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Abstract

The steady increase in air traffic imposes a need for enhanced airport capacity, and the desire to safely reduce existing separation minima. An important capacity constraint factor is the risk imposed by wake vortices. In view of the uncertainties and the difficulties in understanding the wake vortex phenomena, a novel WAke Vortex Induced Risk assessment (WAVIR) model has been developed to evaluate wake vortex induced risk. The probabilistic model incorporates sub-models for wake vortex evolution, wake vortex encounter, and flight path evolution, and relates the severity of wake vortex encounters to incident / accident risk probability. The model is applied to evaluate the risk related to different separation distances between aircraft landing on a single runway. An extensive initial risk assessment is carried out to evaluate the impact of weather and wind conditions and procedural aspects on incident/accident risk. The risk assessment results are compared with proposed risk requirements to assess safe and appropriate separation distances. It is shown that a reduction of the current separation minima – and consequently an increase of capacity – might be possible under most operational and weather conditions. However, it is also shown that the separation distances might need to be increased under some particular weather conditions (e.g. low atmospheric turbulence).

Keywords
Wake vortex evolution, Wake vortex encounter, Safety assessment, Separation distances, Risk based policy making, Single runway approach, Air Traffic Management.

Contents

(12 pages in total)

1 Introduction

The current separation minima for single runway approaches stem from the early 70's. Although over the last 30 years they have 'proven to be sufficiently safe', the current safety level is unclear. At the busiest airports, pilots continue to report wake vortex related incidents. With the steady increase in air traffic, the design of new high capacity aircraft and the continuous changes in Air Traffic Management (ATM) concepts and procedures, there is an urgent need to re-examine the current wake vortex separation rules. It is also recognised that safety is a key quality that should be guaranteed. This requires tools and methods to enable quantitative assessment of wake vortex safety. In view of the uncertainties and the difficulties in understanding of the wake vortex phenomena, this study follows a probabilistic approach. WAVIR is based on a stochastic framework that incorporates the following sub models:

- Wake vortex evolution model: to predict wake transport and decay in different weather conditions;
- Wake vortex encounter model: to predict the aircraft upset during an encounter;
- Flight path evolution model: to predict the aircraft movements and speed along the flight track.

WAVIR can be used to assess the incident / accident risk related to different separation minima for the current practice, and for promising new concepts that may enable a safe reduction of the current separation minima. Identified safety bottlenecks can be fed back to the ATM designers, who can use these results to redesign or improve their proposed ATM concept.

This paper outlines the WAVIR methodology and illustrates its application to single runway approaches under different weather, wind and operational conditions.

2 Wake vortex risk based policy making

The methodology to assess wake vortex induced risk proposes that a safety management approach to regulate and control wake vortex induced risk should be based on an assessment of incident/accident risk probabilities, followed by a comparison with risk criteria. This requires the development of a probabilistic relation between wake vortex encounter severity and risk metrics that are related to the severity of accidents, incidents and related conditions. Classification schemes from International Civil Aviation Organisation (ICAO (1994, 1998)) and Joint Aviation Authorities (JAA, 1994) are combined to obtain the risk event classification (see Speijker et al. (2000a)):

1. *Catastrophic accident:* the aircraft encountering a wake vortex 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*: the encounter results in inconvenience to occupants or an increase in crew workload.

In close co-ordination with National Air Traffic Services (NATS), a method to derive safe and appropriate separation minima for different operational, weather and wind conditions has been introduced (see Mason (2000)). The method is based on a comparison with risk criteria in terms of Target Level of Safety (TLS):

- Risk metrics in terms of incident / accident probabilities per movement;
- Risk requirements derived on the basis of historical incident data from Heathrow airport (Table 1).

Table 1: Risk Requirements (Probability Per Movement)

Risk Events	Catastrophic Accident	Hazardous Accident	Major Incident	Minor Incident
Proposed TLS	0.9×10^{-8}	3.0×10^{-7}	1.0×10^{-5}	5.0×10^{-4}

The method proposes that all four risk requirements are to be satisfied, and that the most stringent requirement determines the required separation minima (see Figure 4).

3 Probabilistic safety assessment model

To numerically assess wake vortex induced risk the three sub models for flight path evolution, wake vortex evolution, and wake vortex encounter are integrated in the WAVIR tool as sketched in Figure 1.

