COMPUTER SIMULATIONS OF AIRCRAFT WAKE VORTICES:  
GOOD ENOUGH TO QUANTIFY SAFETY?

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Abstract: Vortices behind aircraft are inherently related to the generation of lift and decay  
very slowly. When strong, they present a safety problem for the following aircraft and for that  
reason specific separation distances are recommended by ICAO (the International Civil  
Airline Organisation). At the same time, they limit the number of aircraft that can land on a  
particular runway. Recently, both in the USA and in Europe, studies are made to see if for  
specific conditions a decrease in separation distances is feasible.  
To see if capacity can be increased without loss of safety, computer simulations are made of  
the air traffic situation, the generation and the decay of wake vortices and the flight  
mechanical effects on the follower aircraft when a vortex is encountered. The aim is to  
quantify both the capacity change (e.g. expressed as the number of landings per hour) and the  
safety (e.g. expressed as a target level of safety like a chance of 1.55x10⁻⁸ on a fatal accident).  
The prediction of the weather dependent decay of wake vortices is a critical issue here. Large  
eddy simulations that include the specific features of the weather can describe the decay of  
vortices in a physically correct way. These calculations can be imbedded in a probabilistic  
safety assessment to calculate with Monte Carlo simulations the level of safety. Are these  
results sufficiently reliable to determine an absolute safety level or can they only be used in a  
relative way? And are the models used in these studies sufficiently validated to convince the  
regulatory authorities that separation distances can be reduced indeed?  
These questions will be discussed in some detail. The presentation is a personal view of the  
author, to a large part based on the findings of the European Thematic Network WakeNet2-  
Europe that was active between March 2003 and March 2006 and in which the major players  
in this field (Industry, Research Institutes, Universities, Air Traffic Service Providers,  
Weather Bureau’s and pilots) were represented. The author was the coordinator of this  
network.
1. INTRODUCTION

Wake turbulence separations are a major factor limiting the capacity at many European airports. Several additional movements per hour, depending on weather conditions, seem possible if the behaviour of the trailing vortices can be predicted accurately enough. Such a capacity benefit seems achievable at comparably low cost; however, no-one so far has succeeded to develop, implement and operate such a system or procedure on a routine basis. Several concepts of operation (CONOPS) are currently investigated.

For wake vortex related procedural changes, one has to proof that the system or procedure meets a certain pre-defined and agreed target level of safety. The basic requirements for such an analytic approach are laid down in ESARR4 that specifies a ‘target level of safety’ (TLS) for the ATM related activities: per flight hour the chance of a catastrophic accident (involving loss of life) should be less than $1.55 \times 10^{-8}$. This number has been derived from the requirement that the safety should remain on the present level for the years ahead when the air traffic has doubled.

To proof that such an absolute target level of safety is reached for wake vortex applications is difficult, mainly due to the complexity of the problem. The methods used to calculate the safety level should simulate all aspects of the system in great detail. If it can be proven that a new system or procedure is at least equally safe as the one it replaces, a relative safety assessment might be sufficient for those elements that are affected by the proposed change. Relative estimates will be less susceptible to certain model simplifications.

For each proposed CONOPS (rule and/or procedural change) a safety case will have to be made to convince all users and the authorities that the proposed change is safe. A probabilistic safety assessment can be part of this and two such methods for wake turbulence are in development in Europe:

- WAVIR, the oldest one and developed by NLR\(^{3,4,5}\) and
- WakeScene/VESA developed more recently by DLR/AIRBUS\(^{6,7}\).

There appears to be a difference in thinking between ‘the model builders’ for probabilistic safety assessments and the ‘operational people’ that work on new concepts of operation. Where ‘model builders’ will show impressive figures how well their method compares with available experiments, the ‘operational people’ often claim that these models are hardly validated if of use at all.

In the so called ‘Research Needs Document’\(^1\) that concluded the activities of the Thematic Network WakeNet2-Europe it was concluded that: ‘For a better acceptance of these methods, it is essential that the methods used in the proposed probabilistic safety assessments are traceable, transparent and validated. They should also be open for judgement by independent experts’.

This paper is a critical review of various elements of a probabilistic safety assessment for wake vortices. The purpose is to show to a larger public the detail that is represented in these methods. At the same time, it might be of use for those developing various sub-models by showing the larger context of their work. In addition, the question of what kind of validation is required will be discussed.
Finally, a word of caution has to be given. The author of this paper has some knowledge on wake vortices but is certainly not an expert on ‘Probabilistic Safety Assessment’, ‘Weather Prediction’ or ‘Computational Fluid Dynamics’. It is not the intention here to ‘solve’ the problem or to formulate stringent requirements for validation. Rather, one should see this contribution as a ‘discussion paper’: to formulate and communicate (a personal view of) the problem such that the respective experts might be guided to find the best solution to this ‘multi-disciplinary’ problem.

