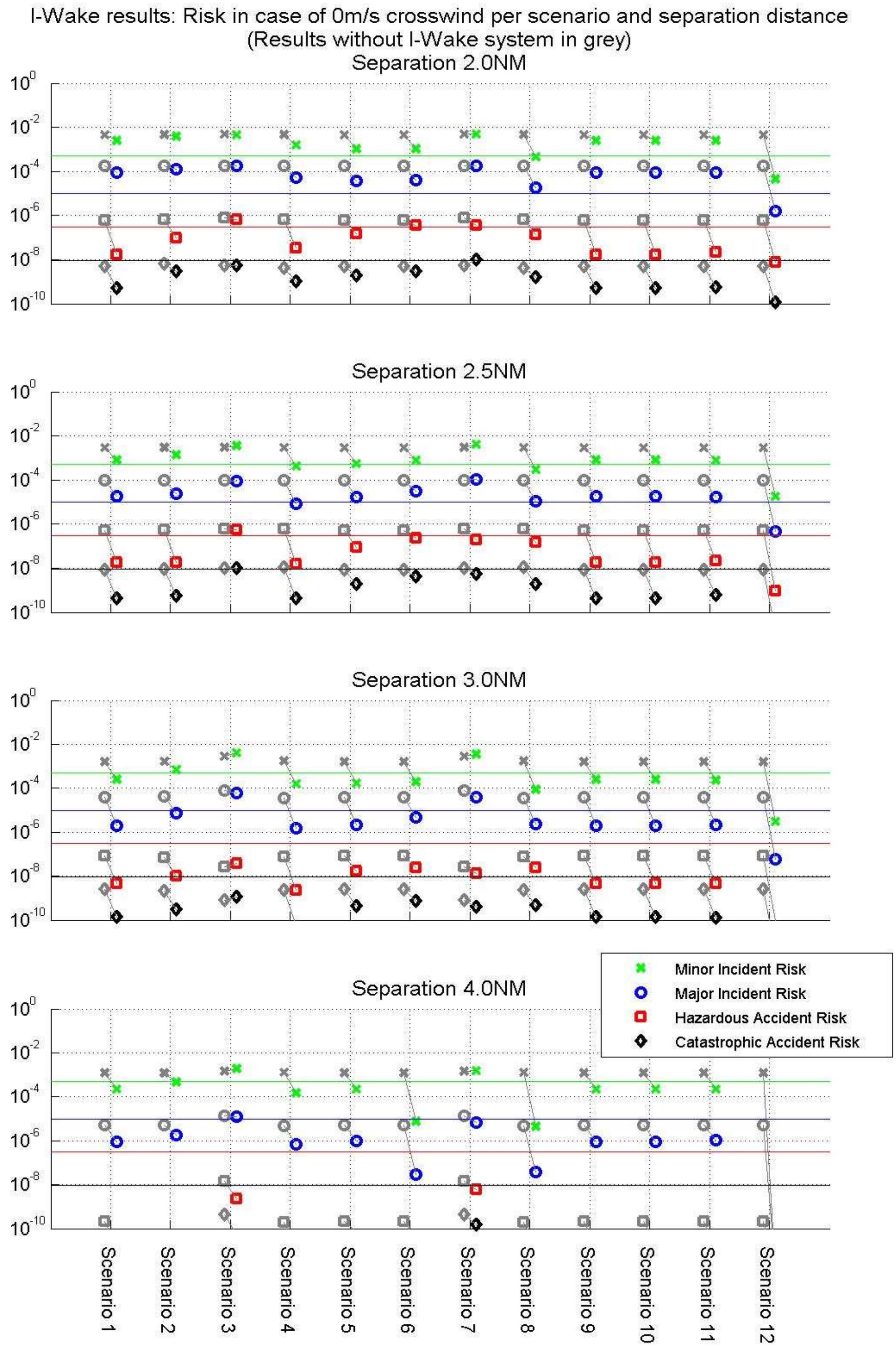

Figure 5-1 Risk in case of 0 m/s crosswind for scenarios 1-12

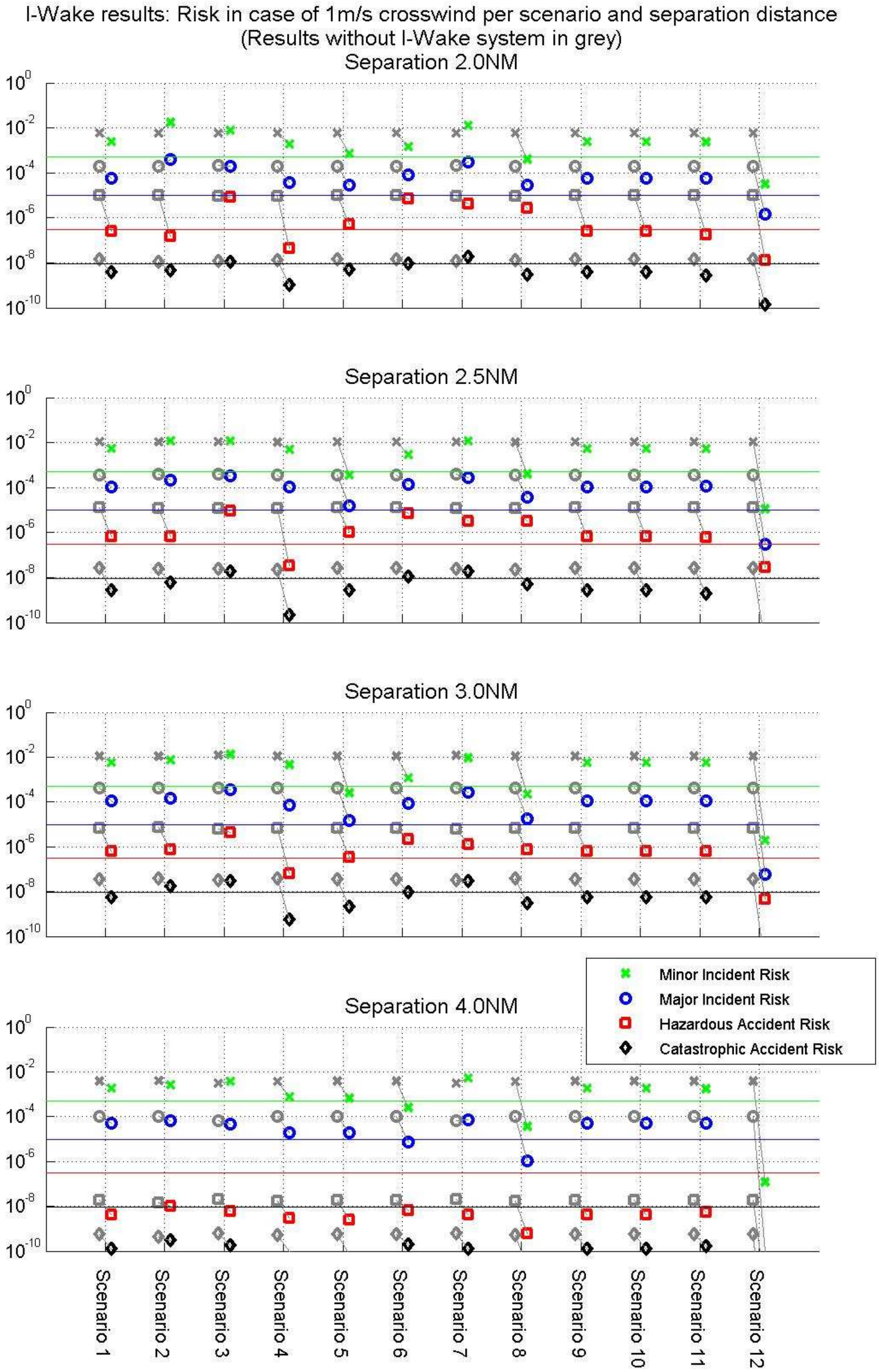

Figure 5-2 Risk in case of 1 m/s crosswind for scenarios 1 - 12

