

ASSESSMENT OF WAKE VORTEX SEPARATION DISTANCES USING THE WAVIR TOOLSET

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Abstract

Increases to the capacity of the National Airspace System (NAS), and reduction of delayed and cancelled flights, can be achieved by increasing the landing and takeoff capacity of the runways at the nation's busiest hub airports. NASA and the FAA are evaluating the feasibility of increasing runway capacity through reduced wake vortex separation distances between aircraft in the arrival and departure flows. 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.

This paper describes the WAVIR toolset, developed by the National Aerospace Laboratory NLR (the Netherlands), for evaluation of wake vortex separation distances. WAVIR is an analytic tool that uses stochastic models for wake vortex generation, wake vortex encounter, aircraft separation, and pilot/aircraft response to an encounter of varying magnitudes. The WAVIR tool provides the ability to evaluate the feasibility of different separation distances between fleets of heterogeneous aircraft under different operational, weather and wind conditions. The approach is applied to evaluate the safety related to current practice single runway arrivals.

Introduction

During the last four decades overall system safety (e.g. accident risk per flight hour) of the National Airspace Systems (NAS) has improved despite the growth in number of operations conducted [1, 2]. 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 [3]. Researchers have

concluded that as the air transportation system asymptotes at its capacity limits, the introduction of new technology to improve overall network system safety yields diminishing returns [4]. 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 [5] 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 generation, 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 [6].

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 to the dynamic stochastic nature of the system behavior, and the absence of historic data for rare-events [7, 8]. 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 [9].

The National Aerospace Laboratory NLR, of the Netherlands, 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, 11]. WAVIR is also being used in the European projects for ground based wake vortex prediction and detection (ATC-Wake) and cockpit instrumentation for wake vortex detection and avoidance (I-Wake).

This paper describes the WAVIR tool for evaluation of wake vortex separation distances between fleets of heterogeneous aircraft in a stochastic flow under different operational, weather, and wind conditions. The next section provides an overview of wake vortex separation procedures during approach and landing. The following section describes a historic account of how separation distances have been determined in the U.S. Then the next section describes the WAVIR tool. The final section provides conclusions and describes future work.

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. [9].

Wake vortex separation standards have a significant impact on airport departure and arrival capacity especially at the busiest hub airports [12]. 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 [5].

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 [13].

Currently three concepts of operation are under consideration by NASA and the FAA [5, 12] 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 [14] to enable dependent parallel runway arrival operations with parallel runways separated by less than current standard (2500') 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 based on measurements of existing weather conditions [13].

Determining Wake Vortex Separation

Prior to the introduction of large wide-body jets, wake vortex upsets or turbulence encounters by a trailing aircraft were considered to be “prop-wash” or “jet wash” and not considered a flight hazard. The introduction of large wide-body turbojet aircraft with increased weight and wingspan in the late 1960's changed this perception and initiated the detailed study of wake vortices and their impact on trailing aircraft.

In mid 1969 a series of flight test experiments were conducted by Boeing and the FAA to generate detailed information on the wake vortex phenomenon [9]. By using smoke towers and probing aircraft (737-100, F-86, NASA CV-990) the wake vortices of a B747 and B707-320C were characterized.

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

- VFR rules – following aircraft remain above of the flightpath of the leading aircraft

- 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 [15, 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 always been increased with two exceptions:

- (1) 2.5 mile spacing for similar sized aircraft and short runway occupancy times, and
- (2) reduction to 3 aircraft categories.

Classical Methodologies for Determining Separation Distances

Three methodologies have been used in the United States to define safe separation standards [9]:

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 [9]. 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 like 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 [9]. 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 National Airspace System (NAS) asymptotes at the capacity limits set 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.

WAVIR Tool

The WAVIR tool was developed by NLR [10, 16, 17, 18, 19] 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. These modules are incorporated in the WAVIR toolset in the screenshot shown in Figure 1 [19].

