**Nationaal Lucht- en Ruimtevaartlaboratorium**
National Aerospace Laboratory NLR

## Executive summary

# ATC-Wake: Integrated Wake Vortex Safety and Capacity System

**Problem area**
With the increase in air traffic, airports are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the separation distance between aircraft at take-off and landing without compromising safety. ATC-Wake aims to allow variable aircraft separation distances, as opposed to the fixed distances presently applied.

**Description of work**
The ATC-Wake project has developed, built and applied integrated ATC Wake Vortex Safety and Capacity *platform*:

- To evaluate the interoperability of ATC-Wake with existing ATC systems currently used at various European airports;
- To assess the safety and capacity improvements that can be obtained by local installation of the ATC-Wake system at various European airports;
- To evaluate operational usability and acceptability of the ATC-Wake system;

ATC-Wake can be used in the planning phase where weather and wake vortex forecast information are used together with aircraft separation rules to establish the arrival and/or departure sequence. For approaches, the aim is to manage separation distances down to 2.5 nautical miles. For departures, the aim is to reduce the time separation between departing aircraft to 90 seconds. Weather now-casting and wake vortex prediction and detection information is used to monitor and control safe separation. Wind forecast data is used to determine time frames suitable for reduced separation. Criteria on crosswind and associated safe separation minima are derived from safety assessment results obtained with the NLR WAke Vortex Induced Risk assessment (WAVIR) methodology.

**Results and conclusions**
The technical and operational feasibility analyses and the safety and capacity studies have built confidence in the operational concept and system design for the application of reduced separations to represent a sound ATC evolution, to deliver significant benefits for runway throughput and average delay per flight without major rework to the current ATC systems, while maintaining safety.

**Applicability**
Next step will be to complete the validation through production of a Safety Case, Human Factors Case, Business Case, and a Technology Case towards installation of the ATC-Wake at one or more European airports. The best would be to continue with airport shadow mode field trials.

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# Contents

# ATC-Wake: Integrated Wake Vortex Safety & Capacity System

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## Abstract

With the steady increase in air traffic, civil aviation authorities are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the separation distance between aircraft at take-off and landing without compromising safety. ATC-Wake aims to develop and build an integrated system for ATC (Air Traffic Control) that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. The ATC-Wake project has developed and built an integrated ATC Wake Vortex Safety and Capacity platform. A variety of subsystems is integrated and used within a test bed role:

- To evaluate the interoperability of ATC-Wake with existing ATC systems currently used at various European airports;
- To assess the safety and capacity improvements that can be obtained by local installation of the ATC-Wake system at various European airports;
- To evaluate operational usability and acceptability of the ATC-Wake system;

The ATC-Wake system is used in the planning phase where weather and wake vortex forecast information are used together with aircraft separation rules to establish the arrival and/or departure sequence. For approaches, the aim is to manage separation distances down to 2.5 nautical miles, in favorable weather conditions, for all aircraft types regardless of size. For departures, the aim is to reduce the time separation between departing aircraft to 90 seconds (in favorable wind conditions). Weather nowcasting and wake vortex prediction and detection information is used in the tactical phase to monitor and control safe separation. Wind forecast data is used to determine time frames suitable for reduced separation. Criteria on crosswind and associated safe separation minima are derived from safety assessment results obtained with the NLR WAke Vortex Induced Risk assessment (WAVIR) methodology. As main conclusion the ATC-Wake technical and operational feasibility analyses and the safety and capacity studies have built sufficient confidence in the operational concept and system design for the application of reduced separations to represent a sound evolution from existing ATC procedures and working practices, to deliver significant benefits for runway throughput and average delay per flight without major rework to the current ATC systems, while maintaining safety. The next step will be to complete the validation through production of a Safety Case, Human Factors Case, Business Case, and a Technology Case towards installation of the ATC-Wake at one or more European airports. The best would be to continue with airport shadow mode field trials, i.e., with direct involvement of airports and air traffic control centers.

## Introduction

With the steady increase in air traffic, civil aviation authorities are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the separation distance between aircraft at take-off and landing without compromising safety. One major limiting factor is that aircraft always give each other a wide berth to avoid each another's wake turbulence.

Figure 1. Wake vortices behind aircraft

With the aid of smart planning techniques however, these distances can be safely reduced, significantly increasing airport capacity. 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. However, with the aid of accurate meteorological data and precise measurements of wake turbulence, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains of up to 10%, which has major commercial benefits.

ATC-Wake aims to develop and build an integrated system for ATC (Air Traffic Control) that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports [1, 2]. The present minimum separation of six nautical miles for light aircraft (coming in behind a larger one), and three nautical miles for larger aircraft is designed to counter the problems aircraft can encounter in the wake of larger types. If these fixed distances can be reduced in favorable weather conditions without compromising safety, then an airport's aircraft-handling capacity increases accordingly. For approaches, the aim is to manage separation distances down to 2.5 nautical miles, in perfect weather conditions, for all aircraft types regardless of size. For departures, the aim is to reduce the time separation between departing aircraft to 90 seconds (in favorable wind conditions).

The ATC-Wake system integrates weather and wake sensors, weather forecasting and now-casting systems, a wake vortex predictor, a separation mode planner, and Air Traffic Controller interfaces. When used with new European wake vortex safety regulation, it should be able to provide airports and aircraft handling organizations a significant increase in punctuality and capacity, while maintaining safety. The main objective of ATC-Wake is to develop and build an integrated ATC Wake Vortex Safety and Capacity *platform* [3]. A variety of existing subsystems are integrated such that this *platform* is used in a test bed role:

- To evaluate the interoperability of ATC-Wake with existing ATC systems currently used at various European airports [5],
- To assess the safety and capacity improvements that can be obtained by local installation of the ATC-Wake system at various European airports [4, 5], and
- To evaluate operational usability and acceptability of the ATC-Wake system [5]

## Operational Concept, System Requirements

Before 1970, aircraft of similar weights and low traffic density mitigated the risk of wake vortex encounters. In 1970 and during the following years some wake vortex related incidents occurred due to the introduction of the Boeing 747 and the constant traffic growth. Between 1969 and 1976, extensive collection of data led to the definition of the ICAO separation standards based on aircraft maximum takeoff weight classes. These standards are felt to be over-conservative in most weather conditions and, likely, insufficient in some specific conditions.

In current ATC operations, no exchange of information concerning wake vortex is provided between ATC and aircrews, specific procedures exist only for the heaviest freight aircraft (Beluga, AN-22). As a consequence there is no system integrating all the sources of wake vortex related information together at a single source, accessible by all ATC service providers (en-route, approach, tower and arrival/departure managers). Since 1993, several European Union research and development programs have been launched to get better knowledge of the physical and safety aspects of the wake vortex phenomena and to develop technologies for wake vortex detection and prediction. Taking benefit of such technologies, the ATC-Wake operational concept and procedures have been defined on the principle of evolution

## Table 1. ATC-Wake System Components

| | |
|---|---|
| ATC-Wake Separation Mode Planner | Determines the applicable separation mode (ICAO mode or ATC-Wake mode) and advises about minimum aircraft separation distance.<br>The advisory includes the expected time for future mode transitions, and an indication of the aircraft separation minimum applicable |
| ATC-Wake Predictor | Predicts for individual aircraft the wake vortex behaviour ("Wake Vortex Vector - WVV") in the pre-defined arrival or departure area(s). The Wake Vortex Vector is part of the critical area (e.g. ILS Glide Slope) potentially affected by the wake vortex |
| ATC-Wake Detector | Detects for individual aircraft the wake vortex position, the extent and – if possible – also strength in the pre-defined arrival or departure area(s) |
| ATC-Wake Monitoring and Alerting | Alerts Air Traffic Controllers in case of :<br>• significant deviation between wake vortex detection and wake vortex prediction information which raises the risk of wake vortex encounter<br>• failure of one or several wake vortex components |