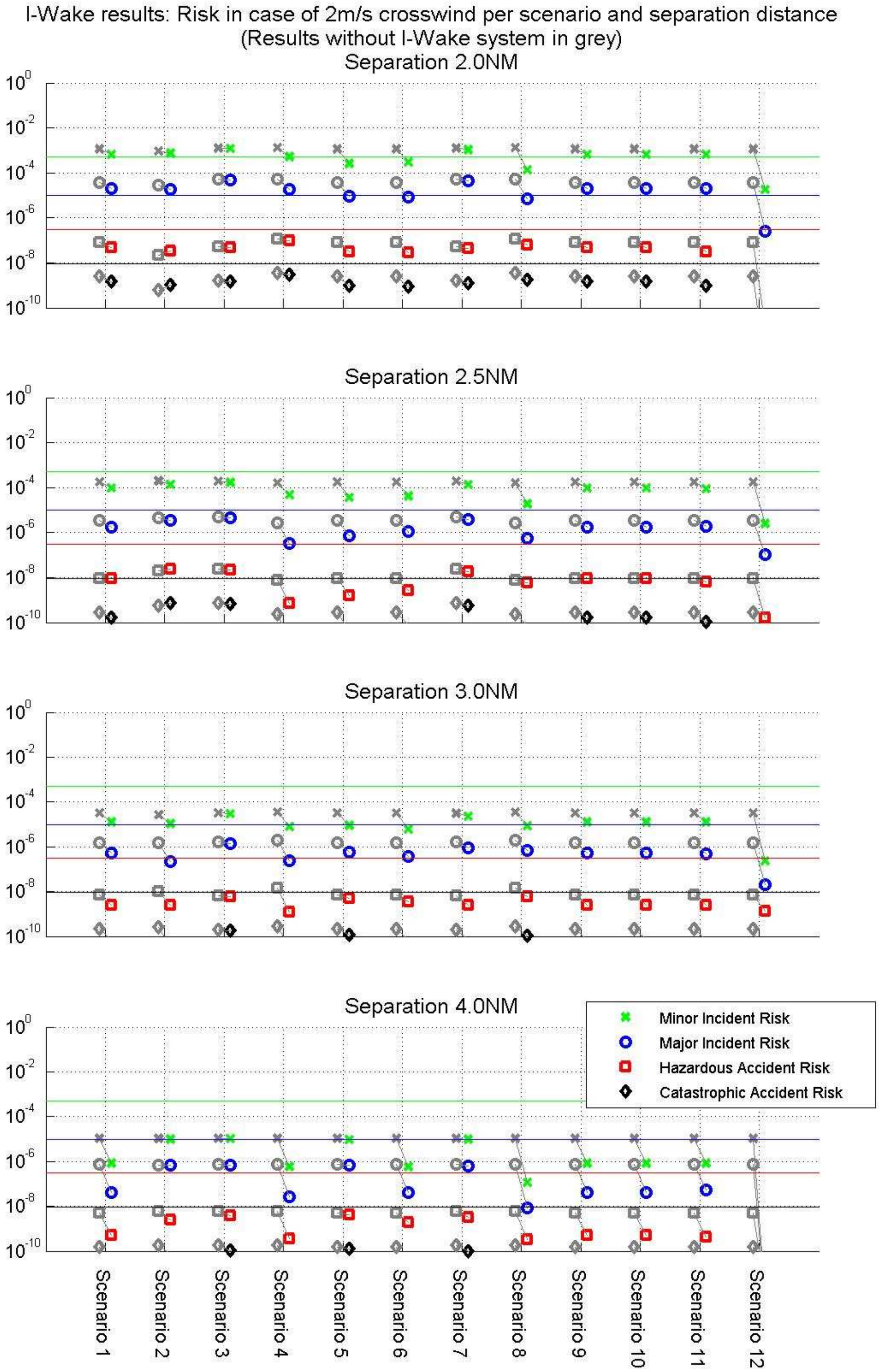

Figure 5-3 Risk in case of 2 m/s crosswind for scenarios 1 - 12

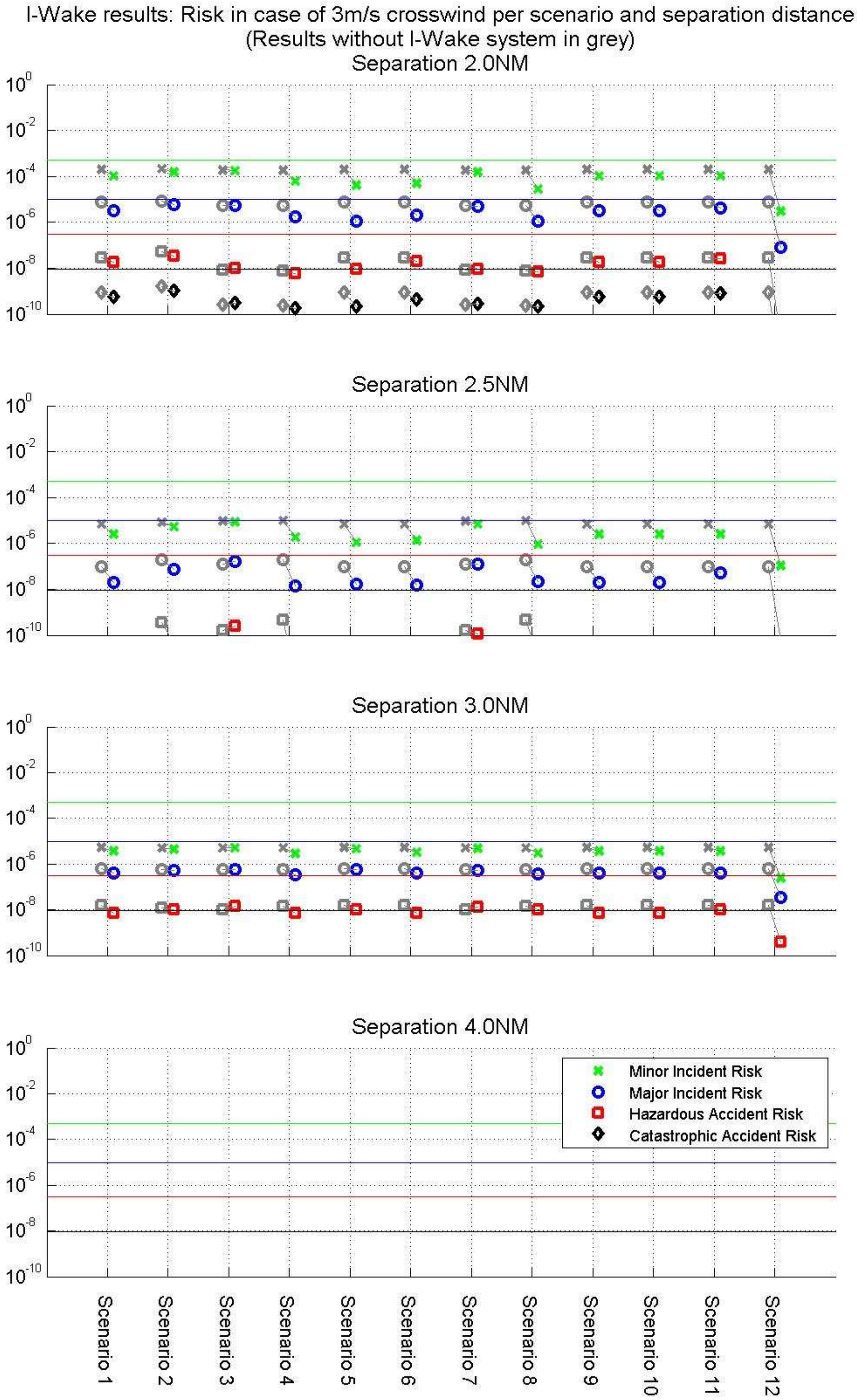

Figure 5-4 Risk in case of 3 m/s crosswind for scenarios 1 - 12