2. THE PROCESS: DECAY OF VORTICES AND WAKE ENCOUNTERS

Vortex formation is inherently related to the lift generated by the aircraft wing to support the aircraft weight: the air trapped between the vortex pair is pushed downward proportionally to the momentum required to keep the aircraft aloft. The basic physics of a vortex pair behind an aircraft are well understood. When generated, the vortex strength \( \Gamma_0 \) follows from:

\[
\Gamma_0 = \frac{W}{\rho U b s} = \frac{1}{2} \frac{C_L U b}{A R s}
\]

with \( W \), \( b \), \( A R \) and \( C_L \) the weight, wing span, wing aspect ratio and lift coefficient respectively of the aircraft. \( U \) and \( \rho \) are the aircraft speed and air density, \( s \) is a dimensionless parameter defined by the distance between the vortices divided by the wing span \( b \). It depends on the wing loading and is equal to \( \pi/4 \) for an elliptical lift distribution.

As soon as the vortices have been formed, they will ideally move downwards with a velocity \( V_0 = \Gamma_0 / 2\pi b s \) (due to their mutual induction), they will be transported by the local winds and they will decay, due to diffusion and the local weather conditions. The evolution of the wake vortex behind an aircraft is described either by its distance \( x \) to the aircraft, normalised by the aircraft wing span \( b \) (\( x* = x/b \)), or by a non-dimensional time \( \tau* = t/t_0 \). Here \( t_0 \) is the time in which a vortex pair propagates the distance of one initial vortex spacing \( b s \). In terms of aircraft parameters \( t_0 \) can be written as:

\[
t_0 = \frac{b s}{V_0} = \frac{2\pi \rho U (b s)^3}{W} = \frac{4\pi A R b s^3}{C_L U}
\]

The larger the value of \( t_0 \), the slower the vortex decays.

The following meteorological parameters influence transport and decay of wake vortices:

- mean wind (all three wind components),
- wind shear, the variation over the height of the horizontal wind component,
- turbulence, expressed as Eddy Dissipation Rate (EDR) or turbulence intensity,
- and virtual potential temperature,

All these quantities should be known as a function of the height since the wake traverses the atmosphere when it moves downwards. In exceptional cases (strong thermal inversions, strong shear, strong vertical winds) the wakes can ‘stall’ or move back up to the glide path, a conditions that will be critical for the safety. For conditions of strong windshear, the windward vortex will increase in strength whereas the leeward vortex will become weaker. As
a result, the vortex pair will tilt, and one of the vortices will rise. The vortices will also decay much faster when the atmosphere is turbulent or with strong thermal stratification. For ‘normal’ conditions the wake will decay very slowly and can persist up till values of \( \tau^* = t/t_0 = 5 \) and beyond. As soon as it approaches the ground, the vortices move side ways and/or bounce back into the atmosphere. Depending on the specific cross wind conditions, the wake can also ‘stall’ above the runway. These conditions are specifically critical for safety as figure 1 indicates: most wake vortex encounters do occur close to the ground.

![Figure 1: Reported wake vortex incidents in the UK airspace depending on the height of the aircraft. Note that there is a peak very close to the ground (due to vortices that bounced up) and around 3000 ft. (glide path intercept). Information from the NATS voluntary reporting scheme.](image)

Two models are available in Europe to describe the wake vortex as generated by the aircraft and transported and decayed by the local, ‘ad-hoc’ weather conditions:

- **P2P**: the ‘Probabilistic Two-Phase wake vortex and decay model’ as developed by DLR\(^1,8,9\) and
- **P-VFS**: the Probabilistic ‘Vortex Forecast System’ developed by an international team for ‘Transport Canada’ and further developed by UCL\(^1,10\).

Both methods are a mixture of direct calculations (e.g. using vortex methods), parameterization derived from Large Eddy Simulations (LES) and empirical information (e.g. of the observed variations in wake vortex strength and position). This requires some kind of validation as will be discussed in section 5.

From the vortex position and its strength the induced velocity field can be calculated. These induced flow velocities can be so large that they give a serious upset to the follower aircraft, possibly leading to mechanical failure, injuries or even non-controllable situations and flight into terrain. In the encounter simulations, the aerodynamic loads are derived from an aerodynamic model. The resulting effect on the aircraft can be derived from off-line flight simulation calculations or from ‘Pilot-in-the-Loop Simulation’ with simulators. A vortex encounter goes so fast that the pilot hasn’t much time to react. Trials with wake encounters in
‘Blue Print’ of Probabilistic Risk Assessment for Wake Turbulence

This chart describes elements of a possible “Probabilistic Risk Assessment”. The methods in use today are similar but not necessarily identical to the one here described.