## Table 2. Existing ATC Systems Interfacing with ATC-Wake Components

| | |
|---|---|
| ATCo HMI | Provides the traffic situation picture and automated support for various ATCo tactical roles (Approach, Tower). |
| Arrival Manager | Determines automatically optimum arrival sequence and provides advises for realising this sequence. Communicates forecast sequence upstream to en-route and / or approach ATSUs |
| Flight Data Processing System | Keeps track of every flight information and updates, in particular the flight plan, the trajectory prediction, ETA and ETD, aircraft type and equipment. |
| Surveillance System | Provides and maintains the air traffic situation picture using all available detection means (radars, air-ground data links) |

## Table 3. ATC-Wake Users and Involved Actors

| Actor | Current Responsibility | Specific/additional Role in ATC-Wake |
|---|---|---|
| Airport ATC Supervisor | Monitors ATC tower and ground operations | Decides on arrival and departure separation mode and in case of ATC-Wake separation decides on the rate to be applied |
| Arrival Sequence Manager | In charge of arrival planning management for one or several runways, in co-ordination with adjacent ATC Units (sequencing and spacing of aircraft can be assisted by an arrival manager) | Uses wake vortex prediction information for determination of aircraft sequencing and spacing in the final approach corridor.<br>Co-ordinates forecast sequence upstream to en-route and / or approach ATSUs |
| Initial Approach Controller | In charge of inbound traffic from the Initial Approach Fix (IAF). Responsible for holding stacks management. | Establishes arrival sequence based on WV. |
| Intermediate Approach Controller | In charge of intermediate approach, ILS interception. Establishes sequence for final approach and landing | Establishes final approach sequence based on wake vortex prediction and informs about deviations |
| Tower Controller | In charge of final approach, landing, and take-off phases | Monitors safe and optimal separations using wake vortex detection and short term forecasting of the wake vortex movements. Instructs aircrew on any necessary evasive action. |
| Ground Controller | Organises and monitors aircraft and vehicles ground movements. Sequences departures according to landings | Uses wake vortex detection and short term forecasting of the wake vortex movements to optimise departure sequencing |
| Aircrew | Navigates aircraft safely | Complies with Controller's instructions to meet arrival sequence constraints based on wake vortex prediction information. Takes necessary evasive actions to avoid a wake encounter if instructed by ATC or alerted by on-board equipment (I-Wake). |

not revolution. As far as possible, existing concepts and procedures for arrivals and departures have been reused. In this context, the proposed ATC-Wake operations aim to allow [2]:

- Safe and efficient use of wake vortex detection and prediction information;
- Determination and implementation of appropriate separation between aircraft;
- Sequencing of approach and runway operations in a seamless way.

Depending on weather conditions influencing wake vortex transport out of so-called critical areas, two modes of aircraft separation have been defined: ICAO standard separation and ATC-Wake (reduced) separation. To implement an operational concept with these two modes of operation, four new ATC-Wake components are introduced (Table 1), which will interface with existing ATC systems (Table 2). The ATC-Wake system use is described in Table 3.

Based on meteorological conditions, ATC-Wake will advise the ATC Supervisor about applicable separation mode and associated validity period (start/end). The ATC Supervisor has the responsibility to decide the minimum separation to be applied for approach or departure as well as the landing rate to be used for arrival sequencing (using Arrival Manager (AMAN) or not). The time horizon to be considered for arrival sequencing is 40 min if an AMAN is used, 20 min otherwise. Based on planned traffic and meteorological conditions (wind profiles), an assessment of wake vortex transport and decay is performed in order to advise the ATC Supervisor about the applicable minimum separation for a fixed period of time (start / end of ATC-Wake operations). The transition from ICAO to ATC-Wake separation mode will begin by considering the incoming or departing aircraft that have a planned arrival time included in the start / end time period for ATC-Wake operations. The re-planning of arrivals (if necessary) will be performed by the Arrival Sequence Manager or by AMAN and transition information will be distributed to concerned ATCos. The time adjustments will be implemented by en-route controllers. This will be done through speed modifications and/or holding patterns.

It is assumed that the wake vortex situation will be monitored by comparing results of the ATC-Wake Prediction and ATC-Wake Detection. From ATC supervisor or operator viewpoint a typical refresh rate of such information is 30 minutes. In case of a discrepancy between prediction and detection information, an alert is provided to the controllers, who may instruct the pilot to initiate a wake vortex avoidance manoeuvre. To support the controllers with such monitoring and alerting procedure, Human Machine Interfaces (HMIs) visualizing the wake vortex, via a so called 'Wake Vortex Vector' (WVV) behind aircraft will have to be developed. In case of an alarm, the color of the WVV will change to orange and an audio alarm will be raised. In case of a caution or alert, the following actions shall be performed:

- Caution: all the other air traffic controllers shall be informed, but no instruction to the pilot is needed;
- Alert: a missed approach or turn instruction to the pilot of the potentially endangered aircraft is required, and the pilot shall initiate it as soon as practicable.

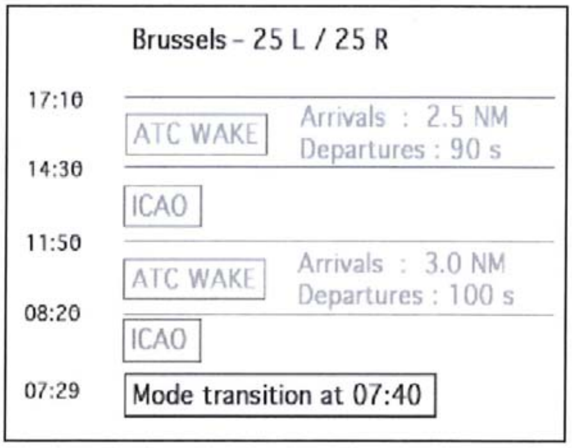


**Figure 2. Planning of Separation Modes**

## Integrated System Design and Development

The ATC-Wake Operational System includes four new functional components, which interface with existing and/or enhanced ATC system components. The new components are:

- ATC-Wake Separation Mode Planner,
- ATC-Wake Predictor,
- ATC-Wake Detector,
- ATC-Wake Monitoring and Alerting,

Existing ATC systems are: Arrival Manager (AMAN) or Departure Managers (DMAN) (if in use), Flight Data Processing System, and Surveillance Systems. Enhanced ATC systems are: Meteorological Systems, Supervisor HMI, and ATCo HMIs. For the meteorological systems, enhancements in prediction and update rates are foreseen and the HMI's for supervisor and ATCo shall be extended with ATC-Wake symbology. Figure 3 shows all relations between all the components. Note that new systems are indicated in yellow, existing systems in blue and enhanced systems in green. The functional dataflow allows: *Separation Mode Planning, Separation Mode Transition, and handling of aircraft during Intermediate and Final Approach and Departures.*

To support the ATC supervisor with planning of separation modes, an ATC-Wake Separation Mode Planner (SMP) has been developed and implemented [7]. In the SMP, Now-casting Wake Vortex Impact Variables (NOWVIV) wind forecast data is used to determine time frames suitable for reduced separation [7, 11]. Criteria on crosswind and/or head/tailwind and associated safe separation minima are derived from safety assessment results (e.g. using WAVIR [4, 7]). To enable interfacing between the Separation Mode Planner and the WAVIR safety assessment results, a WAVIR database has been set up. This database also enables users to review WAVIR parameter settings and retrieve WAVIR results via interfaces. In the context of "safety monitoring", such WAVIR database might be used to evaluate wake vortex safety performance indicators at an airport. Results from safety monitoring activities can also be fed back in the WAVIR database to tailor the database to specific airports, and to increase the performance and reliability of the Separation Mode Planner. In this first design of the Separation Mode Planner, relatively simple wind criteria have been proposed. Depending on the benefits that can be achieved with such criteria and the users requirements, further study may focus on elaborating these criteria.