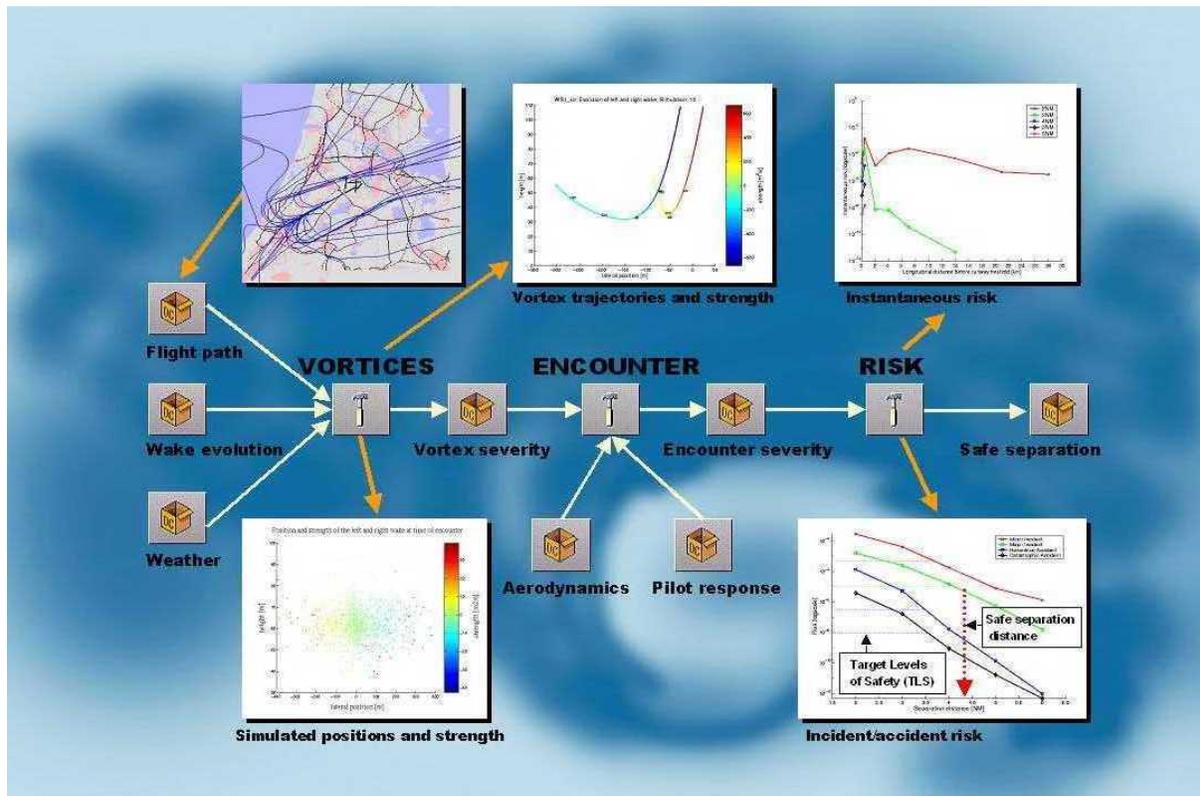


Figure 1. Screenshot of WAVIR Tool
SPINeWare provides middleware [20]

Components of WAVIR Toolset

The WAVIR toolset is composed of the following 4 modules [10]:

- 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.
- Wake Vortex Generation (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 [10, 11]. 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 (see Figure 2).
- 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 [10]:
 - 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.

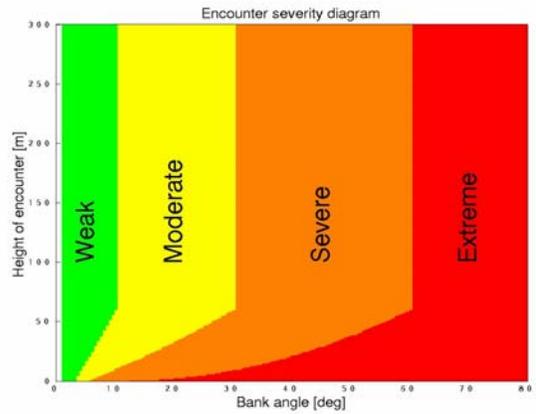


Figure 2. Encounter Severity Classification Scheme

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 [10, 11]. A safety assessment is carried out in nine steps:

- 1) Define the “Gates” on the Flight Path:
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 (see Figure 3). In each of these ‘gates’, the wake evolution and wake encounter simulations will be performed.