<table>
<thead>
<tr>
<th>INPUT</th>
<th>CALCULATION</th>
<th>COMMENT</th>
</tr>
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<tbody>
<tr>
<td>AIRPORT SITUATION</td>
<td>traﬃc mix, runway layout, ATM structure</td>
<td></td>
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<tr>
<td>LEADER AIRCRAFT</td>
<td>position, speed, weight...</td>
<td></td>
</tr>
<tr>
<td>WEATHER PREDICT</td>
<td>wind 3 components, turbulence, stratification &amp; shear, persistence, variation along glide path</td>
<td></td>
</tr>
<tr>
<td>FOLLOWER A/C</td>
<td>position, speed, attitude, flight dynamics model</td>
<td></td>
</tr>
<tr>
<td>AGREED HAZARD CRITERIA</td>
<td>roll angle ?, vertical acceleration ?, height dependence?</td>
<td></td>
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<tr>
<td>AGREED TARGET LEVEL OF SAFETY</td>
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<tr>
<th>PROBABILITY</th>
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<tr>
<td>wake position and initial vortex strength</td>
<td>specific weather conditions</td>
<td>to have a wake vortex with a strength $\Gamma$ at a certain position</td>
</tr>
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</table>

FILTER

WAKE CALCULATION

FILTER

ENCOUNTER CALCULATION

FILTER

MEETS THE TARGET LEVEL OF SAFETY ?

from statistical glide path information

from weather statistics from assessment of prediction accuracy

from Monte Carlo simulations with the wake evolution model

from ‘safety box’ estimate

from Monte Carlo off-line flight simulations check again specific severity criteria

Figure 2: ‘Blue Print’ of a probabilistic risk assessment for wake vortices
flight have been flown with a ‘fixed stick’. The severity of a wake encounter has to be judged from a ‘severity criterion’ like the ‘roll control ratio’ (the ratio between the roll control needed to compensate the upset and the maximum achievable roll control), a maximum roll angle, a maximum roll-rate, a maximum vertical acceleration, etc.

3. MODELLING THE UNCERTAINTIES

3.1 General aspects

Landing aircraft will never encounter a wake under ideal conditions: no crosswinds, updrafts, shear, stratification . . . . Due to the mutual induction the wake vortex pair of the leader aircraft will move downward under the glide path. And even close to the ground (in ‘ground effect’) the wakes will move sideways, out of the way. But for actual weather conditions, the wake motion is less predictable. Moreover, aircraft are not precisely on the glide slope: the leader might be a bit higher whereas the follower approaches on the low side, increasing the possibility of an encounter. This indicates that not the nominal values but the variations in the aircraft positions / conditions and the variations in weather conditions are critical for the wake encounters. These variations can be described mathematically with ‘Probability Density Functions’ (PDF’s) and they form the essential input for a probabilistic safety assessment.

In an absolute quantitative safety assessment for wake vortices one has to show that the probability of a catastrophic accident is of the order of ‘10\(^{-8}\)’ per landing. Such an extremely unlikely event will take place only for an unfavourable combination of one or more extremes in the parameters that describe the wake evolution and encounter. Consequently the modelling of all aspects of the problem (the air traffic situation, the wake behaviour in relation with the weather, the encounter characteristics) should describe these unfavourable conditions as

![Figure 3: Separation distance as calculated by WAVIR for a typical application](image-url)

Figure 3: Separation distance as calculated by WAVIR for a typical application.
accurate as possible in a probabilistic sense. The devil is in the (de)tails of the PDF’s and the
proof will have to be given that the physical/mathematical model in combination with the
measured/predicted weather conditions is sufficiently accurate. See section 5.

The first formulation for a probabilistic safety assessment for wake vortices was given by
Speijker et al\textsuperscript{3} of NLR. This model (with further developments) has been implemented in
WAVIR\textsuperscript{4,5}. In this method the probability for an ‘incident’, an ‘accident’ and a ‘crash’ is
calculated from PDF’s of the input variables (e.g. aircraft type, weight, speed and position,
weather conditions). The wake vortex strength and decay are derived from Monte Carlo
simulations using algebraic relations. The encounters are described either by a simple one-
dimensional model (based on the so-called ‘roll control ratio’) or by a more advanced ‘5
degree-of-freedom’ simulation. The WAVIR model has been used in various European
programs like S-Wake\textsuperscript{11} and ATC-Wake\textsuperscript{12}. A typical application of the derivation of safe
separation distances for various specified ‘target levels of safety’ (in this case for minor and
major incidents, hazardous and catastrophic accidents) is illustrated in figure 3.