*The ATC-Wake Predictor* is a new sub-system of the ATC-Wake system, which assesses the suitability of the separations, suggested by the SMP [8]. It determines the part of the glide slope potentially affected by wake vortices. The two main inputs of the ATC-Wake Predictor are the Meteorological Nowcast data provided by the Meteorological Systems and the traffic situation provided by the Surveillance Systems. Locally measured meteorological data are to be used as much as possible by the ATC-Wake Predictor. In ATC-Wake, two European real-time models have been used: the "Probabilistic use of the Vortex Forecast System (P-VFS)" and the "Probabilistic Two-Phase Decay" model (P2P) [12]. The P2P and the P-VFS are wake vortex predictors based

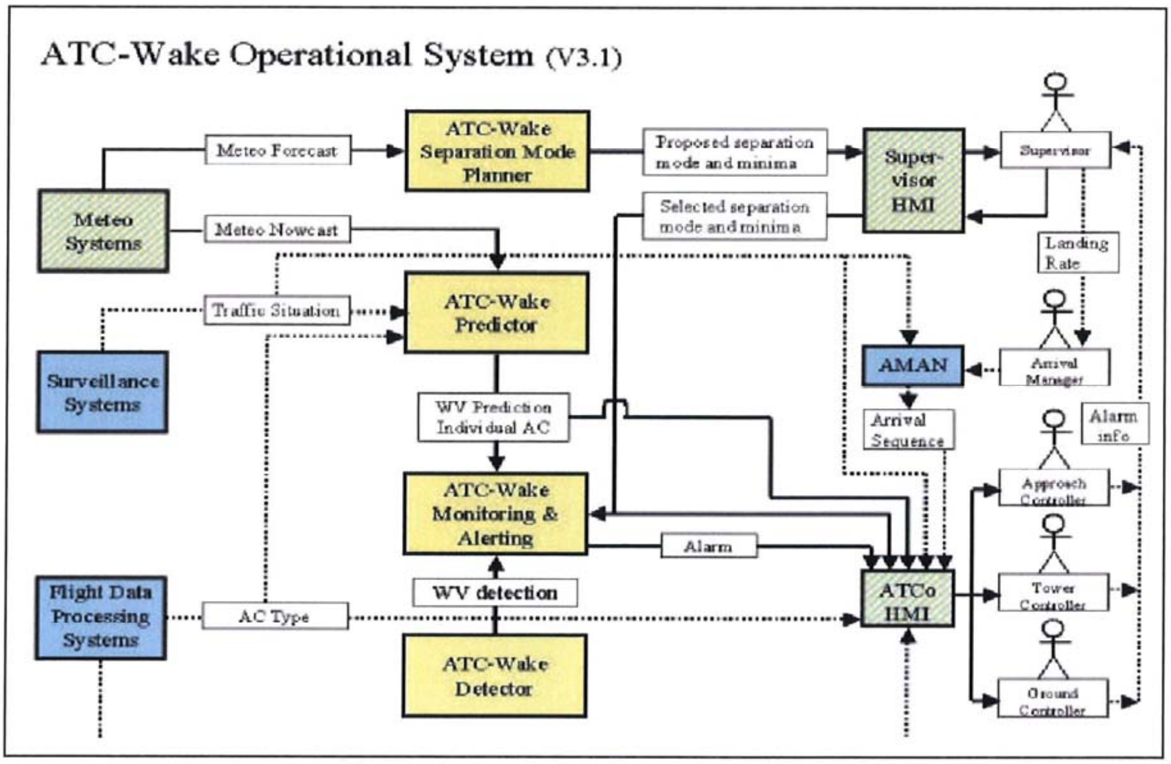
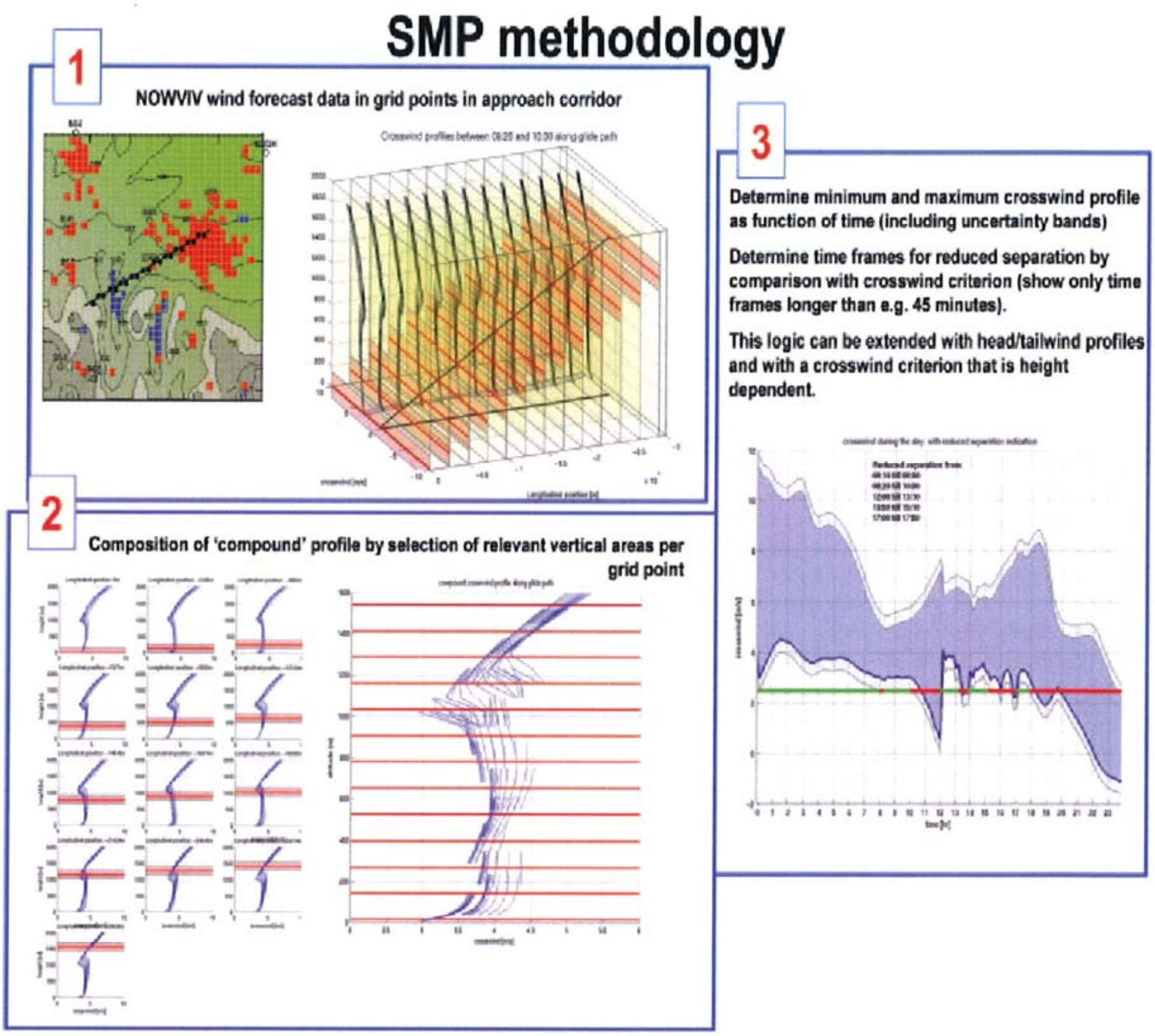


Figure 3. Functional flow of the ATC-Wake operational system



SMP methodology

1 NOWVIV wind forecast data in grid points in approach corridor

2 Composition of 'compound' profile by selection of relevant vertical areas per grid point

3 Determine minimum and maximum crosswind profile as function of time (including uncertainty bands)

Determine time frames for reduced separation by comparison with crosswind criterion (show only time frames longer than e.g. 45 minutes).