5.3 Wake vortex induced risk with reduced aircraft separation

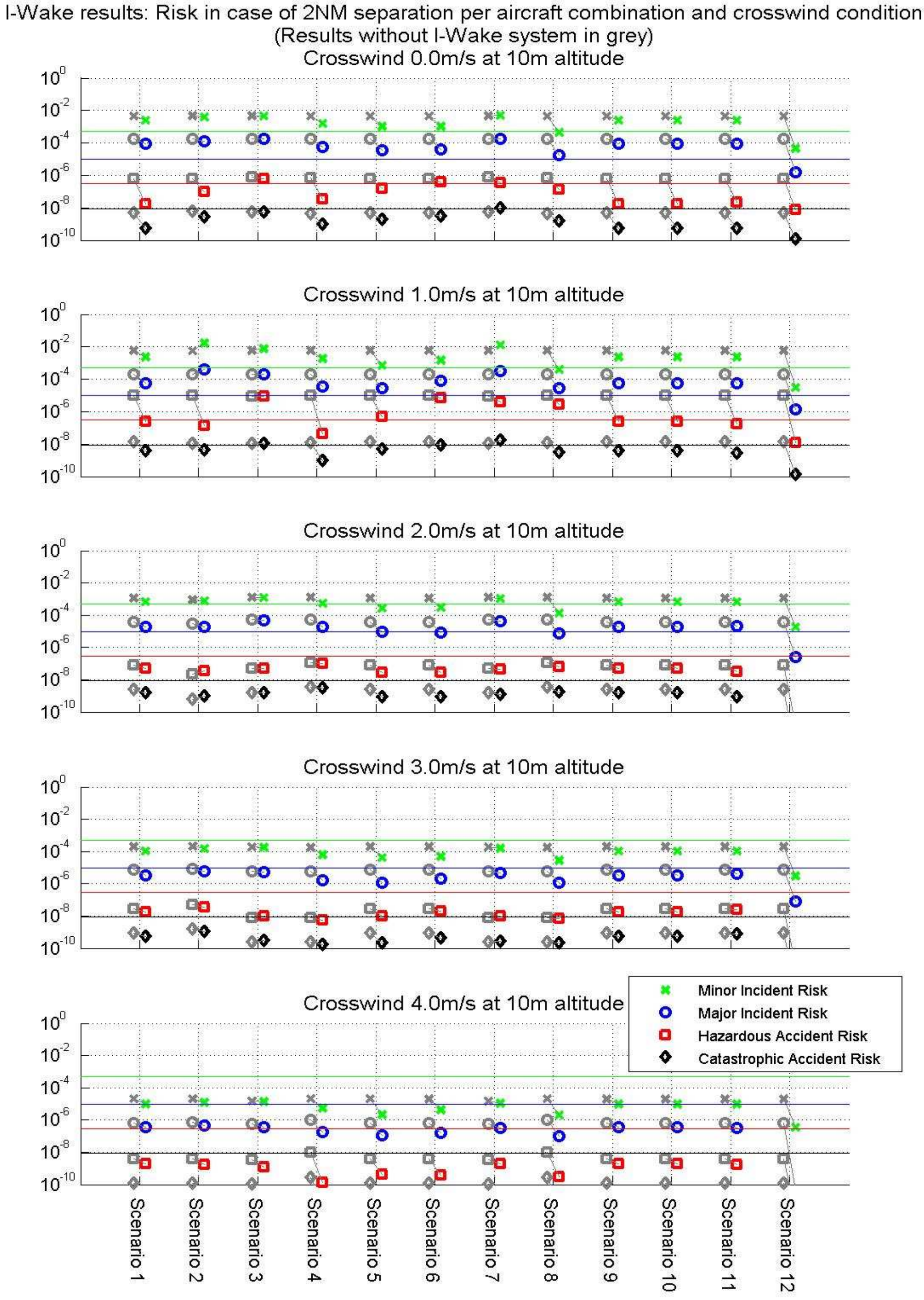

Figure 5-5 Risk in case of 2 NM separation for scenarios 1 - 12

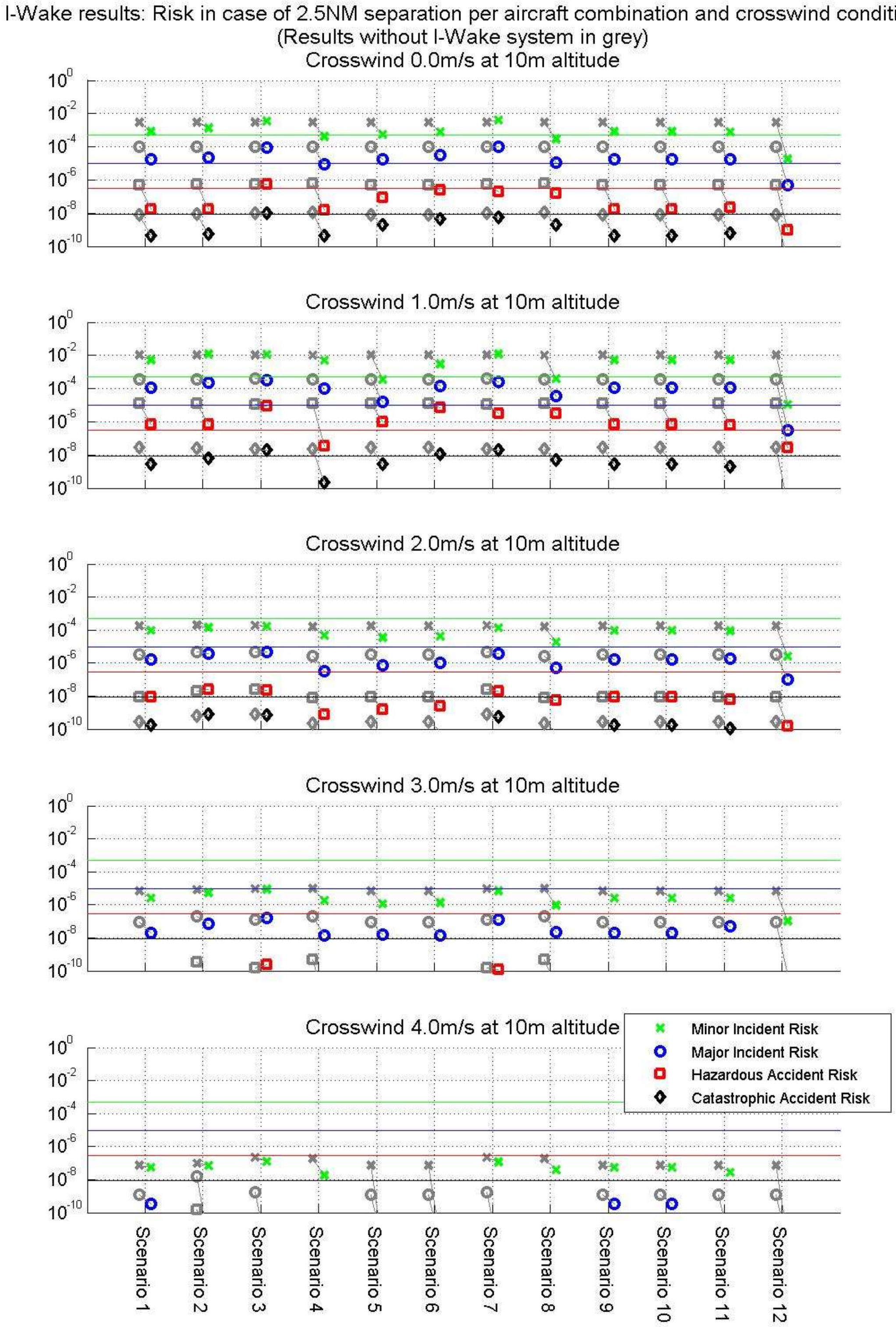

Figure 5-6 Risk in case of 2.5 NM separation for scenarios 1 - 12