The second European method that uses a probabilistic safety assessment is WakeScene\textsuperscript{6,7}
developed by Airbus and DLR. This method employs the wake evolution model P2P of DLR
as well as the VESA wake encounter model of Airbus. These models are imbedded in the
program package ‘MOPS’ of DLR.

3.2 Elements of uncertainty

Below all ‘uncertainty elements’ are listed, roughly following the scheme of figure 2. Most
of these elements are incorporated in WAVIR and/or WakeScene. Arguments will be given
below in support of specific improvements that should be considered.

[a] Traffic mix
The evaluation to be done in pairs of leader and follower aircraft types

[b] Variation in (height, lateral) position of leader aircraft
Deviation from nominal course, e.g. from glide path

c] Variation in distance to follower
This determines how much the wake has been ‘aged’ Also, one should know how the
actual applied separation distances compare to those prescribed (see figure 4) to
establish if a capacity improvement results from the proposed changes.

![Figure 4: Spread of inter-arrival times during landing at Atlanta Airport (data taken by R.C. Haynie, George
Mason University \textsuperscript{23}). Zero Time corresponds to a distance in accordance with the prescribed separation
distances (recommended for IFR conditions only in the US)](image-url)
[d] Variation in speed and weight of leader aircraft
   This determines the initial wake vortex strength
[e] Statistical variation in weather conditions
[f] Accuracy of weather data and/or prediction
[g] Randomness of the actual wake vortex realisation
   There are variations in wake vortex behaviour even for nominally identical weather
   conditions, e.g. due to short term fluctuations in space and time
[h] Variation in strength and position of the aged vortex
   This follows from [a] till [g] with Monte Carlo simulations using an appropriate
   ‘Wake Evolution Model’. To be expressed as function of time / distance behind the
   follower. The elements [e] till [h] are very critical and form an essential part in the
   analysis; they will be discussed in more detail in section 3.3.
[i] Variation in orientation of local vortex axis
   Not yet incorporated in WAVIR or WakeScene. Vortices can be distorted by
   atmospheric effects (figure 5). DLR\(^6\) has derived from LES calculations the

Figure 5: Wake vortex visualised by smoke during the so called ‘IDAHO Falls’ campaign. With atmospheric
   turbulence the vortices are not straight anymore. (courtesy NASA).

orientation of the vortex axis, expressed as a probability as function of the non-
   dimensionalized vortex strength (a measure for the vortex life time). Such a
   probabilistic distribution is shown in figure 6 for the azimuth angle.
[j] Variation in (height, lateral) position of follower aircraft
   Deviation from nominal course of the follower, e.g. from glide path
[k] Variation in orientation and state of the follower aircraft
   The weight, configuration, all speed components and accelerations along the aircraft
   axis and the (direction of the) flight path determine the initial conditions of the
   follower aircraft for the encounter simulations.
[I] Encounter effects

They are calculated with Monte Carlo Simulations in flight dynamic simulations using [h] till [k] as input variables. This is the second most critical element in the assessment and will also be discussed in more detail in section 3.4 below.

Figure 6: Plot of the probability of the azimuth angle $\psi$ of the instantaneous vortex axis as function of the (normalised) vortex strength $\Gamma^*$ as evaluated from LES simulations by DLR$^6$. Similar figures have been made for the inclination and roll angle.

Most of the variations listed above can be considered as input variables for the Monte Carlo simulations. They can be derived from observations for operational conditions or simulation of the air traffic system. The final safety assessment reflects essentially the relation that:

$$\text{The probability of a severe encounter} = \text{the probability that the wake of the leading aircraft is at a certain position with a certain strength} \times \text{the probability for the follower aircraft to enter that wake and to exceed a certain severity criterion (roll angle, vertical acceleration, . . . )}$$

3.3 The wake evolution model

A very large effort has been spent in the last 10 years to calculate the transport and decay properties of the wake. The problem is complex due to the non-linear vortex-dynamic phenomena and the stochastic nature of the weather. A solution to this problem is based on a mix of approximate analytical models and curve fits obtained from field data, more detailed fluid dynamic calculations and large eddy simulations (LES) incorporating ‘constants’ set according to actual observations. As mentioned before, the two most advanced models in Europe for the wake evaluation are P2P from DLR and P-VFS from UCL$^1$.