This logic can be extended with head/tailwind profiles and with a crosswind criterion that is height dependent.

Figure 4. Separation Mode Planning Methodology

respectively on probabilistic and deterministic approach. Every 6 seconds, the Predictor takes a snapshot of the entire traffic situation around the airport. For each aircraft, it computes, using the weather data at the aircraft position, the time evolution of the danger volume which contains the wake vortices generated by this aircraft. The following local data needs to be available: runway co-ordinates, meteorological measurement point co-ordinates, and radar accuracy. The main output of the Predictor is the "Wake Vortex Vector" (WVV) of aircraft in the so-called critical area. The length of the WVV is defined as the distance between the generator aircraft and the first gate considered as "Vortex Free". As mentioned before, the Predictor data is continuously compared with the Detector data to verify correctness.

*The ATC-Wake Detector* is to detect wake vortices and to provide this information to the ATC-Wake Monitoring and Alerting system. The Detector serves as a safety net and is a stand-alone technique, which only reports its monitoring result. The Detector is necessary at least for an initial time period after installation of ATC-Wake, and measures the turbulence in real-time in the critical area with ground-based equipment. Wake detection is performed using ground-based equipment (e.g. pulsed LIDAR), which scans along the critical area (ILS glide path) in pre-defined windows. No connection to airborne equipment is assumed, but detection may be complemented using airborne equipment. Ideally, the whole glide path should be monitored for wake vortices, while the focus should be on the wake detection close to the surface where a wake vortex encounter may be most critical. Operationally, such a LiDAR system is used at Hong Kong to detect clear air turbulence along the glide path (however, not the whole glide path can be covered by this system; the range is approximately 8.5 km).

*ATC-Wake Monitoring and Alerting* is a product of the output of the ATC-Wake Predictor from the Wake Vortex Vector (WVV) of an aircraft in a so-called critical area. This information can be presented as enhancement of a Plan View Display (PVD). The PVD shows the information received from the airport radar combined with flight track data. For the controllers, the "Variable Wake Vortex" HMI has been developed and tested with active controllers from five countries (see Figure 6) [3]. New is the blue colored vector behind each aircraft, representing the WVV and varying (using information from the Predictor) along the glide slope. Also a micro-label with the distance to the preceding aircraft is proposed. The ATC-Wake Monitoring and Alerting module will monitor every aircraft in the critical area and raise appropriate alarms to ATCo's in case of significant deviation between WV detection and WV prediction information with a risk of WV encounter. In this case, the color of the WVV changes to orange and an audio alarm is also raised (see Figure 7).

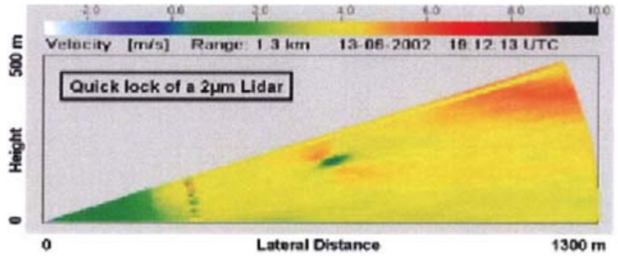


Figure 5. Example of Lidar Scan Result for Wake Vortex Monitoring

## Safety and Capacity Analysis

The overall objective of the Safety and Capacity analysis is the quantification and evaluation of possible safety and capacity improvements when using ATC-Wake. The overall approach taken started with the derivation of capacity aims, using a series of analytical tools and a simulation platform developed by EUROCONTROL for providing performance predictions for a future ATM system [4]. Introducing and/or planning changes to the ATM system cannot be done without showing that minimum safety requirements will be satisfied. Evaluation of wake vortex separation has historically been conducted using three approaches:

(1) Experimental flight test data,

(2) Historic operational data, and

(3) Analytical models.

As the ATC-Wake system is still in the design phase, this study follows the third approach, using probabilistic risk assessment techniques to establish safe separation distances on the basis of predefined safety risk criteria.

The ATC-Wake safety assessment has been performed in two steps. The first step consists of a qualitative safety assessment, so as to identify the hazards and safety bottlenecks associated with the proposed operational concept. The ATC-Wake operation is then analyzed quantitatively through the use of the NLR Wake Vortex Induced Risk assessment (WAVIR) methodology and toolset [4]. This second step includes estimation of the new ATC-Wake (reduced) separation minima proposed under favorable weather conditions.

### *Qualitative safety analysis*

A qualitative safety assessment has been performed to get a global overview of the risks associated with the proposed ATC-Wake operation for Single Runway Arrivals (SRA), Single Runway Departures (SRD) and closely spaced parallel runway arrivals (CSPRA) [4]. In

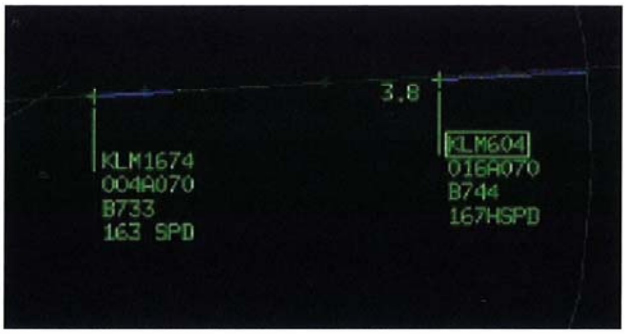


Figure 6. Approach controller HMI

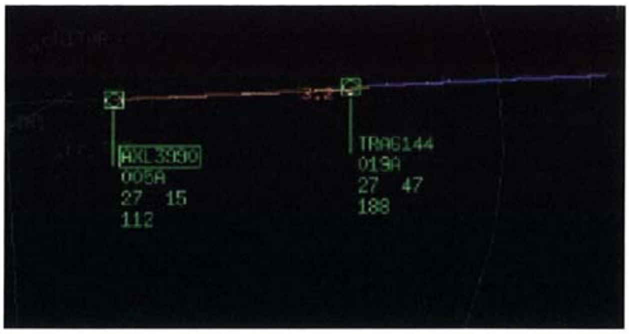


Figure 7. Alerting for tower controllers

various brainstorming sessions with operational experts, hazards have been identified that could occur in the considered operation. After the identification of hazards, these hazards have been structured into conflict scenarios, which describe all relevant ways how these hazards may lead to conflicts or worsen them. Using operational experts' judgment and knowledge from other studies, for each of these conflict scenarios the severity and frequency has been assessed. Subsequently, an evaluation of the acceptability of the risk of each scenario was given. The conflict scenarios and the outcome of the assessment, including potential safety bottlenecks, are given in Table 4.