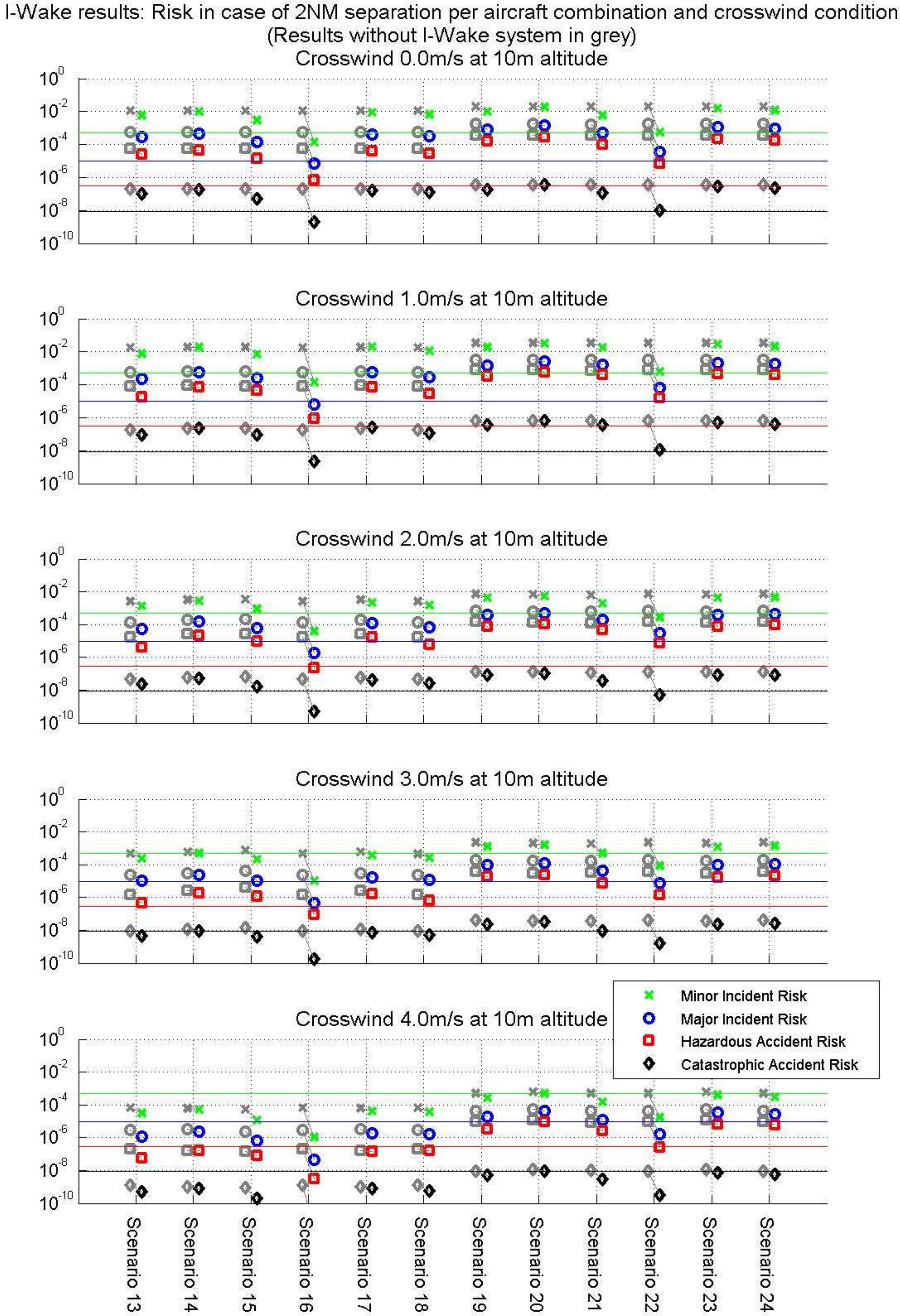

Figure 5-7 Risk in case of 2 NM separation for scenarios 13 - 24

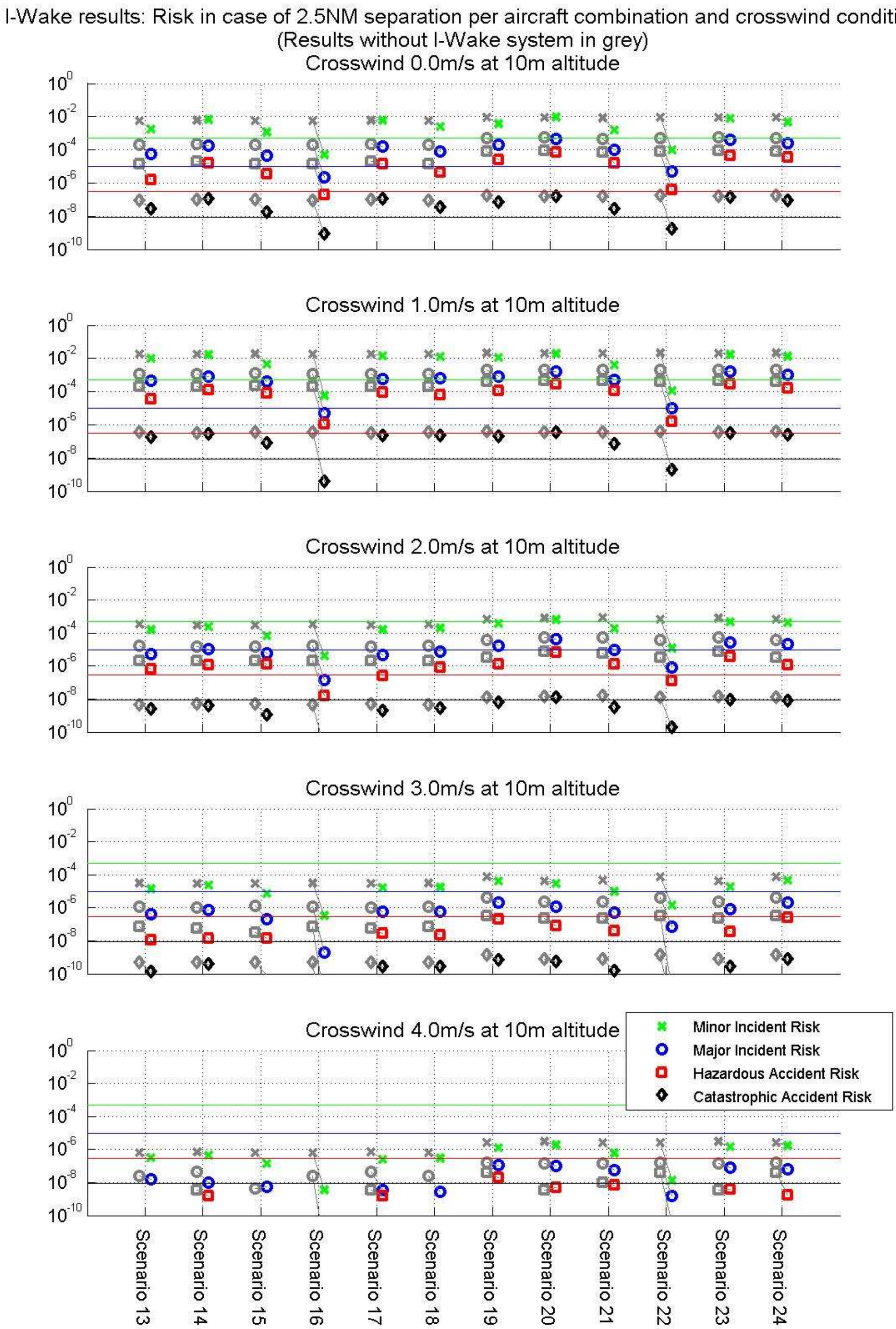

Figure 5-8 Risk in case of 2.5 NM separation for scenarios 13 - 24