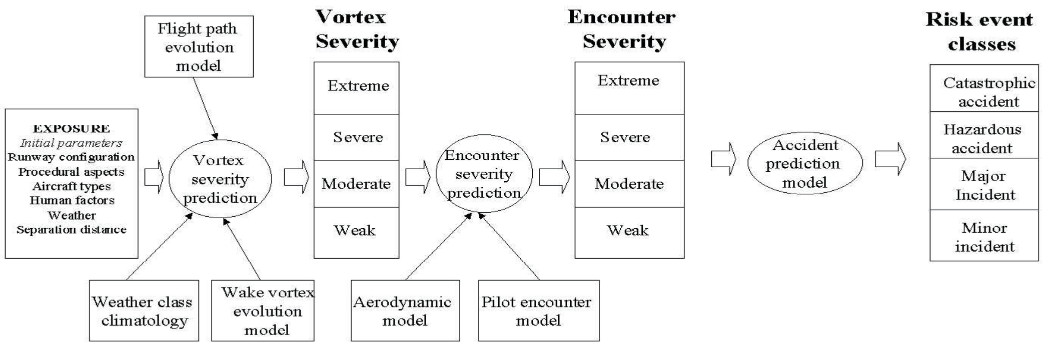

Figure 1: Overview of WAVIR modelling relations and dependencies

In this paper the model is applied to the approach phase of aircraft, but the method can also be applied to other flight phases. For the relevant input parameters probability distributions, based on empirical data and/or state-of-the-art literature, are determined. Monte Carlo simulations are carried out with wake vortex evolution and encounter models to calculate the (conditional) instantaneous risk at different positions along the aircraft flight track. The wake vortex induced incident/accident risk is then obtained by maximising these instantaneous risk curves over the entire aircraft flight track. For a given longitudinal position x along the aircraft flight track, the flight path evolution model yields probability distributions for the lateral and vertical position of leader and trailer aircraft. Conditional on prescribed separation distance at the runway threshold, a probability distribution is determined for the period of time elapsed between the generation of the wake and the time instant that the trailer has position x along the aircraft flight track. This time period distribution is then used to predict the vortex position and strength at the time of encounter with the trailer.

The wake vortex evolution model predicts the motion and decay of the vortex pair. The physical evolution of wake vortices is strongly influenced by weather and wind. Wake vortex decay is enhanced in an ambient turbulence environment. Under stable stratification conditions, vortices will decay but may stall or rise. Wind shear, with weak turbulence and weak stable stratification may enhance stalling or rising vortices without significant decay. Vortices may stall or rebound to the glide path in the convective, stable stratified and sheared boundary layer (Gerz et al. (2001)). Different wake vortex evolution models are available, and it is remarked that the presented results are based on the models of Greene (1986) and Corjon & Poinsot (1996, 1997) and account for stratification, atmospheric turbulence, ground effects, and wind effects (headwind, tailwind, crosswind and vertical winds).

Within this study, roll control ratio is used as encounter severity metric. Different models are available (e.g. Tatnall (1995), Kuzmin (1997), Woodfield (1995)) to determine the roll control ratio, and it is noted that the wake vortex induced rolling moment on the trailer is computed and compared to its maximum roll control moment following Tatnall (1995). An overview of basic scaling laws and methods to assess the roll control ratio is given in De Bruin (2000).

A more extensive overview of the WAVIR methodology – including the incident / accident prediction model that relates the severity of encounters to the risk events – and its initial application to the single runway approach can be found in Speijker et al. (2000b, 2001). The tool is being validated through a comparison of results with incident data obtained at Heathrow airport using Flight Data Recorder (FDR) data analysis of up to 80,000 flights, including actual encounters.

4 Assessment of incident/accident risk

WAVIR has been applied to study the wake vortex safety aspects of single runway approaches. An initial risk assessment – with a Boeing 737 landing behind a Boeing 747-400 – has been carried out. The impact of weather and wind conditions (turbulence, stratification, crosswinds and head- and tailwinds) and procedural aspects (e.g. glide slope intercept altitudes, navigation accuracy, glide path angles, steep descent approaches) on incident/accident risk has been evaluated.

Figure 2 shows the positions and strengths of vortex pairs generated at 400 m before the runway threshold for a trailer aircraft with 5 NM prescribed separation. The ellipse indicates a 2σ interval of the trailer aircraft position. Figure 3 shows the Major Incident Risk along the Instrument Landing System (ILS) glide path with prescribed separation distances of 2, 3, 4, 5, and 6 NM at the runway threshold (and with average atmospheric turbulence and stratification, and no crosswind). Similar figures can be derived for the other three risk events. Clearly the risk is highest near the runway threshold, a conclusion also found for the other three risk events (Speijker et al. (2001)). This leads to the conclusion that the impact of procedural changes further along the glide path on incident / accident risk will be low.