## Quantitative safety analysis

Indicative safe separation (crosswind) minima have been determined for Single Runway Arrivals (SRAs), Single Runway Departures (SRD) and Closely Spaced Parallel Runway Arrivals (CSPRA) [4]. The first two are now discussed in this paper. For the latter, see also Speijker [4]. These indicative separations may only be applied in case the ATC-Wake system (and operation) is used, and the system components meet certain performance requirements. In particular, sufficiently stable and reliable meteorological forecast/now-casting data and wake vortex detection information is a prerequisite for safe implementation and operational use.

Note that this study focused on crosswind only. Strong headwind conditions are known to be beneficial as well. EUROCONTROL is now investigating the use of Time Based Separation for arrivals in strong headwind conditions [10].

### *Separation distances for ATC-Wake single runway arrivals*

The quantitative safety assessment was performed with the WAVIR tool, for a variety of simulation scenarios representing London Heathrow weather climatology. A Large jumbo jet and Medium jet as Leader Aircraft (LAC) were combined with a Large jumbo jet, Medium jet, Regional jet, and Light turbo prop as Follower Aircraft (FAC). Crosswind was varied between 0, 1, 2, and 4 m/s at 10 m altitude, assuming a logarithmic profile with height. Evaluated separation distances (at runway threshold) were 3.0, 4.0, and 5.0 NM. The indicative separation minima are given in Figure 7. Taking into consideration that ATC-Wake reduced separation should be applied to all aircraft combinations and that because of radar separation criteria 2.5 NM is currently the minimum spacing, Table 5 provides indicative safe separation minima for the assessed operation for certain crosswind intervals.

### *Separation distances for ATC-Wake single runway departures*

## Table 4. Overview of Potential SAFETY BOTTLENECKS for the Conflict Scenarios

| Conflict scenario | Potential SAFETY BOTTLENECK in the ATC-Wake operation | | |
|---|---|---|---|
| | SRD | SRA | CSPRA |
| Wake vortex encounter during departure | Yes | NA | NA |
| Wake vortex encounter during single runway arrival | NA | Yes | NA |
| Missed approach during single runway arrival | NA | No | NA |
| Wake vortex encounter before ILS interception | NA | No | No |
| Wake vortex encounter during arrivals on CSPRs | NA | NA | Yes |
| Missed approach during arrivals on CSPRs | NA | NA | No |
| Higher traffic rates in TMA, holding, sector, or runway | Yes | Yes | Yes |
| Turbulence | No | No | No |
| More landings in crosswind | NA | Yes* | Yes* |
| Transitions between ICAO & ATC-Wake separation mode | Yes* | Yes* | Yes* |
| Effects on ICAO separation mode | Yes* | Yes* | Yes* |

** The risk tolerability of these conflict scenarios could not be assessed in detail. NA =Not Applicable*

## Table 5. Indicative ATC-Wake Separation for Single Runway Arrivals

| | Proposed separation (the largest value in a row applies) | | |
|---|---|---|---|
| Crosswind interval | Wake vortex induced separation minima | Radar separation minima | Runway Occupancy Time (ROT) minima |
| uc ≤ 2 m/s | ICAO | 2.5 NM | aircraft/runway dependent |
| 2 ≤ uc ≤ 4m/s | 2.5 NM | 2.5 NM | aircraft/runway dependent |
| 4 m/s ≤ uc | 2.0 NM | 2.5 NM | aircraft/runway dependent |

The quantitative safety assessment was performed with the WAVIR tool, for a variety of simulation scenarios representing London Heathrow weather climatology. The crosswind was varied between 0, and 5 m/s at 10 m altitude, assuming a logarithmic profile with height. An important departure specific and aircraft dependent parameter is the lift-off point. In the assessment a distinction has been made between early and late lift-off of the aircraft. The variation of lift-off points results in a variation of departure tracks. When the follower aircraft lifts off early behind a leader aircraft that lifts off late, the departure path of the follower aircraft well exceeds that of the leader aircraft, and as a consequence the associated risks are low. To stay on the conservative side, the risk results have been maximized over the variation in lift-off point before deriving the safe separation minima presented in Figure 8. The variety of flight tracks in the departure operation, because of differences in climb performance and lift off points, results in interesting observations. For example, a Light business jet behind a Large jumbo jet might be separated with just 60s [4]. Taking into consideration that ATC-Wake Mode should be applied to all aircraft combinations, Table 6 indicates safe separation minima for different crosswinds. Reduced separation of 90s may be applied when crosswind exceeds 3m/s, while 60s separation can be applied with crosswind above 5m/s.

## Overview of Proposed ATC-Wake Separations

Indicative separation minima have been derived for each of the three ATC-Wake operations, and tables have been derived that link the prevailing crosswind speed to the separation to be applied in ATC-Wake Mode. The results are summarized in Table 7. The crosswind intervals have been split up in bins of 1m/s width. A crosswind climatology based on 400,000 observations at about 10 European airports has been used to determine the probabilities of occurrence of the crosswind interval. The data source itself is confidential. Crosswind from left and right appeared to be equally likely. The resulting crosswind probabilities listed in Table 7 give the likelihood of certain crosswind conditions. [4]

### *Runway Throughput and Delay*

To derive the potential benefits of the ATC-Wake operation at an airport with average (wind) conditions, the statistical data on the occurrence of crosswind at an airport, and the ATC-Wake separation schemes as function of crosswind are combined. Table 8 provides a summary of the runway throughput and delay characteristics of the SRA and SRD operation [4, 5]. Results are promising as already a 1 or 2% increase in throughput leads to substantial economic benefits. The current study focused on crosswind only. Strong headwind conditions (as studied in Time Based Separation), is known to be beneficial as well. It is thus recommended for future work to focus on elaboration of the current approach towards an evaluation of individual airports with their local weather conditions.

### *Main conclusions and results from the safety and capacity analysis*

WAVIR simulations for the SRA operation indicate that reduced separation of 2.5 NM might be applied safely in ATC-Wake Mode provided that crosswind is forecasted to be above a certain limit. During ATC-Wake arrivals, the Monitoring and Alerting component will anticipate

## Table 6. Indicative ATC-Wake Separation for the SRD Operation

| Crosswind interval | Proposed wake vortex separation |
|---|---|
| 0 ≤ uc ≤ 2m/s | ICAO |
| 2 ≤ uc ≤ 3m/s | 120s |
| 3 ≤ uc ≤ 5m/s | 90s |
| 5m/s ≤ uc | 60s |