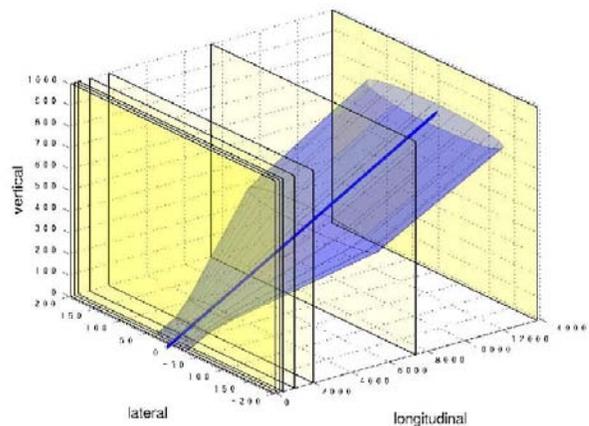


Figure 3. Approach Glide Path Safety Corridor with an Example Selection of Gates for Evaluation of Safety

- 2) **Initialize the Wake Vortex Generator:**
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 Vaisala frequency) (Figures 4 and 5 represent atmospheric conditions at Heathrow).

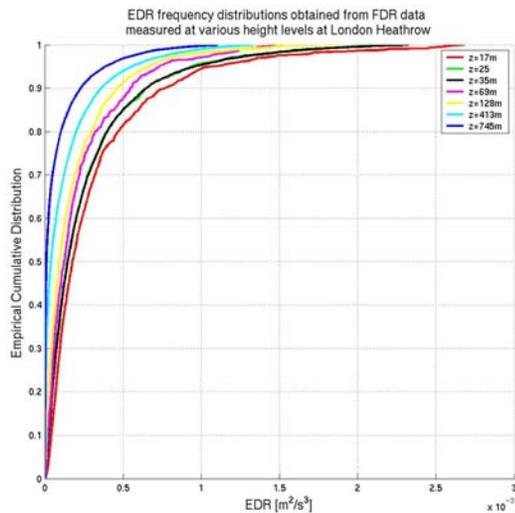


Figure 4. Frequency Distribution of Eddy Dissipation Rate (EDR) at Various Height Levels

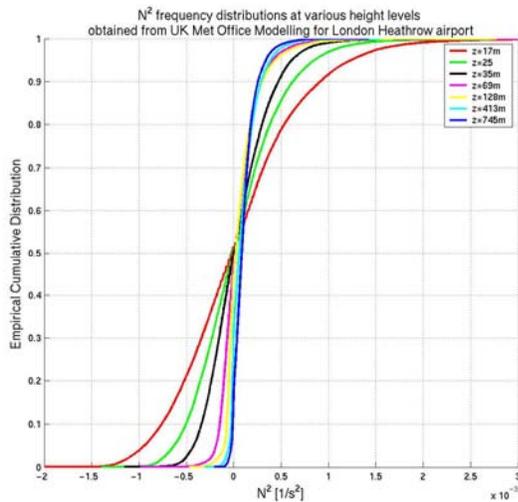


Figure 5. Frequency Distribution of Brunt-Vaisala Frequency (N²) at Various Height Levels

- 3) **Initialize Flight Path Evolution Generator:** Samples of aircraft (lateral and vertical) position and speed in the selected gates are obtained with the flight path evolution model (Figure 3). Speed profiles representing the aircraft movements are also needed as input for this model (Figure 6 represents atmospheric conditions at Heathrow).

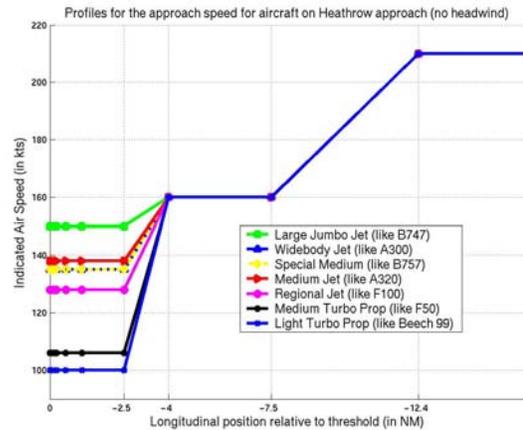


Figure 6. Aircraft Speed Profiles (Representing Atmospheric Conditions at Heathrow Airport)

- 4) **Run Wake Vortex Generator:** 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) [10].
- 5) **Compute Wake Vortex Flow Field for Lead Aircraft at Each of the Gates:** 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 each of the gates.