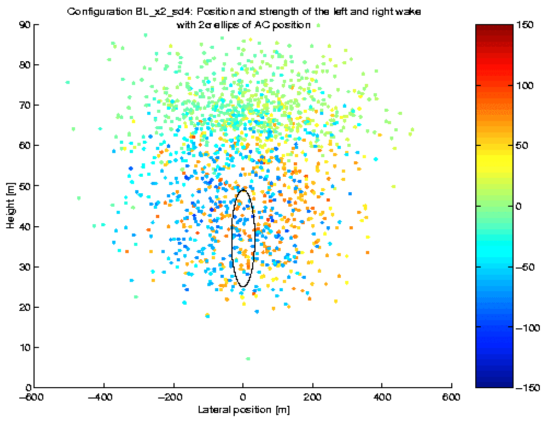

Figure 2: Position and strength data of vortices with 2σ ellipse of the position of the follower aircraft at 5 NM separation

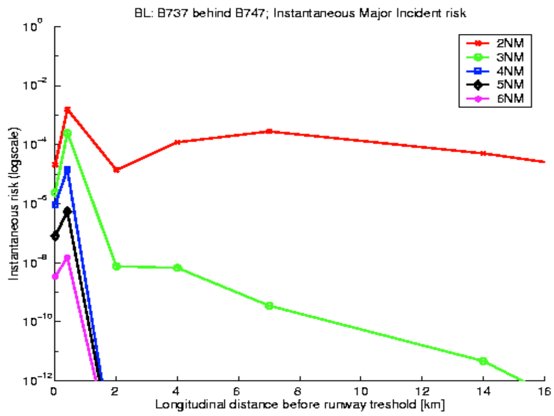

Figure 3: Instantaneous Major Incident risk curves for different separation distances.

Provisions governing wake turbulence separation minima are published by ICAO (1996a, 1996b, 1984), and depend on the weight classes of the involved aircraft and the available equipment (e.g. radar or non-radar operations). Figure 4 illustrates the method to derive safe and appropriate separation distances for a specific operational, weather and wind condition. Clearly under these conditions, the current ICAO prescribed separation minima of 5 NM might be reduced to facilitate an increase in runway capacity.

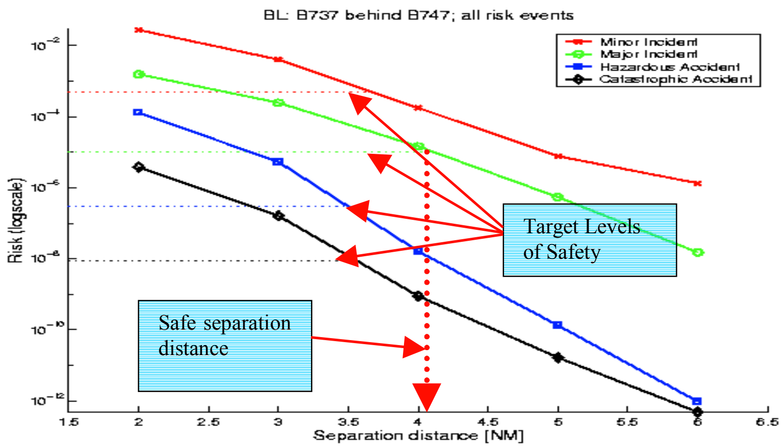

Figure 4: Method to derive safe and appropriate separation minima

The probabilistic model has been applied to evaluate the sensitivity of incident/accident risk to variations in lateral and vertical navigation performance, atmospheric turbulence, stratification effects, wind situation, and different flight tracks of the trailer aircraft (different glide slope intercept altitude and different glide path angles). The results are summarised in Figure 5 below.