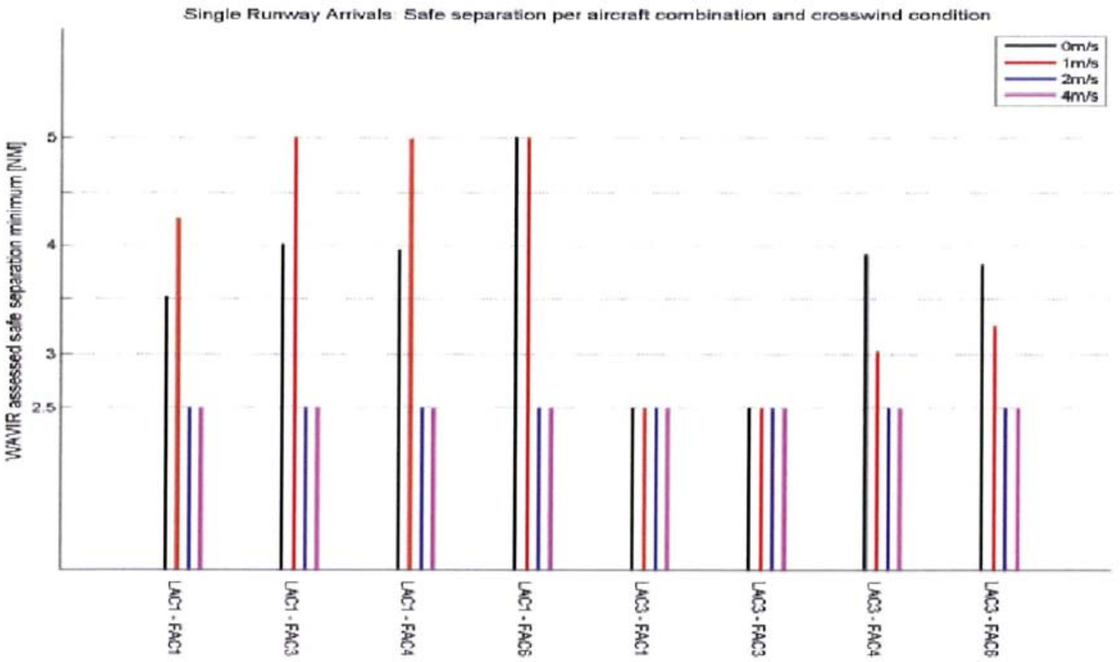


Figure 8. Overview of WAVIR Assessed Safe Separation Minima for SRA Operation

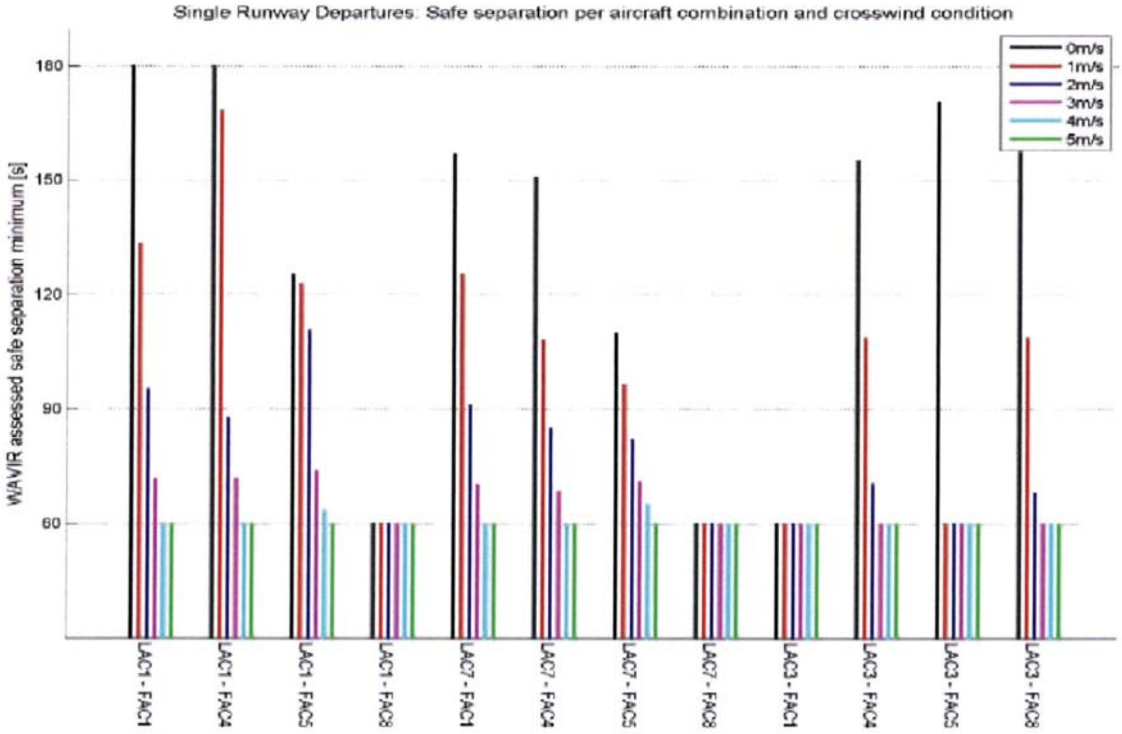


Figure 9 – Overview of WAVIR assessed safe separation minima for SRD operation

potential wake encounters in time (and generate an alert). Nevertheless, if the meteorological forecast information is not accurate and stable enough, this might be achieved at the cost of a relatively large number of missed approaches [4]. Simulations indicate that, provided that certain requirements are met, about 30% of the approaches might be performed with 2.5 NM aircraft separation in case ATC-Wake is used. WAVIR simulations for the SRD operation also indicate that reduced separation of 90 seconds can be applied safely with ATC-Wake, provided that crosswind is forecasted to be above a certain limit. If the accuracy of the wind forecast information is too low, the Monitoring and Alerting component could provide a relatively large number of alerts. A potential issue is that immediately after takeoff, i.e., at relatively low altitude, it will not be feasible for the pilot to turn away from the wake vortex of a preceding aircraft. This implies that the provision and use of meteorological now-casting information by the controller will be very beneficial (and might even be needed), in order to support the pilot to prepare for a potential encounter in case of a sudden change of the wind conditions.

Various activities have been performed to validate the safety assessment (including verification and validation of the wake evolution models, wake encounter models, and aircraft performance models). Nevertheless, it has become clear that the wake vortex phenomena during departures is still not fully understood, i.e. further research is needed before the outcome of the departure safety assessment is ready for approval by regulatory authorities. The full Safety Case needs to account for the local wind conditions of the airport envisaged for ATC-Wake introduction.

## Evaluation of Operational Feasibility

Next step is the evaluation of ATC-Wake operational feasibility of the proposed ATC-Wake system for ATC operations, including the analysis of interoperability with existing ATC systems and usability and acceptability by ATC Controllers. This included the following steps:

- Evaluation of the operational concept and procedures, analysis of the issues raised by a group of ATC Controllers involved in real-time simulations and other issues raised by the ATC-Wake participants.

### Table 7. Indicative Separation per Crosswind Interval for ATC-Wake

| | Proposed separation | | Crosswind probability |
|---|---|---|---|
| Crosswind interval | SRD operation | SRA operation | Crosswind probability per interval |
| 0 ≤ uc ≤ 1m/s | ICAO | ICAO | 0.080 |
| 1 ≤ uc ≤ 2m/s | ICAO | ICAO | 0.208 |
| 2 ≤ uc ≤ 3m/s | 120s | 120s | 0.206 |
| 3 ≤ uc ≤ 4m/s | 90s | 90s | 0.164 |
| 4 ≤ uc ≤ 5m/s | 90s | 90s | 0.118 |
| 5 ≤ uc ≤ 6m/s | 60s | 60s | 0.081 |
| 6 ≤ uc ≤ 8m/s | 60s | 60s | 0.053 |
| 8m/s ≤ uc | 60s | 60s | 0.090 |

- Evaluation of the interoperability with existing ATC systems: ATC-Wake user and system requirements have been evaluated against existing airport systems and the size of the required changes has been assessed.
- Airport and airspace simulations: a series of fast-time simulations aiming at measuring the size of the operational benefits for ATC-Wake. The simulations have been prepared considering existing airport operations, a generic airport layout and existing traffic samples (see Vidal [5]).

