

Wake Vortex Avoidance versus Landing Capacity

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Wake vortex separations are limiting factor in landing capacity of airports. The increasing air traffic forms the need for more flexible separation procedures taking into account the actual weather situation and the parameters of a more individual aircraft pairing. The present separation standards have to be investigated carefully with the aim to discover possible margins by improving the limiting constraints without adverse effects on safety. Separation reductions can also be achieved by wake vortex avoidance using prediction systems for the wake related hazard zones their development and movement. Avoiding these zones allows safe and undisturbed flight operations. The definition of a reliable and validated safety criterion is the fundamental element for the determination of hazard areas. The presented definition is based on the normalized required roll control power of the encountering aircraft. For manually controlled aircraft the limit of the acceptable normalized roll control power can be established using full flight simulator studies and in-flight simulations. Parameterization of the relevant parameters leads to the universally applicable concept of the "Simplified Hazard Area Prediction" method (SHAPE). SHAPE provides the hazard area dimensions for specific approach situations. SHAPE is part of a Wake Vortex Prediction and Monitoring System developed within the DLR project *Wirbelschlepppe II* for creating safe and reduced landing separations. Some general results for specific approach conditions on a single runway are presented.

Nomenclature

b	= wing span	t	= time
c	= derivative	u	= longitudinal component
GS	= glide slope	v	= lateral component
H	= altitude, HEAVY AC	V	= airspeed
L	= rolling moment, LIGHT AC	w	= vertical component
LOC	= localizer	W	= weight
m	= mass	Δ	= difference
M	= MEDIUM AC	γ	= flight path angle
N	= load factor	Γ	= circulation
p	= roll rate	ε	= eddy dissipation rate
r	= radial coordinate	ξ	= roll control input
t	= time	$*$	denotes normalized quantity
u	= longitudinal component	\bullet	denotes a time derivative
v	= lateral component	\rightarrow	denotes a vector
<u>subscripts</u>			
0	= initial value	max	= maximum
age	= vortex age	min	= minimum
$calm$	= calm air condition	nom	= nominal
F	= follower aircraft	req	= required
G	= vortex generator aircraft	W	= wind quantity
K	= flight path related	WV	= wake vortex
l	= roll derivative		

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abbreviations

AC	aircraft	NOWVIV	nowcasting wake vortex impact variables
ATTAS	Advanced Technologies Testing AC System	P2P	probabilistic two phase model
DoF	degrees of freedom	RCR	roll control ratio
DLR	German Aerospace Center (<i>Deutsches Zentrum für Luft- und Raumfahrt</i>)	ROT	runway occupancy time
H-H	heavy aircraft in trail of heavy aircraft	SHA	simplified hazard area
H-M	medium aircraft in trail of heavy aircraft	SHApe	simplified hazard area prediction
ICAO	International Civil Aviation Organization	SD	separation distance
ILS	instrument landing system	ST	separation time
IFR	instrumental flight rules	TEK	turbulent kinetic energy
IFS	in-flight simulation	VMC	visual meteorological conditions
MLW	maximum landing weight	WV	wake vortex
MTOW	maximum take off weight	WSVBS	Wake Vortex Prediction and Monitoring System (German abbreviation)

I. Introduction

THE generation of lift is inseparably linked to the creation of wake vortices. The strength of the vortices increases with the weight of the vortex generating aircraft. Therefore, weight dependent separation distances have been established for approach and landing to avoid unacceptable wake vortex encounters. These proven separation distances are limiting the landing capacity of airports. The main motivation for the revival of the past years interest in wake vortices is the increase of actual air traffic and its forecast¹ saying that roughly a doubling can be expected about every 15 years. Very recent news even state that air travel is expanding above expected rates. Mainly the predicted corresponding traffic throughput at airports is the driving factor for investigations into reduced but safe wake vortex separation. This demand forms the need for more flexible separation procedures. Especially for approach and landing all aircraft are forced to fly nearly identical tracks down the nominal point of touchdown.

The current standard separations can be assumed to be proven by their daily operational application. Starting from these accepted standards considerations can be developed to discover possible margins which could be used to solve current and future capacity problems at airports. To allow for more individual a/c pairing and/or time based separations can help to alleviate capacity restrictions. Further promising is the application of dynamic separations taking into account the actual weather situation. Within this scope a Wake Vortex Prediction and Monitoring System (German abbreviation: WSVBS) is under development in the frame of the DLR *Wirbelschleppes II* project to reduce aircraft approach and landing separation and to improve flight safety. It has to be emphasized that this paper is not thought to provide practicable operational methodologies. Rather it should help to understand what are the maximum theoretical capacity gains that can be expected due to wake vortex separation reduction and what are the relevant parameters.

II. Fixed Longitudinal Separations for Approach and Landing

In the past the general idea of wake vortex separation was based on the assumption that a certain space between the aircraft gives the vortices enough time to vanish by diffusion or at least to decay to a negligible air motion. Since the strength of wake vortices mainly depends on the produced lift the current wake vortex separations are using the aircraft's mass respectively the certified MTOW. Different categorizations with various mass limitations using graduations from 3 to 5 groups exist (see Fig. 1). The following investigations will use the common ICAO classification (see Tab. 1) and the corresponding separation minima as defined in Doc 4444-RAC/501². It is further assumed

- solely single runway operation is considered
- runway is exclusively used for landings
- traffic mix includes only HEAVY and MEDIUM aircraft
- constant approach speed and constant aircraft separation
- no ground effects are taken into account

Although some of these assumptions are rough simplifications the principle effect of parameters of influence and specific measures can be discussed.

a/c class	mass
HEAVY (H)	$m \geq 136\,000\text{ kg}$
MEDIUM (M)	$7\,000\text{ kg} < m < 136\,000\text{ kg}$
LIGHT (L)	$m \leq 7\,000\text{ kg}$