In these calculations the effect of the weather on vortex decay and transport is calculated. All three wind components and their variability, turbulence, temperature gradient and wind shear should be known as a function of the height since the wake traverses the atmosphere
when it moves normally downwards. Weather conditions can be measured quite accurately. As an example the system installed at Frankfurt Airport should be mentioned\textsuperscript{13}. This system comprises a wind-temperature radar with a radio acoustic sounding system (WTR/RASS) for real-time measurements of wind and temperature profiles. For probabilistic safety assessments it is essential to know the statistical variation of the weather conditions. This can be derived from observations over a long period. As a typical example, the measurements at Frankfurt indicated that during 1.5\% of the time, vertical wind speed at 300 m above ground exceeded 1 m/s. In 0.6\% (0.2\%) of the cases the vertical wind speed at 300 m exceeded 1.5 m/s (2 m/s)\textsuperscript{13}. These are rare events but critical for safety since they transport the wakes back to the glide path. Another example of the same data set is the variation in potential temperature gradient as shown in figure 7. Large potential temperature gradients (‘inversion’) might also favour rising vortices, a critical condition for safety. The example illustrates that the ‘tail’ of the PDF really matters.

![Stratification statistics](image.png)

Figure 7: Inversion, defined by a positive gradient of the potential temperature gradient $dT/dh$ might give rise to situations where the vortex pair bounces up back into the glide path. These conditions are rare as the ‘long tail’ in the figure illustrates but of critical importance for the safety. Data from DFS\textsuperscript{13}.

In a practical probabilistic safety assessment, one cannot deal with an infinite number of possible weather conditions for the input of Monte Carlo simulations. This presents a real problem that needs further attention. Two possible solutions are:

- Assume ‘constant’ weather conditions (wind speed, potential temperature gradient, turbulence, shear . . . ) over the height of interest as was done in the original WAVIR method
- Fill a data base with a very large number of actually observed weather conditions, each with a ‘weight factor’ according to its probability. This is the most complete solution, but how many realizations are required? Both the P2P and P-VFS are set-up to take the detailed weather profiles into account (see e.g. figure 8).

For each solution it should be assured that the true statistics of the weather conditions ARE well represented. On top of this, there are three more uncertainties to deal with:

- Depending on the instrumentation, the measurements are accurate within certain error bounds (instrumentation accuracy, position errors, time averaging used . . ).
There will be a variation in weather conditions in time and space (e.g. along the glide path). DLR\textsuperscript{14} has shown that there are large variations in wake position and strength for nominally identical (averaged) conditions. Such variations have been observed in field trials and simulated and quantified in LES calculations. The two wake evolution models deal with these aspects in different ways. In the P2P method $2\sigma$ (95.4\%) and $3\sigma$ (99.7\%) uncertainty bounds are added based on actual wake vortex observations. In the P-VFS the uncertainties are included in the input variables and in the ‘constants’ used in the transport and decay models; their effects are subsequently calculated in a ‘Monte Carlo type’ way. An example of the second approach is shown in figure 8.

The ‘prediction horizon’ constitutes a third uncertainty, in its consequences similar to the instrumentation error. How accurate can the weather be predicted 20 minutes to one hour ahead of time? Such a prediction is required for systems (CONOPS) that dynamically adapt the separation distances to the weather conditions. The accuracy of these predictions (‘the forecast skill’) has to be established from large data collection campaigns over long periods (see e.g. \textsuperscript{15}).

This third uncertainty, related to the quality of the weather forecast, should also be introduced explicitly in the safety assessments of CONOPS that rely on the predicted weather, since it might contribute significantly to the risk.

Figure 8: Example of a typical P-VFS result obtained by UCL\textsuperscript{1}. The symbols denote the actually measured values (+ for starboard vortex and o for port vortex). The lines represent the predictions: red and blue lines denote mean behaviour of the port and starboard vortex respectively; green and light blue lines envelopes for 95.4\% and 99.7\% probabilities. The figure right below indicates the weather conditions that are used as input: vertical profiles of wind (mean profile in solid black and uncertainty bounds in dash-dotted black) and temperature (green; no uncertainty assumed).
3.4 The ‘Wake Encounter Model’

The second process that justifies a more detailed description is modelling the wake encounter. Two different approaches can be followed:

- simulating the interaction in all detail and
- ‘by-passing’ the interaction using a so called ‘safety box’ around the wake

The wake vortex strength and position, as derived from the Monte Carlo Simulations, can be represented as a probability distribution or scatter plot at various positions along the glide path (see figure 9). From this information the induced velocity flow field of the wakes can be derived in principle (see also section 5.2). If the initial conditions of the follower aircraft before it penetrates the wake are known, the interaction follows from a straightforward flight-dynamical calculation as is done in WAVIR or VESA. There are three important aspects here.

First of all, the initial aircraft (dynamic) conditions when entering the wake should be known in a probabilistic sense (e.g. from actual Flight Data Recordings or from simulations. Secondly, the orientation of the aircraft that flies into the wake relative to vortex axis has a large effect on the interaction. DLR\(^6\) has derived the statistics of the direction of the vortex axis from LES calculations (see figure 6) and expressed as probability distributions. This work is just starting and more simulation and validation will be required.