- 6) Compute Wake Vortex Encounter: 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 (see Figure 7). 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.

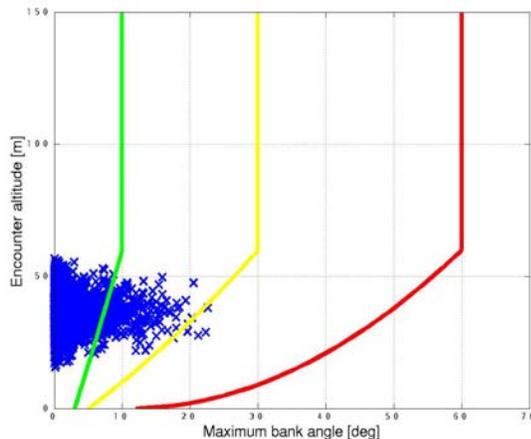


Figure 7. Example Wake Encounter Simulation Results (Relatively Close to the Runway Threshold)

- 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 [10]. As an example, Figures 8 – 11 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.

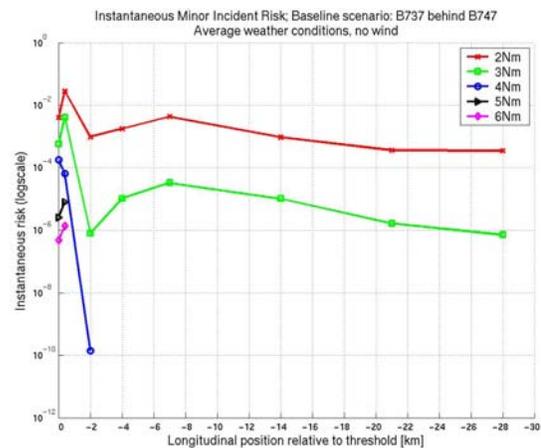


Figure 8. Instantaneous Minor Incident Risk along the Glide Slope

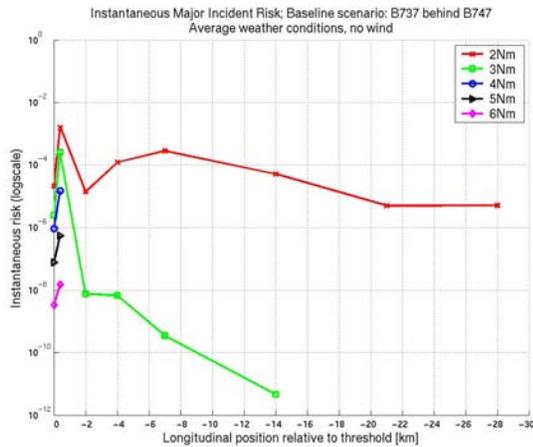


Figure 9. Instantaneous Major Incident Risk along the Glide Slope

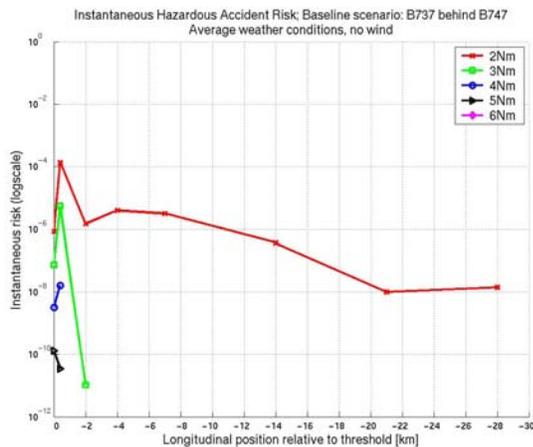


Figure 10. Instantaneous Hazardous Accident Risk along the Glide Slope

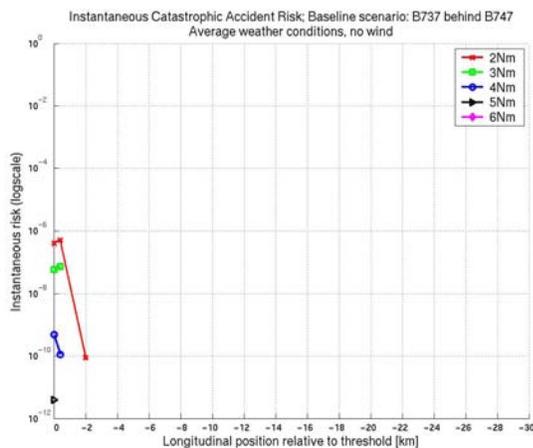


Figure 11. Instantaneous Catastrophic Accident Risk along the Glide Slope

8) Compute Incident/Accident Risk Per Movement: The wake-induced incident/accident risk is obtained by integrating over x the risk obtained in Step 5. This step, which is repeated for different prescribed separation standards, provides the 4 incident/accident risk curves as functions of the separation distance (see Figure 12).