Table 1. ICAO aircraft mass categorization

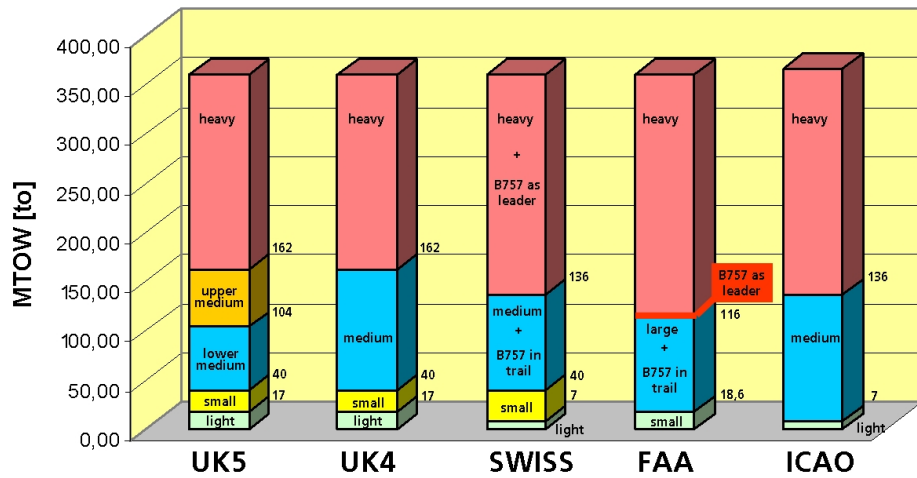


Figure 1. Aircraft categorization based on MTOW

A. Wake turbulence separation using 3 categories of aircraft types

After ICAO² a time based wake vortex separation has to be applied for non-radar operation. The Separation Time (ST) of LIGHT behind HEAVY or MEDIUM aircraft has to be at least 3min. For MEDIUM behind HEAVY this interval is 2min. No non-radar separation minimum exists for HEAVY behind HEAVY aircraft but the absolute separation minimum is fixed by the minimum runway occupancy time $ROT_{min} = 50s$. For practical use ROT can be assumed to be $ROT = 60s$ as an average.

Using radar information the wake turbulence separation minima² are based on distances (due to precise position data) as illustrated in Fig. 2. Focusing on a traffic mix of HEAVY and MEDIUM aircraft pairings only H-H and H-M are of interest since for MEDIUM leading aircraft minimum radar separation is already applied and no further reduction is possible. The separation distances (SD) can be transformed into separation time by means of the approach speed. For a specific separation interval the runway capacity (aircraft/hour) can easily be calculated. The approach speeds of some existing aircraft are plotted in Fig. 3. The scattered data

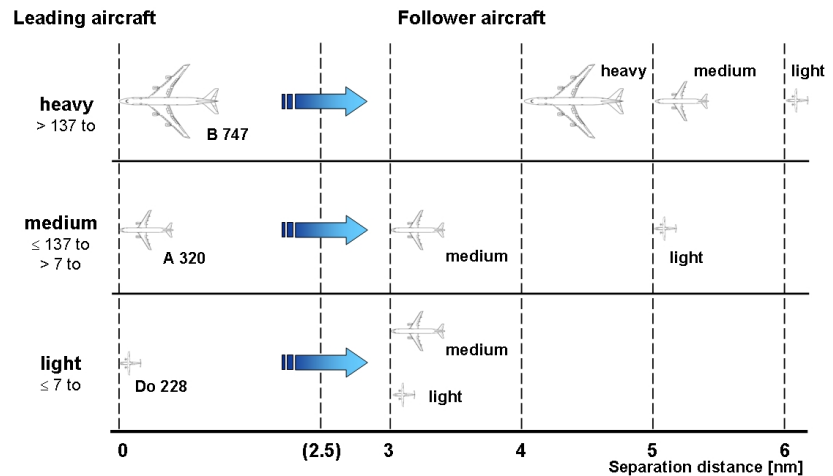


Figure 2. ICAO standard separations

can be enveloped by curves representing the upper (red) and lower (green) boundaries.³ The relevant range of airspeed is about $62m/s \leq V \leq 75m/s$ (shaded area). The corresponding runway capacities versus approach speed for radar and non-radar separations for H-H and H-M aircraft pairings are shown in Fig. 4. It is obvious that the capacity from the transformed SDs is airspeed dependent while the STs are not.

From Fig. 4 it can be seen that the absolute maximum capacity for a single runway is $72AC/h$ (aircraft per hour) and a more realistic value is $60AC/h$. The non-radar separation enables the landing of $30AC/h$. For aircraft separations based on distances the runway capacity increases with approach speed. The tendency can be described by the equations

$$H-H: \frac{d(AC/h)}{dV} = 0.49 \frac{AC/h}{m/s} = 0.25 \frac{AC/h}{kt} \quad (1)$$

$$H-M: \frac{d(AC/h)}{dV} = 0.39 \frac{AC/h}{m/s} = 0.20 \frac{AC/h}{kt} \quad (2)$$