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 5-9. 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 5-10.Note that the coloured bars denote the crosswind (at 10 m altitude). Results without I-Wake are provided in grey.

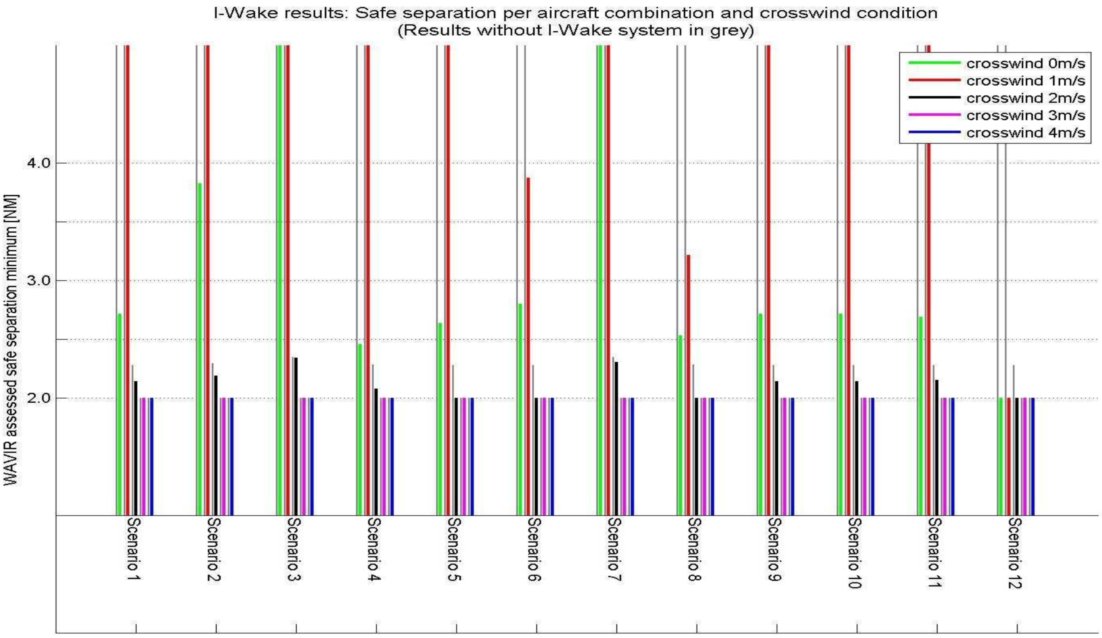

Figure 5-9 Minimum required separation distances with I-Wake (scenarios 1 - 12)

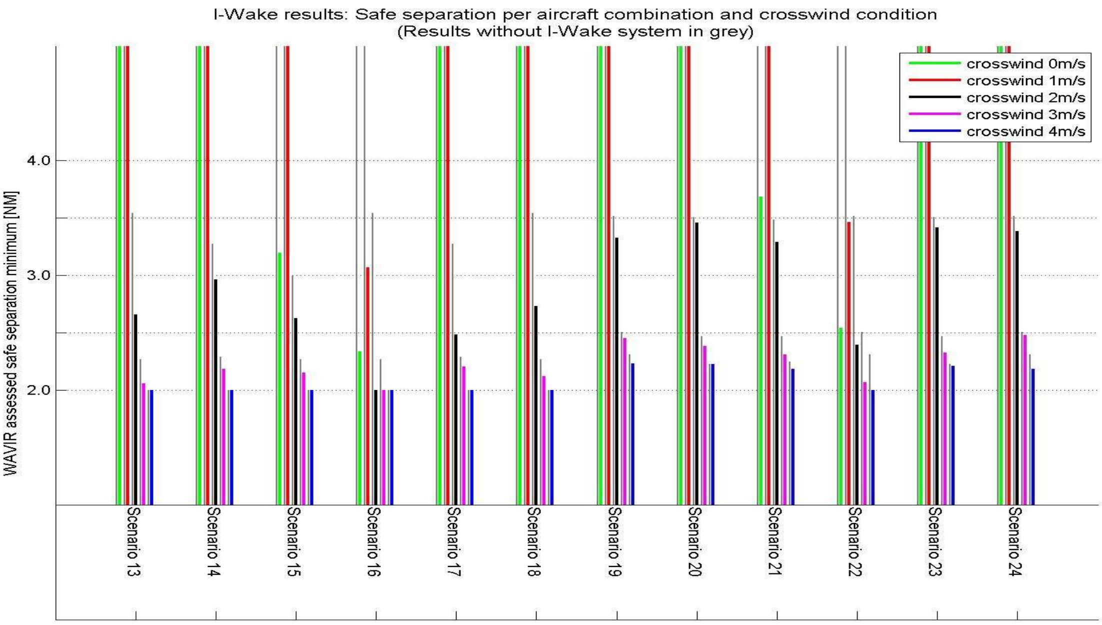

Figure 5-10 Minimum required separation distances with I-Wake (scenarios 13 - 24)

5.5 Discussion of the initial 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 WV DWA 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 200 ft. This is discussed next.