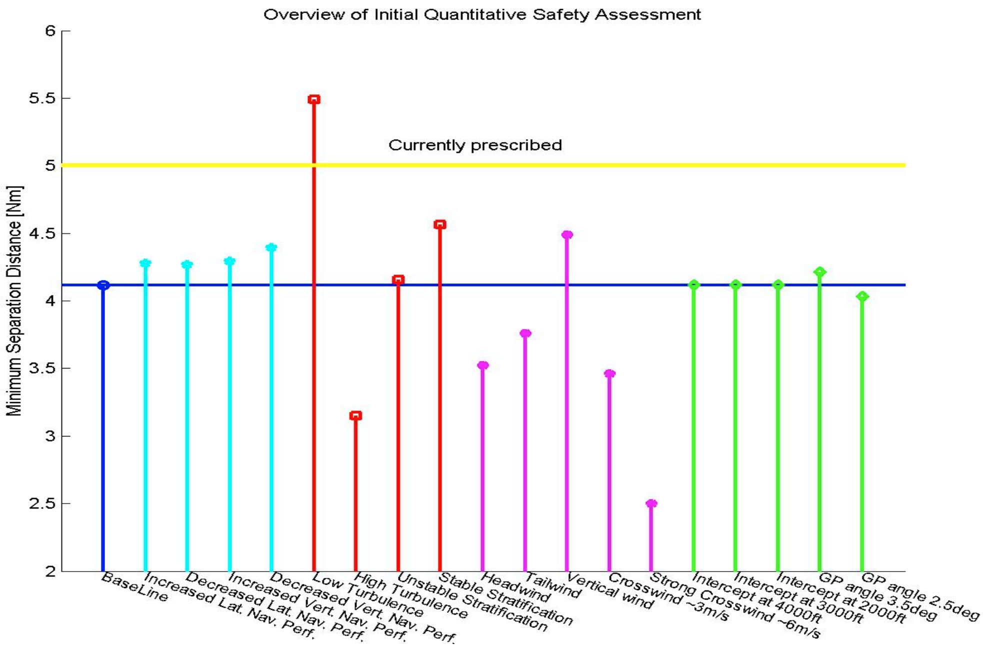

Figure 5: Derived Separation Minima under different operational and weather conditions for a B737 behind a B747.

Figure 5 shows that a reduction of the current separation minima - and consequently an increase in capacity – might be possible under most operational and weather conditions. However, it is also shown that the separation distances might need to be increased under some particular conditions. The results show that the impact of the investigated procedural aspects – as compared to the impact of weather and wind conditions – is relatively small, which implies that the evaluated changes in ATM procedures at present will not allow safe reduction of separation distances. In order to do so, the first step should include a reduction of risk near the runway threshold (e.g. definition of measures to reduce the probability and/or consequences of such an encounter). The risk assessment results also show that – for single runway approaches – the largest runway capacity improvement might be achieved through exploiting weather conditions favourable for a rapid decay (or destruction) of the vortices. Since weather is airport dependent, it might be possible to safely authorise different separation distances for different airports around the world. This leads to the conclusion that *warning* for unfavourable evolution of the vortices (in terms of position and strength in relation to the encountering trailer aircraft) is most efficient. This can be achieved through an integrated Air Traffic Control (ATC) wake vortex system that can be used by controllers or on-board instrumentation for wake vortex detection and avoidance.

5 Conclusions and recommendations

A probabilistic approach has been followed to evaluate wake vortex induced risk in relation to different separation distances between landing aircraft on a single runway. The WAVIR methodology – integrating sub models for wake vortex evolution, wake encounter and flight path evolution – has been incorporated in a stochastic framework that facilitates the evaluation of e.g. newly proposed ATM procedures, aircraft design changes and/or wake alleviation instrumentation systems. The initial risk assessment results have been compared with proposed risk requirements to derive safe and appropriate separation minima for different operational, weather and wind conditions. It has been shown that a reduction of the current separation minima might be possible under most operational and weather conditions. However, it has also been shown that separation minima might need to be increased under some particular weather conditions. It was also found that the evaluated changes in ATM procedures at present will probably not allow safe reduction of separation distances. It was found that the highest risk is located near the runway threshold. This implies that weather based prediction, monitoring and warning systems should focus on exploiting weather and wind conditions favourable for rapid transport and decay of the vortices near the runway threshold. Clearly the first step towards such an operational system should include a reduction of risk near the runway threshold, including measures to reduce the probability and/or consequences of a wake vortex encounter. A risk management framework has been proposed to judge the acceptability of wake vortex induced risk. It is recommended that this framework is further elaborated by regulatory authorities towards new and modified harmonised wake vortex safety regulation with the aim to support the introduction of new wake alleviation systems and procedures. It is also recommended that the WAVIR tool is further developed towards a real-time aircraft spacing predictor which can be incorporated in an integrated ATC wake vortex decision support system that facilitates the use of dynamic weather dependent separation minima by controllers. As regards to weather prediction, such system should include a validated probabilistic nowcasting weather model for short term (i.e. at least 20 minutes) prediction of wind and temperature at or near the runway threshold.

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