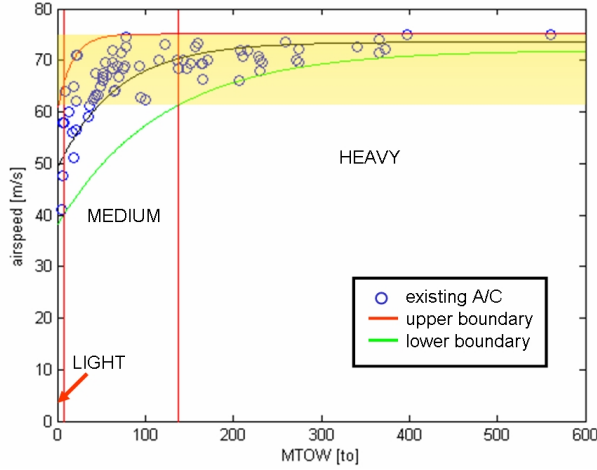


Figure 3. Approach speeds of existing aircraft

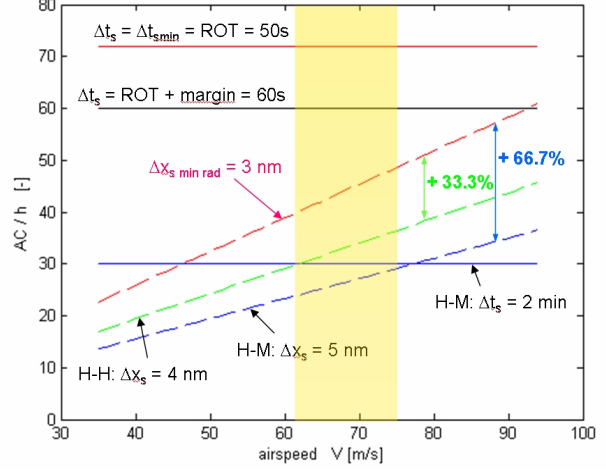


Figure 4. Capacity limitations due to separation

An airspeed increase of **4kt** respectively **5kt** can improve the capacity by **1 AC/h**. If higher approach speeds (→ higher sink rates) are assumed to be a suitable measure to expand runway capacity this is questionable at least from the view point of safety.

For the H-M pairing (blue broken line) the **5 nm** radar separation always leads to lower capacities than the **2min** non-radar separation within the applicable approach speed range (shaded area). For H-H pairings distance separation has always a favorable effect. If it is possible to reduce the SD to the minimum radar separation of 3nm the capacity can theoretically be increased by **66.7%** for H-M and **33.3%** for H-H pairings. In any case a doubling of a single runway capacity without loss of safety is very ambiguous and perhaps impossible.⁴

B. Effect of number of aircraft categories

The stronger the wake vortex the larger the safe SD which should allow the vortices to decay to a harmless airflow disturbance. The strength of wake vortices mainly depend on the aircraft's mass:

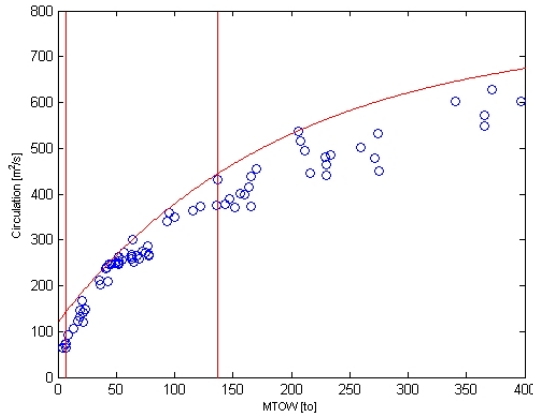


Figure 5. Vortex circulation for MLW

for H-M is **5nm**. This implies that this safe SD still is valid if the lightest MEDIUM aircraft M_{min} with a mass of $m=7to$ follows the heaviest currently certified HEAVY aircraft which has a mass of $m=396to$. Further it applies that the lightest HEAVY aircraft ($m=136to$) behind the heaviest HEAVY ($m=396to$) needs to maintain a SD of 4nm. If this situation is regarded to be safe then the same SD has to be safe for the heaviest MEDIUM behind heaviest HEAVY aircraft. Accepting these facts offers the opportunity to generate continuous SD as a function of the

$$\Gamma_0 = \frac{W_L}{\rho V_L b_L \frac{\pi}{4}} \quad (3)$$

The worst case circulation is produced by the highest aircraft landing mass in flight which is the maximum landing weight (MLW). Fig. 5 shows the vortex strength calculated for MLW of existing aircraft but as a function of MTOW to be compatible to the common ICAO categorization.³ This relation can be approximated by an exponential function which allows a nonlinear interpolation of circulation for any aircraft mass.

Presuming that the current wake vortex separations (originally based on the idea of vortex decay) are regarded to be safe a methodology is imaginable which transfers the coarse discrete separation concept into a continuous or at least into a scheme with higher resolution. The required SD

actual masses of a respective aircraft pairing using the above mentioned interpolation based on the nonlinear relation between MTOW and circulation.

Fig. 6a shows the complete unlimited results for SD as a function of MTOW of generator and follower aircraft. It can be seen that drastic SD reductions seem to be possible, e.g. for heaviest HEAVY behind lightest HEAVY aircraft $SD = 1.2nm$. Even if the minimum radar separation is accepted reductions are possible in a wide range. But the operational application of this very individual separation methodology is only possible by using computer based processes. For a human operator the number of individual pairing respectively the number of aircraft categories has to be limited to a manageable size.