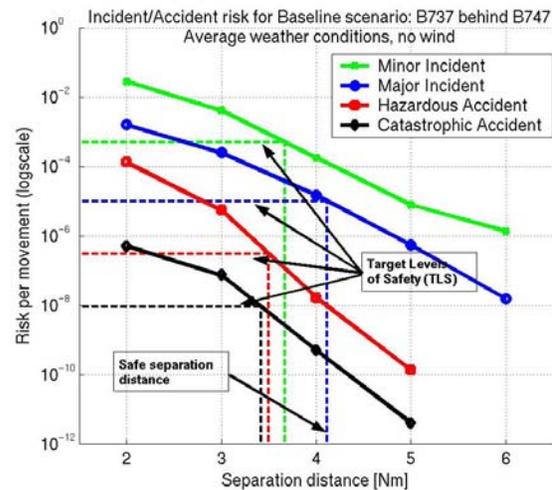


Figure 12. Incident/Accident Risk per Movement (Compared with Target Level of Safety (TLS) Value)

9) Assess Minimum Required Separation Distance: 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. Figures 13 and 14 illustrate such end results obtained for a Regional jet and a Light Turbo Prop landing behind a Large Jumbo Jet.

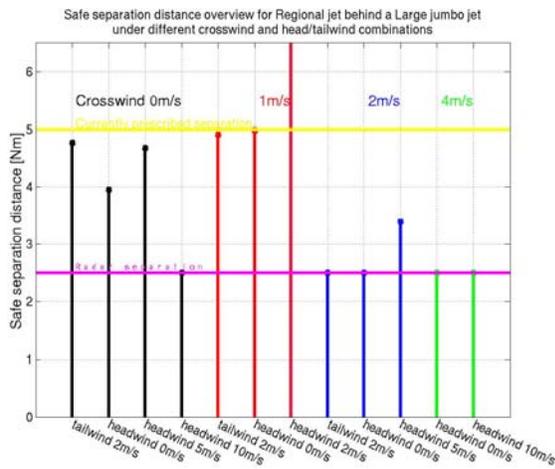


Figure 13. Safe Separation Distance for a Regional Jet behind Large Jumbo Jet

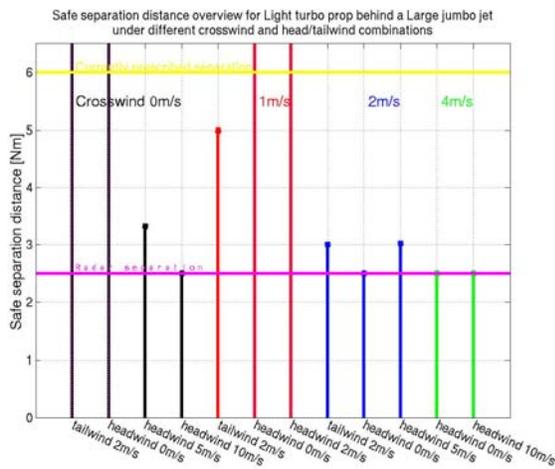


Figure 14. Safe Separation Distance for a Light Turbo Prop behind Large Jumbo Jet

Results from S-Wake Study

For a variety of wind conditions, the wake vortex induced risk has been analyzed [10]. The impact of crosswind, head- and tailwind has been assessed for a variety of leader and follower combinations. The crosswinds are defined by a logarithmic wind profile, with wind speeds increasing with altitude, starting at 10 m (typical wind sensor location).