### *Evaluation operational concept and procedures*

A number of key issues have been identified and further investigated during the operational concept evaluation. Examples are [5]:

- Transitions between ATC-Wake and ICAO separation modes;
- Missed Approaches in ATC-Wake mode;
- Prevention of encounters by using the Wake Vortex Vector;

### Table 8. Summary of Runway Throughput and Delay Characteristics

| Operation | ICAO | ATC-Wake | Change | ICAO | ATC-Wake | Change |
|---|---|---|---|---|---|---|
| SRD | 37.8 | 38.6 | +2.1% | N/A | N/A | N/A |
| SRA | 35.2 | 37.0 | +5.0% | 3.0 | 2.15 | -29% |

These issues have been addressed through questionnaires prepared for 9 ATC controllers from 5 different countries, involved in two real-time simulation experiments on the NLR Air Traffic Control research simulators (NARSIM) [5]. The first simulation was to determine the preferred HMI by the Approach and Tower controller, and the second to verify this result by other controllers and showing them the ATC-Wake concept. The debriefings included discussions on all ATC-Wake topics and results have been used for analysis of the concept and procedures. Answers on the System Usability questionnaires and the debriefing gave a good indication of the usability and acceptability of the ATC-Wake HMI and concept.

The main results of the responses to the questionnaire are summarized below:

- The ATC-Wake concept itself is relatively easy to understand,
- The air traffic controllers like to have the system operational continuously,
- The controllers like to have the ATC-Wake system as safety system,
- It is suggested to eliminate the difference between ICAO and ATC-Wake,
- It is suggested to keep weight category information available in ATC-Wake mode,
- The ATC-Wake mode, with the same separation between all aircraft, is not useful when the separation advised by the SMP is larger than 3 NM, and
- The transition between ICAO and ATC-Wake mode and vice versa is no problem.

But also some Air Traffic Controllers had their doubts. The most important ones:

- Even as they understand the concept, they keep doubts about decline of the Wake Vortex Vector along ILS when the aircraft comes closer to the runway;
- They keep some doubts that the pilots will follow their instructions when they put a medium aircraft close (within the ATC-Wake separation) behind a heavy aircraft.

Two specific issues with respect to the missed approach procedure have also emerged [5]:

- Determination of the separation minima to be applied in ATC-Wake arrivals shall consider wake vortices generated by missed approaching aircraft;
- ATCo training shall be extended with cases where several missed approaches have to be executed for aircraft following in-trail.

Figure 10 – Tower Position

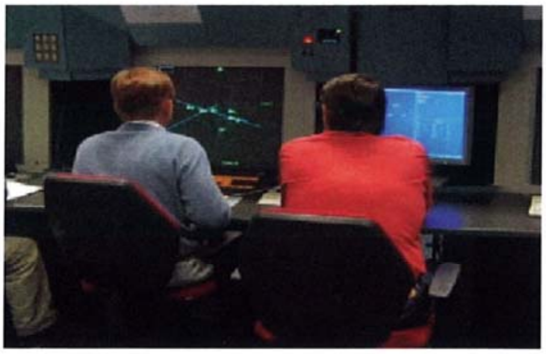


Figure 11 – Approach Position

To be useful as a safety net, ATC-Wake indeed warns the ATC controllers about:

- Wake vortex information lack of integrity: provide alarms when there is a difference between observed and predicted wake vortex behavior (position or decay).

Wake vortex encounter prevention: provide the appropriate alarm to the ATC controller when the risk of encounter is detected for an aircraft, by monitoring the position of aircraft with respect of the "danger area" of the preceding one.

Such results confirm that there are no major concerns with respect to the proposed operational and user requirements. The ATC controllers have recognized that the ATC-Wake concept is an evolution from the current concept applied in Europe. The integration of information on wake vortex detection and prediction both for planning and tactical operations has been positively received. The transition between ICAO standard separation and reduced separation has been compared with the current meteorological transitions (wind direction or visibility) that influence airport operations (change in runway directions, application of low visibility procedures).

## Evaluation of Interoperability with Existing ATC Systems and Size of the Required Changes

The main change implied by ATC-Wake (as compared with the current operational procedures) is the transition from the fixed wake vortex separation minima defined by ICAO to the ATC-Wake separation minima, which is updated regularly (with at least a 40 minutes pre-notice). From ATC controller perspective such transition can be compared with a runway configuration change (e.g. from west to east configuration) and therefore does not represent a revolution for aerodrome operations. Another significant change is the issue of wake vortex related alerts (indicating the potential risk of a wake vortex encounter) by the ATC-Wake system. Such alerts do not exist in the today operational procedures. The main new actions required for the ATC controllers will be limited to informing the pilot and supporting his/her decisions by providing guidance and/or separation with other traffic.

## Operational benefits assessment

Fast-time simulations have allowed us to assess the potential gains for runway throughput and flight times considering a number of potential scenarios for the reduction of minimum separation (distance or time) and the runway usage (arrivals only, departures only, mixed mode) [5]. The potential gains following the application of reduced separation are significant. However, the actual gains will be dependent on a number of factors:

- Favorable meteorological conditions: to take benefit out of sufficient crosswind a minimum 20 minutes reliable wind forecast is necessary to plan traffic. Good visibility conditions are required for reduced separation operations.
- Traffic pressure: reduced separation operations will deliver benefits only when a high traffic load exists and sufficient notice is made to ATC to plan movements.
- Traffic distribution: potential benefits of the application of reduced separations are highly dependent on the traffic distribution.
- Airport layout: the general behavior of departing and landing aircraft is highly related to the selected airport layout.

## Main operational feasibility results

The assessment of operational feasibility for ATC-Wake implementation has included:

- Evaluation of the correctness, usability and acceptability of the operational concept by ATC Controllers. The real-time simulations performed by NLR indicate that the ATC-Wake concept of operations has been easily adopted by a team of ATC controllers and positive feed-back for its use in operations has been received. The size of the changes from operational perspective (airport infrastructure, training) fits with the existing airport evolutions to cope with the increasing traffic demand.
- Impact on existing ATC systems: the analysis of interoperability issues has confirmed that the main changes to systems concern the implementation of specific atmospheric sensing systems (e.g. weather radar or LIDAR) and the introduction of ATC-Wake tools for ATC (Speijker [1]).
- Operational benefits: the potential ATC-Wake gains for runway throughput and flight times considering have been assessed through fast time simulations [5]. The gains following the application of reduced ATC-Wake separations could be significant.

## Conclusions and Recommendations

The ATC-Wake project has developed an integrated platform for ATC (Air Traffic Control) that will allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports [1, 2, 3]. A variety of subsystems has been integrated and used within a test bed role:

- To evaluate the interoperability of ATC-Wake with existing ATC systems currently used at European airports [5],
- To assess safety and capacity improvements that can be obtained by local installation of ATC-Wake at European airports [4, 5], and
- To evaluate operational usability and acceptability of the ATC-Wake system [5].

As a first step towards use of an ATC-Wake system at airports, the operational concept and requirements for the application of reduced aircraft separation under favourable weather conditions have been established. During the development and evaluation of the system requirements, it was concluded that sufficiently stable and reliable meteorological forecast/ now-cast data and wake vortex detection information is a prerequisite for safe implementation of ATC-Wake. The reduced wake vortex separation, targeted under crosswind conditions are:

- 2.5 NM separation between all aircraft on the same final approach path.
- 90 seconds between all aircraft departing on the same runway.