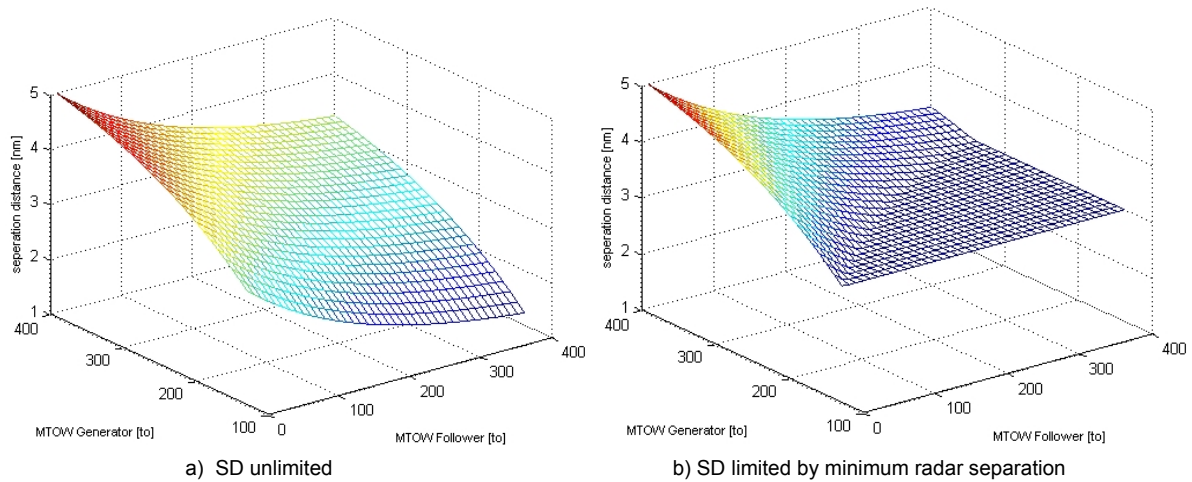


Figure 6. Individual mass dependent separation distances

The possible capacity gain for a given number of groups can be calculated from a specific traffic mix. Assuming a traffic mix which is typical for international airport (67% MEDIUM, 33% HEAVY, and negligible number LIGHT aircraft) the resulting maximum gain is illustrated in Fig. 7. The results consider the fact that no SD shorter than radar minimum separation is accepted (see Fig. 6b). The axes of the bottom plane show the number of subclasses for MEDIUM and HEAVY categories. Fig. 7a shows the capacity gain for the H-H and H-M pairings referred to the basic capacity of these two groups of pairings themselves. In Fig. 7b the same capacity gain is related to the total basic capacity (that is all possible basic pairings including M-H and M-M). It is obvious that related to the over all traffic the possible capacity gain turns out to be smaller. But in both figures it can be seen that capacity gain increases with the number of subgroups in the HEAVY and MEDIUM categories. For a subdivision into 10 groups of both the categories HEAVY and MEDIUM Fig. 7a shows a capacity increase of almost 30% and even

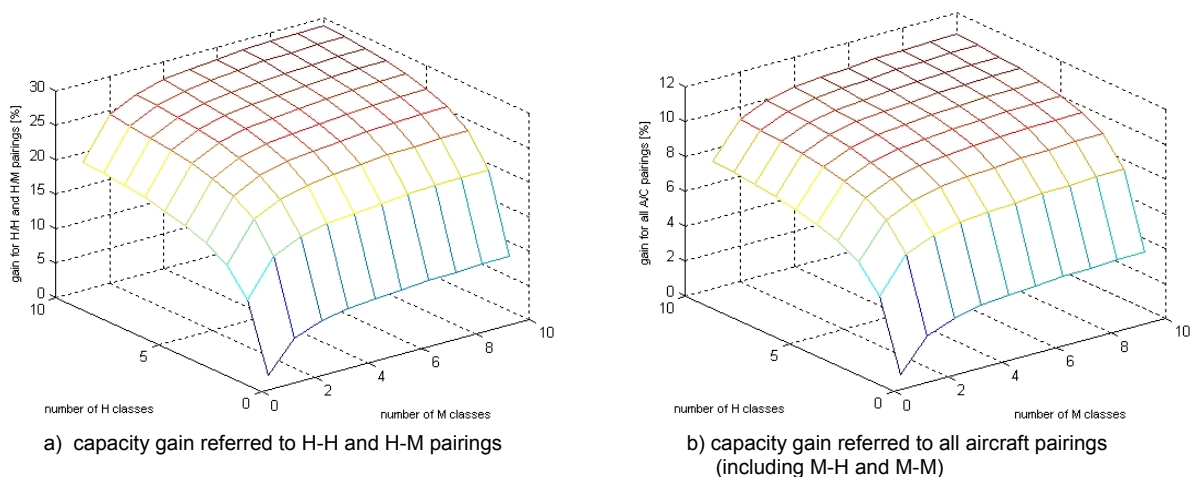


Figure 7. Capacity gain due to subdivisions of HEAVY and MEDIUM aircraft categories
(traffic mix: HEAVY=67% , MEDIUM=33% , no LIGHT)

referred to the total basic capacity the gain is more than 10%. Both diagrams indicate that a subdivision into more than 3 or 4 groups for each category does not bring much additional benefit. These results support the idea of the UK5 categorization splitting the lower weight-categories (see Fig. 1). But looking at the gradients of the planes in Fig. 7 it is clear that a subdivision of the HEAVY aircraft category has a more favourable effect than splitting the MEDIUM class.⁴ Applying this concept can improve capacity but does not permit a doubling of single runway capacity. As already stated this concept is based on the assumption that the current safe separation distances give a sufficient decay of the wake vortices to a safe residual of circulation. Recent research results suggest that decay is cannot always be the main cause which makes the existing standard separations safe⁵ but wake vortex motion plays an important role^{6,7,8}.

III. Time or Distance Based Separations

The non-radar separation mentioned in chapter II-A is a time based separation. The separation time $ST=2min$ for H-M combination yields a constant capacity of $30AC/h$ (see Fig. 4). For fixed separation time the runway capacity is independent of approach speed or present wind situation. In calm air condition this has the advantage that the minimum vortex age and therefore its strength is clearly defined by the separation time in case of a possible encounter of a trailing aircraft. Again this is independent of the actual airspeed which is different from the use of fixed wake vortex separation distances.