Unfavorable Wind Conditions for Reduced Wake Vortex Separation

Figures 15 and 16 provide the safe separation distances for a light crosswind of less than 2 m/s (3.7 knots). The WAVIR computed safe separation

distance is shown in each cell with the ICAO standard in parentheses.

Follow	Lead Jet	Large Jumbo Jet	Medium Jet
Large Jumbo Jet	Large Jumbo Jet	<u>4.25 nm</u> (4.0nm)	2.5nm (3.0nm)
Medium Jet	Large Jumbo Jet	<u>6.5nm</u> (5.0nm)	2.5nm (3.0nm)
Regional Jet	Large Jumbo Jet	5.0nm (5.0nm)	3.25nm (3.0nm)
Light Turbo Prop	Large Jumbo Jet	<u>6.5nm</u> (6.0nm)	3.5nm (5.0nm)

Figure 15. Safe Separation Distances for a Small Crosswind of 1 M/S (1.8 Knots) and No Head-Or Tailwind

WAVIR Computed Safe Separation Distance
(ICAO Standard Separation Distance)

Follow	Lead Jet	Large Jumbo Jet	Medium Jet
Large Jumbo Jet	Large Jumbo Jet	<u>4.5nm</u> (4.0nm)	2.5nm (3.0nm)
Medium Jet	Large Jumbo Jet	<u>6.5nm</u> (5.0nm)	2.5nm (3.0nm)
Regional Jet	Large Jumbo Jet	<u>6.5nm</u> (5.0nm)	3.0nm (3.0nm)
Light Turbo Prop	Large Jumbo Jet	<u>6.5nm</u> (6.0nm)	3.75nm (5.0nm)

Figure 16. Safe Separation Distances for a Small Crosswind of 1 M/S (1.8 Knots) and a Headwind 2m/S (3.7 Knots)

WAVIR Computed Safe Separation Distance
(ICAO Standard Separation Distance)

Favorable Wind Conditions for Reduced Wake Vortex Separation

Figures 17 and 18 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 lower than those in Figure 15.

Follow	Lead	Large Jumbo Jet	Medium Jet
Large Jumbo Jet		2.5 nm (4.0nm)	2.5nm (3.0nm)
Medium Jet		2.5nm (5.0nm)	2.5nm (3.0nm)
Regional Jet		2.5nm (5.0nm)	2.5nm (3.0nm)
Light Turbo Prop		2.5nm (6.0nm)	2.5nm (5.0nm)

Figure 17. Safe Separation Distances for a Crosswind of 2 M/S (3.7 Knots)

WAVIR computed safe separation distance (ICAO standard separation distance)

Follow	Lead	Large Jumbo Jet	Medium Jet
Large Jumbo Jet		2.5 nm (4.0nm)	2.5nm (3.0nm)
Medium Jet		2.5nm (5.0nm)	2.5nm (3.0nm)
Regional Jet		2.5nm (5.0nm)	2.5nm (3.0nm)
Light Turbo Prop		2.5nm (6.0nm)	2.5nm (5.0nm)

Figure 18. 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)

Conclusions

This paper describes the application of quantitative, stochastic risk assessment for wake vortex separation distances. The WAVIR toolset, developed by the National Aerospace Laboratory NLR of the Netherlands, has been successfully used for probabilistic evaluation of wake vortex safety for proposed European procedures (e.g. S-Wake see [10, 11]). The main results, which are included in this paper, show that an increase in runway throughput might be achieved through exploiting favorable wind conditions (sufficiently strong crosswind and/or strong headwind). It is clear that this can only be achieved through 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 depend heavily on the use of wake vortex prediction and detection information, with explicit roles and responsibilities for the pilots and controllers working with such wake avoidance systems. To meet the need for a sufficiently reliable and accurate safety assessment, the WAVIR toolset is being extended with human performance models using structured expert judgement [21-24].

At present, the WAVIR tool is also being further validated using wake measurements and historical wake encounter data. This is being done within the European ATC-Wake program (see [25]), under coordination of NLR.

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