The ATC-Wake Operational System comprises four new components, which interface with several existing and/or enhanced ATC systems. New ATC-Wake components are the ATC-Wake Separation Mode Planner, Predictor, Monitoring and Alerting, and Detector. These components have been integrated successfully, and it has been shown that the defined functional data flow can be realized in an Operational ATC System. The technical feasibility of the ATC-Wake system has been evaluated by experimental simulations with the Integrated Platform. It has been shown that the functional integration of the components is successful and it will be technically feasible to integrate wake vortex prediction/ detection information into existing ATC systems. Air Traffic Controller Human Machine Interfaces have been designed, specified, and tested successfully through two real-time simulation experiments with nine active controllers from five European countries. As motivation for the use of ATC-Wake, the potential safety and capacity improvements have been evaluated. It has been shown that runway throughput and delay improves noticeably when ATC-Wake is used. Depending on the occurrence of favorable crosswind conditions, the increase in runway throughput is about 2% for ATC-Wake single runway departures and about 5% for the ATC-Wake single runway arrival operation (estimated for a generic airport with average wind conditions).

The safety assessment of the ATC-Wake operation has been performed in three steps. First, as part of the qualitative safety assessment, potential hazards and conflict scenarios related to use of ATC-Wake have been evaluated. Second, through use of the 'classical' WAVIR tool, indicative separation minima dependent on crosswind conditions have been determined. As these indicative separation minima do not yet account for crosswind uncertainty, as part of the third step, the setting of requirements for the ATC-Wake system components was further investigated. It appears that the Monitoring and Alerting system and Meteorological Forecast and now-casting systems are crucial and sufficient accuracy and reliability shall be guaranteed.

WAVIR simulations for the SRA operation indicate that reduced separation of 2.5 NM can be applied safely in ATC-Wake Mode provided that crosswind is forecasted to be above a certain limit. The simulations indicate that, provided that certain requirements are met, about 30% of the approaches might be performed with 2.5 NM aircraft separation in case ATC-Wake is used. WAVIR simulations for the SRD operation also indicate that reduced separation of 90 seconds can be applied safely in ATC-Wake Mode, provided that crosswind is forecasted to be above a certain limit. A potential issue is that immediately after take off, i.e. at relatively low altitude, it will not be feasible for the pilot to turn away from the wake vortex of a preceding aircraft. The simulations were performed for a generic airport. A full Safety Case needs to account for local wind conditions of the airport targeted for ATC-Wake introduction.

The assessment of operational feasibility for the implementation of ATC-Wake operational concept within Europe has been performed along several axes. The real-time simulations performed by NLR indicate that a team of ATC Controllers has easily adopted the ATC-Wake concept of operations and positive feedback for its use in operations has been received. The size of the changes from operational perspective (airport infrastructure, training) fits with the existing evolutions observed at European airports to cope with the increasing traffic demand. Actual operational benefits and gains will be dependent on a number of factors, including favorable meteorological conditions, traffic pressure, traffic distribution, and airport layout. The analysis of interoperability issues has confirmed that the main changes to systems concern the implementation of specific atmospheric sensing systems (e.g., weather radar or LIDAR), the introduction of ATC-Wake tools for ATC (separation mode planning, wake vortex prediction, detection and monitoring tools). An arrival manager would require some modification to support the fluent transitioning between ATC-Wake reduced separations and standard ICAO separations (depending on meteorological conditions).

As a main conclusion, the ATC-Wake technical and operational feasibility analyses and the safety and capacity studies have build sufficient confidence in the operational concept and system design for the application of reduced separations to represent a sound evolution from existing ATC procedures and working practices, to deliver significant benefits for runway throughput and average delay per flight without major rework to the current ATC systems, while maintaining safety. The next step will be to complete the validation through production of a Safety Case, Human Factors Case, Benefits Case, and a Technology Case towards installation of the ATC-Wake at one or more European airports. The best would be to continue with airport shadow mode field trials.

The positive conclusions on technical and operational feasibility as well as potential safety and capacity improvements will need to be traded-off against the actual weather 'windows' to perform such operations and costs for the acquisition and implementation of the new equipments or infrastructure required (wake vortex sensors, new atmospheric sensing systems, enhanced weather forecast capabilities). Recommendations for complete validation of ATC-Wake have been identified:

The requirements for the further validation of the use of wake vortex detection and monitoring systems at the targeted airport have to be specified:

- Perform a year-long measurement campaign that allows gathering a significant sample of correlated weather, wake vortex and aircraft data that will serve as a basis for performance and safety assessment.
- Assess the performance of wake vortex sensors and predictors in the critical areas in particular in the landing and take-off areas.
- Assess the performance of wake vortex predictors in the critical areas.
- The local conditions for application of reduced wake vortex separation at a targeted airport have to be characterised in detail on the basis of collected data.
- The assessment of operational benefits shall be refined using a repository of information for the main external factors influencing ATC-Wake operations, i.e. weather conditions (visibility and wind) and their fluctuations, weather forecast limitations and traffic demand: what are the limitations of traffic tactical re-planning to best use the non-permanent reduction of separation?
- The transition towards the ATC-Wake operational concept shall be assessed.

Intermediate application steps of reduced separations in well defined conditions, delivering less benefits but available on a shorter time frame and supported by a subset only of ATC-Wake systems, may represent significant incentives for airports and pave the way for complete ATC-Wake implementation.

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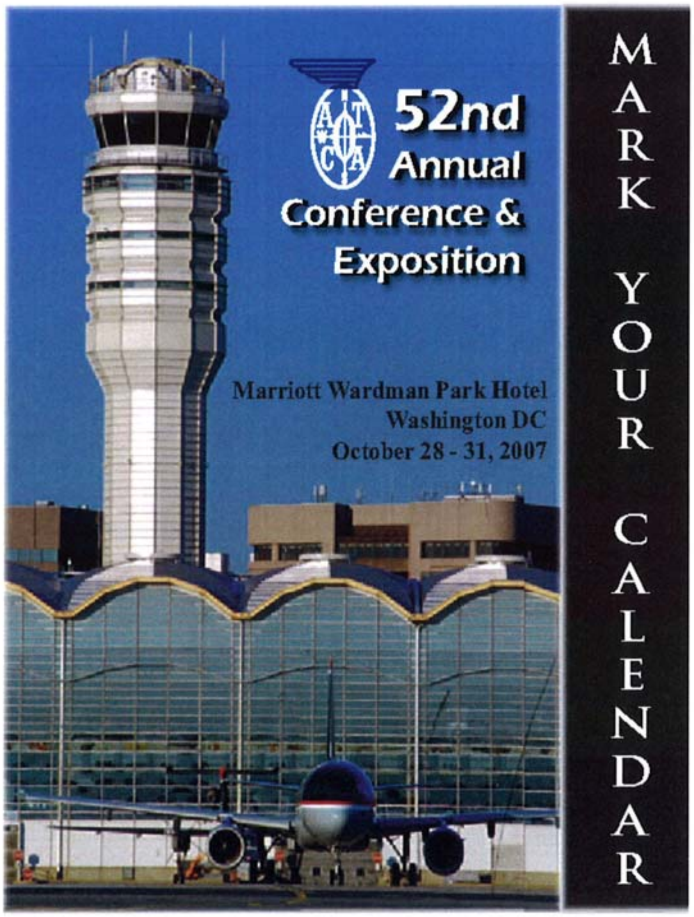
### About the Main Author

Lennaert Speijker (speijker@nlr.nl) was born on June 12th 1967 in Haarlem, Netherlands. He studied Mathematical Engineering at the Delft University of Technology, where he graduated in 1995. He then joined National Aerospace Laboratory NLR, where he started to work on the development and application of various mathematical models to assess the safety of civil aviation. In recent years, following the '9/11' terrorist attacks on New York, he has extended his scope towards air transport security. In this area, he is working on new concepts and systems to improve in-flight security. He is working as a Senior R&D Manager in the Safety and Flight Operations Department of the NLR Air Transport Division.



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