The situation changes if wind has to be considered. Assuming that the approach speed \vec{V} is maintained constant the wind vector \vec{V}_W changes the flight path speed vector \vec{V}_K corresponding to the kinematics of speeds (Fig. 8). In general it applies

$$\vec{V}_K = \vec{V} + \vec{V}_W .(4)$$

For the comparison of time and distance based separations especially the longitudinal wind component u_W is of interest. From equation (4) it is clear that for a constant approach speed a longitudinal wind u_W being an element of the wind vector is changing the flight path speed versus ground. The ground speed of the approaching aircraft is reduced in a headwind (headwind: $u_W < 0$) situation when the amount of airspeed V is kept constant

$$u_K = |\vec{V}_K| \cdot \cos \gamma = V_K \cdot \cos \gamma \approx V + u_W .(5)$$

The latter expression is a good approximation for small flight path angles γ . Then the relation between separation distance SD and separation time ST is

$$SD = (V + u_W) \cdot ST .(6)$$

Finally the effect of longitudinal wind on the vortex age t_{age} as a function of SD or ST can be described by the following equation

$$t_{age} = \frac{SD}{V} = \left(1 + \frac{u_W}{V}\right) \cdot ST .(7)$$

The principle effect of longitudinal winds on time or distance based separations are summarized in Fig. 9 where capacity is assumed to be inverse proportional to the separation time ST . The figure applies for the H-M aircraft pairings and an approach speed of $V=77.2m/s$ (this approach speed provides equal conditions for time and distance based separations for H-M in calm air and it can be considered to be very typical). The figure illustrates that for distance based separations with constant separation distance SD a headwind will increase separation time ST and decrease capacity (due to reduced ground speed). An enhancement of capacity is only possible in tailwind which is counterproductive concerning safety. To avoid a loss of capacity time separation can be applied to provide constant separation time ST and unchanged capacity. To keep the separation time and touchdown intervals constant the equivalent separation SD will have to be reduced if approach speed is maintained constant. This means that the trailing aircraft has to fly closer behind the vortex generating aircraft. But then one has to accept that the wake vortex age t_{age} after equation (7) for a potential encounter is reduced. Since t_{age} is a measure for the vortex strength and for the wake vortex motion off the nominal approach path this again affects safety.

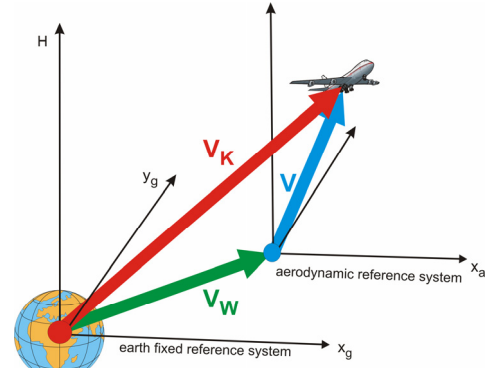


Figure 8. Kinematics of Speeds

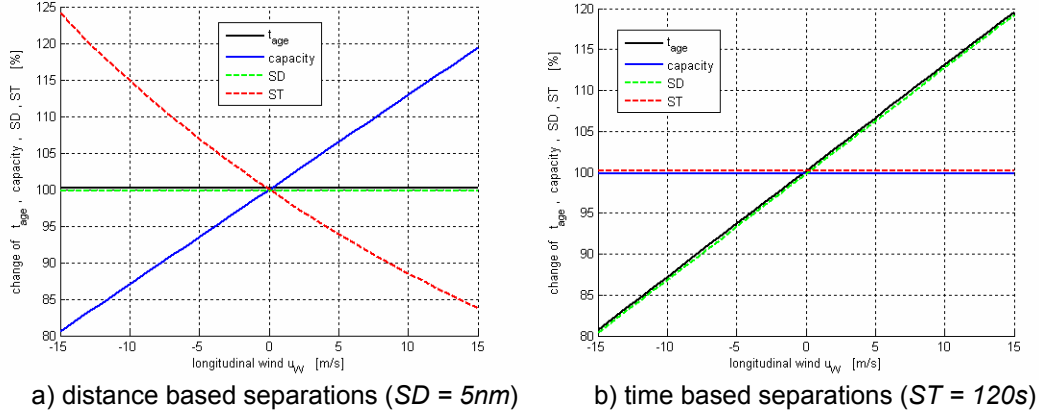


Figure 9. Comparison of time based and distance based separations
(MEDIUM behind HEAVY, $V = 77.2m/s$, headwind: $u_W < 0$, tailwind: $u_W > 0$)

Beside the effect of longitudinal wind on the relation between vortex age, SD , and ST there is another effect on the vertical distance between aircraft and wake vortex. The longitudinal wind does not affect the sink rate of the wake vortex but it moves the wake off the ILS path which results in an equivalent height gain of the wake vortex

$$\Delta \dot{H} = u_W \cdot \tan \gamma \quad (8)$$

The flight path angle γ is negative for descent and $u_W < 0$ applies for a headwind. Therefore, in this situation the wake is further below the ILS than without wind. Once the wake vortex is generated the additional height loss or gain due to u_W referred to no-wind condition is

$$\Delta H = \Delta \dot{H} \cdot t_{age} \quad (9)$$

With equation (7) and using a constant distance separation it applies

$$\Delta H = u_W \cdot \tan \gamma \cdot \frac{SD}{V} \quad (10)$$

and for a constant time separation we get

$$\Delta H = \left(1 + \frac{u_W}{V}\right) \cdot u_W \cdot \tan \gamma \cdot ST \quad (11)$$

Fig. 10 shows the results of equations (10) and (11) for a distance based separation with $SD = 5nm$ and a timed based separation using $ST = 120s$.