5.6 Refined assessment and discussion of results

In a second, refined, assessment the parameters in Table 5-1 have been chosen such that the I-Wake system capabilities provide the lowest risk without setting un-realistic and non-achievable requirements on the I-Wake system development. It is also assumed that a missed approach is not initiated below the Decision Height of 200 ft.

Table 5-1 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

Figure 5-11 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 that the coloured bars denote the crosswind (at 10 m altitude). Results without I-Wake are provided in grey.

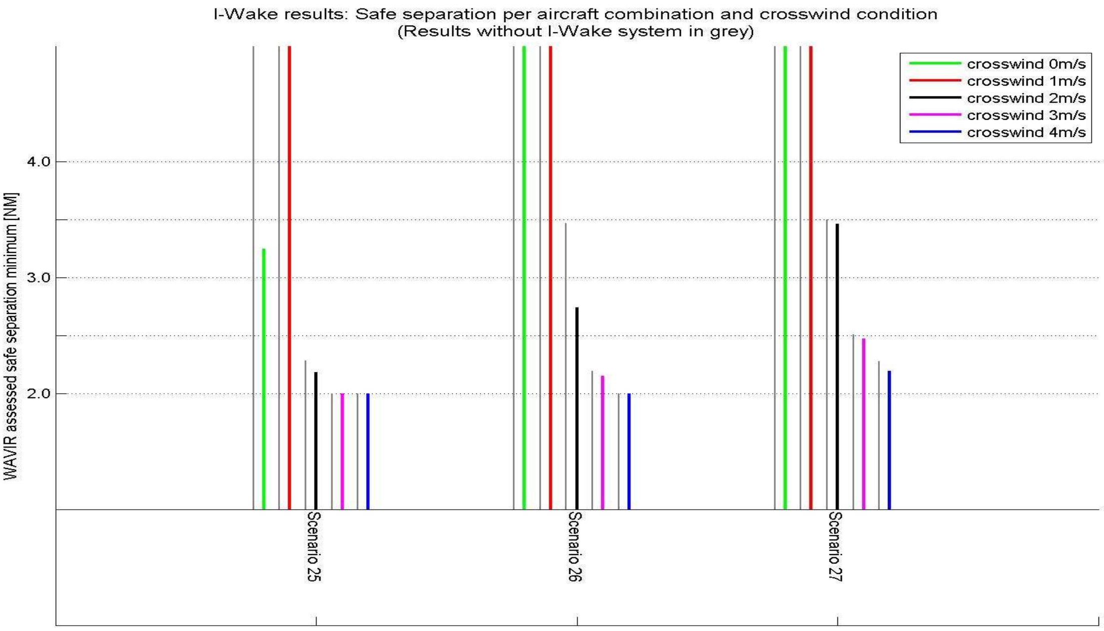

Figure 5-11 Minimum required separation distances with optimal I-Wake system setting

A comparison of Figure 5-11 with Figures 5-9 and 5-10 shows the major impact of not initiating a missed approach below the Decision height of 200 ft. In fact, the use of a WV DWA 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 [1, 2, 7]. Therefore, WV DWA use would be most beneficial at low altitudes, where the probability of encountering a (rebounding) wake is highest. Unfortunately, for safety reasons initiation of a missed approach is not recommendable at low altitudes. Therefore, the operational use of a WV DWA seems to have only minor impact on the wake vortex induced risk during single runway arrivals. This confirms that a WV DWA system is mainly applicable as safety net in support of ATC decided reduced separation (in line with its intended use).

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, which is intended for protection along the glide path from ILS/GS intercept, could be very useful as a 'safety net' in case reduced wake vortex separation is applied in the airport environment. A single runway arrival procedure for aircraft equipped with a WV DWA system 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. This study has now also *quantified* wake vortex risk through the use of the WAVIR methodology, extended with an aircraft/pilot missed approach model and a causal model for DWA 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 WV DWA 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 a WV DWA warning/alert is raised. Usually, the pilot will initiate a missed approach and/or turn away from the wake vortices detected by a WV DWA 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.

The use of a WV DWA 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 [1, 2, 7]. Therefore, WV DWA use would be most beneficial at low altitudes, where the probability of encountering a (rebounding) wake vortex is highest. However, for wake vortex safety reasons the initiation of a missed approach is not recommendable at low altitudes. Therefore, the operational use of a WV DWA system seems to have only minor impact on the wake vortex induced risk during single runway arrivals. This confirms that a WV DWA system is mainly applicable as safety net in support of ATC decided reduced separation.

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