And finally it is of importance how the interaction with the pilot is modelled. There are three options to provide input for Monte-Carlo simulations:

i.) Automatic using an auto-pilot model,
ii.) simulating the interaction assuming ‘fixed stick’ control,
iii.) using a ‘pilot model’.

Figure 9: Position and strength (colour coded) of vortices from the leading aircraft; the ellipse indicates the 2 \(\sigma\) boundary of the position of the follower aircraft at 5 NM separation; calculated by WAVIR\(^4\).
The choice between these options reflects to some extent the operational context. An example of a well documented interaction in ‘auto-land’ mode is given in 16. In 17 a specific ‘flight control system’ is designed to reduce the effects of wake vortex encounters. In the S-Wake program11 wake vortex encounters have actually been flown with a ‘fixed stick’.

Figure 10: Visualization of the flight path during a wake vortex encounter from flight simulation studies (S-Wake results, AIRBUS studies11). Top: slow intercept from above (vertical intercept is 2 deg.), bottom: quick intercept from aside (horizontal intercept angle is 20 deg.)

Should the encounter be evaluated all along the glide path or is it sufficient to calculate the interaction in a limited number of planes (‘gates’) as done in the existing methods? Fortunately the interaction is so quick that the pilot has hardly time to react. In that case, the instantaneous conditions in a particular plane (straight vortices though with a specific orientation relative to the incoming aircraft, a specific realization of the aircraft dynamic state, ‘fixed stick’ control) are sufficient to describe the problem.

The variation in encounter characteristics can subsequently be derived from a large number of Monte Carlo simulations for initial conditions that reflect the actual observed or modelled statistical variation in these initial quantities. It is to be noted that the interaction is very sensitive to the initial conditions. Examples of some typical flight path’s obtained in flight simulator studies are shown in figure 10 and similar results will be obtained from ‘fixed stick’
encounters simulations with stochastically varying input parameters. This approach reflects all elements for an absolute safety assessment.

If an absolute safety assessment is not required and a relative estimate is considered good enough, an important ‘short cut’ can be made as e.g. applied in ATC-Wake\textsuperscript{12} and studied in more detail by DLR\textsuperscript{18}. In this approach the situation is considered safe if the follower aircraft is sufficiently far away from the wake (out of a ‘danger volume’ or ‘safety box’). This greatly reduces the number of parameters that has to be used in simulations. Although it simplifies the problem, it will certainly be over-conservative.

4. IMPLEMENTATION: CAN IT BE DONE?

The ESARR4 requirements specify a probability of 1.55\times10^{-8} per hour for a fatal accident (due to ATM) but its application is not straightforward. What part of the ‘risk budget’ can be used for wake vortex encounters? NATS has provided, as part of the S-Wake Study\textsuperscript{11}, the following risk matrix:

<table>
<thead>
<tr>
<th>Risk requirements (per movement)</th>
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</thead>
<tbody>
<tr>
<td>Catastrophic Accident</td>
<td>0.9 × 10^{-8}</td>
</tr>
<tr>
<td>Hazardous Accident</td>
<td>3.0 × 10^{-7}</td>
</tr>
<tr>
<td>Major Incident</td>
<td>1.0 × 10^{-5}</td>
</tr>
<tr>
<td>Minor Incident</td>
<td>5.0 × 10^{-4}</td>
</tr>
</tbody>
</table>

In the safety assessment calculations the time consuming elements are the Monte Carlo simulations for the wake evolution and the encounter respectively. In the actual calculations, data sets (‘bins’) representative of the actual conditions are specified, e.g. in case of the wake evolution for the initial vortex strength and position and the weather condition. The uncertainties, as discussed in the previous section, should be specified such that the actual statistical properties of all uncertainties are maintained. In the Monte Carlo simulations initial conditions are drawn randomly out of these ‘bins’ to start the calculations. A similar process is used for the encounter modelling.

To calculate an order 10^{-8} event one will need of the order of 10^{10} actual realizations. If the effort is evenly split between the ‘vortex evaluation’ and the ‘encounter’ (the wake generation / evolution and encounter are independent), each of them will require order of 10^{5} Monte Carlo simulations, still a very large number. The distribution and total mount of the data within each bin follows from the requirement to represent in the data all events, including those with a low probability (the ‘tails’ of the PDF’s). This needs a careful consideration, details of which have to be disclosed supported by relevant evidence for particular applications. It is fair to say that this still represent a formidable number of simulations. This can be reduced by applying suitable filters (see figure 2) on the input side of the Monte Carlo simulations. These filters are intended to signal that the calculation can be by-passed for certain conditions. E.g. with a sufficiently strong crosswind all wakes will be blown away.
from the landing strip, rising vortices (out of ground effect) will only occur with significant windshear, inversion or vertical winds and these conditions are rare. For the encounter calculations one can refrain from dynamic simulations when the follower aircraft is outside the ‘danger volume’ as discussed in the previous section. Although the filter will have to be ‘tuned’ for particular applications, its effect will be to reduce the number of Monte Carlo simulations.