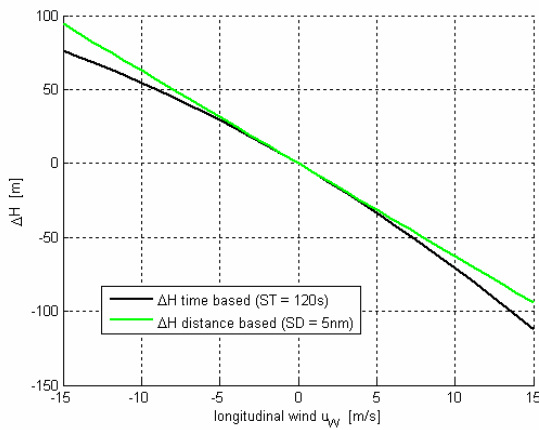


Figure 10. Extra height loss or gain above a wake vortex due to longitudinal wind
(MEDIUM behind HEAVY, $V = 77.2m/s$, headwind: $u_W < 0$, tailwind: $u_W > 0$)

For separations based on a constant SD the wake vortex age for a potential encounter is the same as in calm air (see equation (7) and Fig 9a). The additional vertical separation ΔH between aircraft and wake will increase with raising headwind (see equation (10) and Fig. 10). This can be interpreted as an extra safety margin at the expense of separation time ST respectively capacity. For separations based on a constant ST again the additional vertical separation ΔH between aircraft and wake will increase with raising headwind (see equation (11) and Fig. 10). But the wake at a potential encounter will be younger (see equation (7) and Fig 9b). As a consequence the circulation of the vortices will be higher but due to the reduced vortex age t_{age} they have only covered a smaller downward distance than in calm air. But if the separation time ST is kept constant and for the case that the sink rate of the generator aircraft \dot{H}_{AC} is higher than the downward velocity of the wake \dot{H}_{WW} the total vertical distance between the vortices and the follower aircraft will be larger than in calm air. In fact the following aircraft is exposed to younger vortices at

a larger vertical separation compared to calm air condition.³³ Which effect is predominating and if at least the same level of safety is achieved as in calm air cannot be determined without further investigations. Such a statement is only possible when a suited hazard or safety criterion is applied to the individual wake vortex encounter/fly-by situation. Further more it has to be considered that atmospheric turbulence increases with stronger winds leading to faster decay of the wake vortices relaxing the encounter situation.

A simplified approach for an estimation of a feasible separation time reduction is possible if the sink rate of the wake vortex is assumed to be constant $\dot{H}_{WV} = \text{const.}$ and the effect of the vortex age on the size of the potential hazard area around the wake is neglected which at the latest is no longer true when the rapid decay of the vortices starts. The total vertical distance between a wake vortex and the follower aircraft in calm air is

$$\Delta H_{\text{calm}} = \dot{H}_{WV} \cdot t_{\text{age calm}} = \dot{H}_{WV} \cdot ST_{\text{calm}} \quad (12)$$

If the mentioned simplifications are applied the vertical distance becomes in head-/tailwind conditions

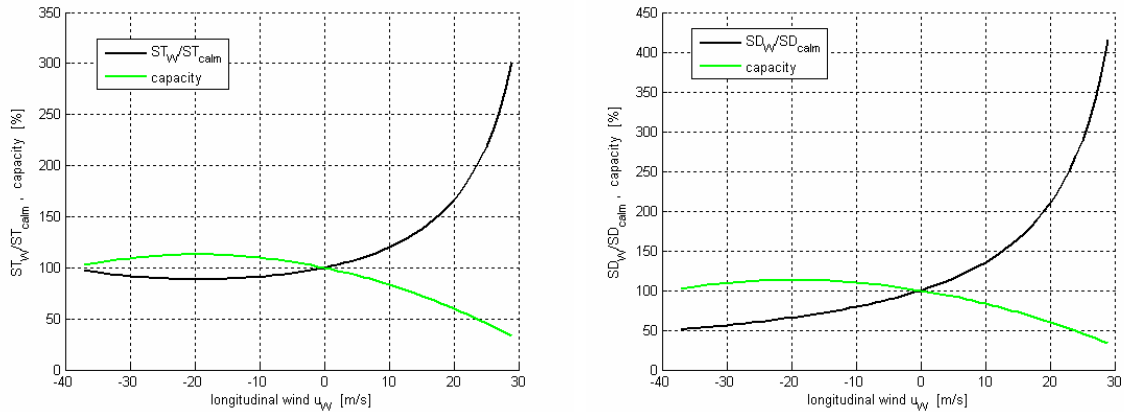
$$\Delta H_W = V_K \cdot \sin \gamma \cdot (ST_W - t_{\text{age } W}) + \dot{H}_{WV} \cdot t_{\text{age } W} \quad (13)$$

It is required that the vertical distance between the wake vortex and the follower aircraft should be the same with or without wind. Together with equations (5) and (7) the following ratio of separation times with or without a horizontal wind can be calculated

$$\frac{ST_W}{ST_{\text{calm}}} = \frac{1}{\left(1 - \frac{u_W}{\dot{H}_{WV}} \cdot \sin \gamma\right) \cdot \left(1 + \frac{u_W}{V}\right)} \quad (14)$$

Applying equation (6) the corresponding ratio of separation distances with and without wind SD_W/SD_{calm} can be calculated. For $u_{Wg} \rightarrow -V$ the separation time ST_W becomes infinite and the corresponding ratio of separation distances becomes $SD_W/SD_{\text{calm}} \rightarrow 33\%$ for the constraints used in Fig. 11. The inverse number of equation (14) gives the possible capacity increase. The results are illustrated in Fig. 11. There is a maximum benefit in headwind conditions for

$$u_{W \text{ opt}} = \frac{\dot{H}_{WV} - V \cdot \sin \gamma}{2 \cdot \sin \gamma} \quad (15)$$



a) ratio of separation time with/without wind

b) ratio of separation distance with/without wind

Figure 11. Ratio of separation time, separation distance and capacity variation due to longitudinal wind

($V = 77.2 \text{ m/s}$, $\dot{H}_{WV} = -2 \text{ m/s}$, headwind: $u_W < 0$, tailwind: $u_W > 0$)

In weak headwinds before the optimum is reached the effect prevails that the aircraft (and with it the origin of the wake creation) sinks faster than the wake itself without wind. With increasing headwinds the vortex age and respectively its vertical descent distance decreases and so does the descent distance of the aircraft due to lower sink rates. Any tailwind situation requires an increased separation time. It is emphasized that the results above are based on the mentioned ideal conditions and simplifications. If for a specific trade-off between ΔH gain and vortex age reduction a capacity increase can be achieved without any adverse effect on safety cannot be determined without further investigations.

IV. Separations Based on a Hazard Area Concept

If atmospheric phenomena like wind and turbulence play a role in wake vortex evolution and motion it will be only consequent when the actual applied separations are assumed to be weather dependent. The commonly accepted position regarding wake vortices is that no planned wake vortex penetration is permitted.⁹ But the question is how close could a wake vortex be passed before it can be distinguished from for example natural turbulence accepted in daily operational flights.

Different approaches exist to identify the safety relevant parameters, for example from US activities in the seventies and recent EU projects.^{10,11,12,13,14,15,16} In connection with wake vortex encounters the terms safety and hazard are frequently used. This suggests that there can be a clear and unambiguous boundary drawn between safety and hazard and that there exists a common understanding of these terms. But it has to be noted that their meaning can be very different depending on the respective context and application. The term hazard covers the range from a fatal accident to an undesired go-around. The envelope of a safe wake vortex encounter reaches from go-around (which is a safe standard flight procedure) to the requirement of undisturbed flight operations without adverse effects resulting from wake vortices (operationally safe).¹² The latter approach of a criterion covering an operationally safe wake vortex passage or better fly by is followed by DLR.^{3,5,17} This criterion was used for the presented investigations and will be briefly described below.

A. The Simplified Hazard Area (SHA)

Aircraft behavior during wake vortex encounter is affected by manifold parameters. The variety of influences complicates the definition of a simple safety criterion. This definition will become easier if strong vortex or even core encounters are excluded. The latter assumption can be made if one looks only for operationally acceptable encounters/wake-vortex-fly-bys.¹⁸ Such a criterion is the Simplified Hazard Area (SHA) concept. The idea of SHA is based on the assumption that it is possible to form a hazardous space around the wake vortex defined by only one single parameter.^{17,18,19} This hazard area shall constitute a region *outside* of which safe and undisturbed operations are possible²⁰. This does not necessarily mean that any penetration of that zone represents an unsafe situation (conservative approach). But avoiding that area allows safe and unhindered operations.

For approach and landing parallel-like encounters are prevailing and wake vortex induced rolling moment is the dominating effect²¹. This rolling moment related to the aircraft's roll controllability is a suited measure to assess the hazard potential the aircraft is exposed to. This can be calculated by different expressions in terms of dimensionless roll moment, derivative, acceleration, and control input

$$\xi_{req}^* = \frac{L(WV)}{L(\xi_{max})} = \frac{c_l(WV)}{c_l(\xi_{max})} = \frac{\dot{p}(WV)}{\dot{p}(\xi_{max})} = \frac{\xi_{req}(WV)}{\xi_{max}} = RCR_{req} \quad (16)$$

leading to the same result which is the normalized roll control ξ^* that is a synonym with Roll Control Ratio

RCR . For $\xi^* = RCR > 1$ the wake vortex disturbance exceeds the control capability of the aircraft. Focusing on undisturbed flight operations this parameter has to be much smaller than 1. Such situations are present for weak encounters. The latter means low (decayed) vortex circulation or/and wake vortex fly-by distances which are not too close to the vortex lines. In this case an acceptable level of RCR limits not only the roll response but covers also all other parameters of influence, e.g. sink rate, load factors, airspeed and flight path deviations. Thus, one single parameter is sufficient to characterize safe flight operations.¹⁹ The problem is the identification of the allowable nominal quantity of ξ_{nom}^* . For the safe area outside the hazard zone it applies

$$RCR_{req} = \xi_{req}^* < \xi_{nom}^* = RCR_{nom} \quad (17)$$

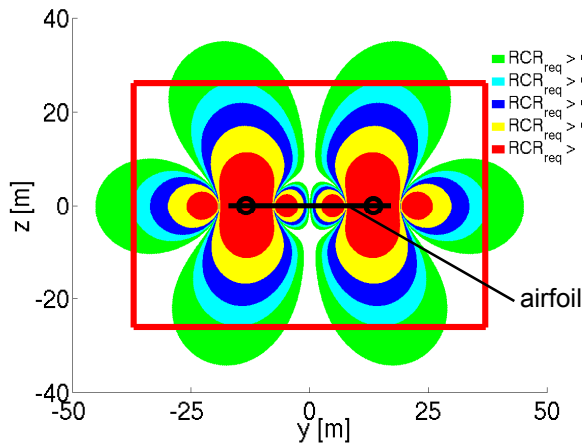


Figure 12. Wake vortex induced required roll control power behind an aircraft wing and simplified hazard area (SHA)

If a validated maximum nominal RCR preventing an intolerable aircraft response is fixed the potential hazard area to be avoided will be completely defined. The areas of different levels of RCR show a complex shape in the cross section behind an aircraft. For simplification it is (conservatively) approximated by a rectangle⁵ as for example illustrated in Fig. 12 for $\xi_{nom}^* = 0.2$.