What is important however is to show for particular applications in the quantitative probabilistic safety assessment how the statistics are modelled, how much data is used in each ‘bin’ and how ‘filters’ are set. As remarked in section 1: ‘For a better acceptance of these methods it is essential that the methods used in the proposed probabilistic safety assessments are traceable, transparent and validated’. The author believes that what has been disclosed of the methods in development today is not sufficient.

5. VALIDATION ASPECTS: GOOD ENOUGH TO SUPPORT A SAFETY CASE?

5.1 Definitions

For any change in the present regulations, one has to convince the authorities that the proposed change is safe: a safety case has to be made. The safety argument in support of the safety case can be described as:

“A reasoned and well-structured accumulation of data, analysis and judgement that shows that the objective of the safety case has been met.”

This implies the following steps: Define & Model the Problem, Collect & Organize the Data, Analyze Data & Evaluate Risk. In an actual safety case, the ‘problem’ is defined by the specific ‘CONOPS’. To ‘model the problem’ the probabilistic safety assessment (as defined in generic terms in section 3) has to be focussed on that particular application. It is interesting to note that ‘collection’ and ‘analysis’ of the data follows the particular model definition and modelization: it is case specific. Nevertheless, following section 3, more can be said on the validation of the models in generic terms. In this context validation means in a very strict sense:

“To proof that the simulations adequately describe the operational reality.”

In the simulations and the models used for these simulations, many implicit assumptions are made. They should be made traceable and transparent such that experts can judge its validity. Validation aspects on both levels, the ‘higher’ ‘operational’ level and the ‘lower’ level for ‘specialists only’ will be discussed below. This distinction more or less coincides with a distinction between ‘validating the method as a whole’ and ‘validating specific elements of the method’. In the latter case one speaks of ‘sub model validation’ and this is sometimes considered the only practical approach towards validation. Validation efforts can be grouped into 5 area’s: operational data, weather characterization, wake transport and decay, encounters and safety criteria. Of these only the last 3 will be discussed below.
5.2 Wake transport and decay prediction

A large effort has been spent in the last decade in this area. So far, the validation of these methods has been mainly concerned with a comparison of measured and calculated wake strength and trajectories for individual cases. E.g. it has been indicated\(^6\) that the P2P method has been validated with 1050 individual cases collected in 6 different campaigns between 1994 and 2004. Many of these cases have also been used for validation of the P-VFS\(^1\). But it is fair to say that, in the various campaigns, different techniques have been used to measure the weather conditions (instrumentation, position and height, averaging times). Moreover, some elements in the calculation methods use ‘constants’ and statistical information derived from field tests. It is not clear if sometimes the same data are used for ‘tuning’ and ‘validation’. The message is that one should be very clear about this.

As far as the physics are concerned, a number of points can be raised that need consideration. Some of the models are based on (curve fitting) results from Large Eddy Simulations (LES). In spite of the impressive results as visualised from these calculations, some fundamental questions still remain. Are the turbulence models (sub-grid modelling) adequate enough? Are all turbulence length scales with relevance for the problem represented? Is a simulation within a confined numerical box with periodic boundary conditions adequate? Do we know all parameters (e.g. the effects of head wind shear) and do we understand all relevant mechanisms that drive the decay of vortices? Some of these questions have been addressed in publications. Others are still under investigation. Nevertheless, in the framework of a validation, the evidence is to be shown.

Validation involves a comparison between calculated and measured data. As argued in section 3, the ‘1.55x10\(^{-8}\) critical event’ is most likely to occur for very specific conditions like vertical winds, significant shear or stratification. These conditions should be addressed specifically in the validation effort to proof that the models are adequate for these conditions. Three different, complementary approaches are to be followed here:

- **‘Building block experiments’**: Experiments performed for very well controlled conditions, aimed directly to address a specific physics aspect of the problem like the effects of external turbulence, the effects of stratification, head wind shear and reflection from the ground. Well defined experiments can be done in the wind tunnel, catapult or towing tank and the results can be compared with calculations that use the same boundary and initial conditions. Such comparisons will result in a better understanding of the physics involved and a clear answer that the model can deal with these effects adequately. Unfortunately, not many examples of ‘building block experiments’ exists.

- **‘Case-comparisons’**: Comparisons with specific cases measured in field campaigns. Figure 8 is an example of such a comparison and many more of these have been made and shown in the past. A problem with these comparisons is the uncertainty in some of the measured conditions. This can be accounted for with the uncertainty bands as shown in figure 8.

- **‘Ensemble comparisons’**: a statistical comparison on the basis of a large amount of data. For a specific (sub)set of weather conditions one can collect vortex data in a field
test and compare with the predictions in a statistical way. Such an approach comes closest to the operational reality. Although the effort is large, it is not unrealistic e.g. in a recent field campaign at St Louis airport, weather and Lidar data have been collected over a year period to provide evidence that the wakes don’t move to the other runway for specifically defined weather conditions. The same (or a similar) set can be used to make an ‘ensemble comparison’ for wakes in ground effect.

One specific issue is still to be mentioned. For the encounter analysis, the vortex induced velocity flow field is required. This is derived in the P2P method from algebraic approximations that use the vortex strength and position. In the P-VFS method the velocity field is actually calculated, even including ground effects, and the problem is solved implicitly. It is felt that validation is required e.g. from field tests with Continuous Wave (CW) Lidars that allow triangulation to locate the position in space.

5.3 Encounters

Similar to the validation of the wake prediction methods, there are various complementary possibilities for the validation of wake encounter modelling:

- ‘Flight simulations’: They have been used extensively e.g. in S-Wake and in Airbus studies. The input flow field is derived from calculations for specifically defined ‘leader’ and ‘weather’ conditions.
- ‘Case-comparisons’: A number of interesting ‘case-comparisons’ have been presented based on actual flights into wakes. In these cases the wake flow field has been reconstructed from flow probes installed on the aircraft. It is argued that more different aircraft types have to be tested.
- ‘Ensemble comparisons’: Information on wake vortex encounters under operational conditions is very limited, and restricted to voluntary reporting scheme’s like the one by NATS on London Heathrow. A good example of the information obtained is shown in figure 1. As argued, the use of ‘flight data recording’ is the only possible way to get more objective data and this is essential to enable a comparison for a large set of data. Only when such data become available, an ‘ensemble comparisons’ can be made.

5.4 Safety criteria

The ESARR4 requirements define an acceptable level of risk, but not precisely enough to be applied directly for wake vortex related risk. A real problem here is the determination of the ‘target level of safety’ for various levels of risk. Clarification is needed here. Also, severity or hazard criteria are not specified. Studies have been made in flight simulators to objectively define such criteria. As argued, this information should be further completed with results from actual Flight Data Recordings’s during encounters.
6. CONCLUSIONS

In Europe two methods for a quantitative risk assessment for wake vortices have been developed in the last decade. These methods model in detail the physics and flight mechanical aspects. Extensive use is made of research from various national and European programs.

An essential part of such a risk assessment methodology is the modelling of rare events that result in vortices rising to the flight path of the following aircraft, events that are decisive in the final risk. Not the nominal conditions but the variations around the nominal values determine the risk and a risk assessment should concentrate on these.

The two methods that are available today model most of the relevant aspects although some refinements (notably for the weather characterization) are recommended.

With these methods a relative quantitative safety assessment can be made. It might even be possible to do an absolute safety assessment to proof that a certain specified Target Level of Safety (‘TLS’) can be met. If this is realistic will depend mainly on:

- the ability to characterize all relevant weather profiles (three wind components, potential temperature and turbulence as function of height) in a very large but still limited number of realizations, such that the statistical variation in weather conditions over a long period can be recovered;
- the validity of the assumption that the encounter characteristics can be derived sufficiently accurate from ‘fixed stick’ off-line flight simulations using local conditions in a limited number of vertical planes (‘gates’) along e.g. the glide path;
- the possibility to limit the number of Monte Carlo simulations by using appropriate ‘filters’ on the input side of the wake evolution and encounter models.

The calculation (validation) of the presently applied separation matrix (for e.g. two representative airports like London Heathrow and Frankfurt) would present a realistic though challenging problem for an absolute assessment. Although this is a large effort, it is felt that this will greatly increase our understanding of the wake related safety issues.

Even if the application for a probabilistic risk assessment in an absolute sense is not completely clear, a quantitative risk assessment method will provide a very detailed analysis of the wake vortex induced risk and might indicate ways to improve the safety. This in itself already justifies it use.

The transparency of the available risk assessment methods needs to be improved. All relevant details are to be given e.g. the extend of the (statistical properties of the) data sets used as input for the Monte Carlo simulations and the number of simulations.

Improvements are necessary for the validation of the methods used, notably the wake evolution model and the wake encounter model. For the wake evolution model, special attention has to be given to the validation of the physical modelling for those conditions that are crucial for the safety aspects (e.g. all parameters that cause the vortices to rise).

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