B. Safe boundaries of SHA

From literature different proposals coming from simulator studies offer different limits for the allowable maximum value ξ_{max}^* (Fig. 13).^{22,23,24} For the determination of the above described operationally safe boundaries of SHA DLR has arranged its own validation process. Based on a full flight simulator study $\xi_{nom}^* = 0.2$ claims to be a proper limit.^{25,26,19} Recent results from real flight test using DLR's fly-by-wire in-flight simulator ATTAS (Fig. 14) seem to support this conclusion.³⁴

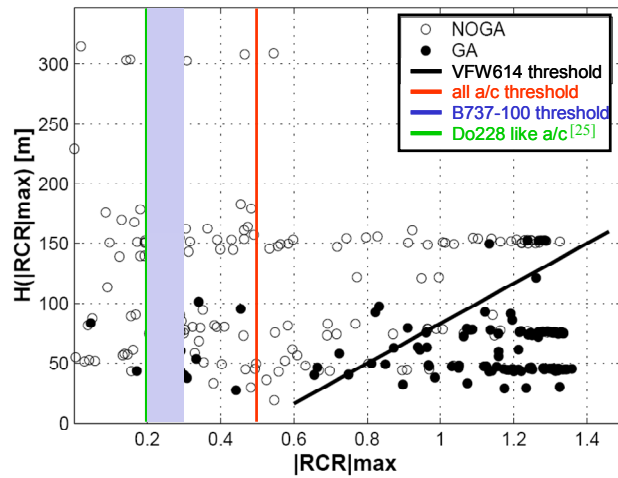


Figure 13. Proposals for safe Roll Control Ratio levels²⁴



Figure 14. DLR's flying testbed and in-flight simulator ATTAS (Advanced Technology Testing Aircraft System)

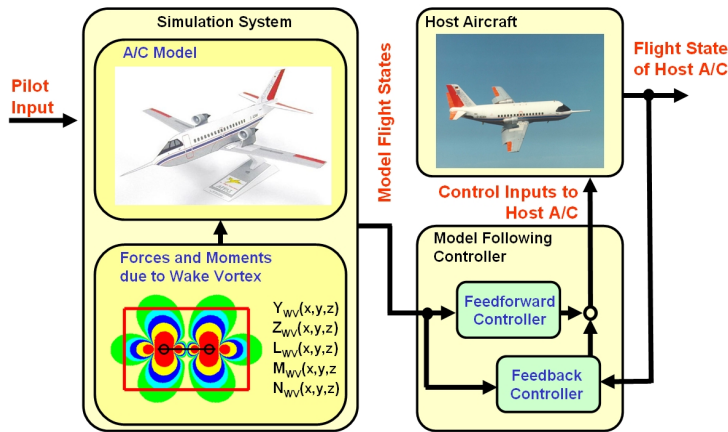


Figure 15. Principle of in-flight simulation

disturbances are fed back into IFS system and control the simulated aircraft. After the encounter initiation at a certain altitude the wake vortices are assumed to be earth fixed. Thus the vortex induced forces and moments depend on the aircraft's flight path through the flow field. The latter results from the disturbance itself and from the control input of the pilot.

All relevant data (e.g. AC state and flight path deviation) were recorded for the subsequent analysis. In addition pilot ratings for each approach were collected in four categories: aircraft control, demands on the pilot, aircraft

The in-flight simulation offers the most realistic simulation environment to an experiment especially for pilot-in-the-loop investigations. Pre-experimental tests confirmed that ATTAS is excellently suited for of wake vortex encounter in-flight simulations.²⁷ The principle of the in-flight simulation is illustrated in Fig. 15. During the flight experiment real IFR ILS approaches under VMC conditions were executed. At some point in the approach wake vortex penetrations were simulated at the on-board computer system of ATTAS. A special control system (model following controller) makes the host aircraft ATTAS behave like the simulated aircraft affected by the wake vortex. For the pilot there is no difference compared to real encounter. His control commands to counteract the

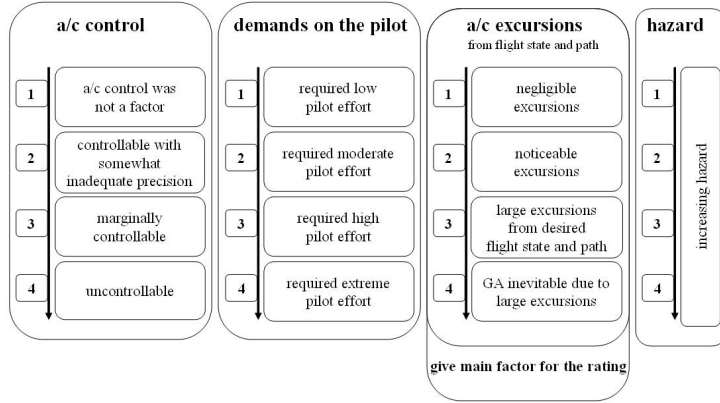


Figure 16. Wake vortex encounter rating scale^{18,25}

the pilot comment on this encounter was that there was something noticeable but nothing more than quite normal “atmospheric” disturbances. The pilot could not even say if it was a wake or not. For all encounters with $RCR_{req} \leq 0.2$ the ratings were summarized in Fig. 18 showing no contradiction to the assumption that $RCR_{nom} = 0.2$ represents

excursions from flight state and path and over all hazard. The rating scale is graduated into four levels, with a rating of 1 denoting a case where no adverse effects are noticeable and a 4 denoting an unwanted serious situation (Fig. 16). If any sub-criterion is rated to be 4 the respective encounter is classified to be unacceptable. Ratings of 1-3 are considered to be acceptable. Fig. 17 shows a typical encounter with maximum $RCR_{req} = 0.2$. The encounter is indicated by red crosses. Even though the actual control input RCR applied by the pilot (blue curve) was slightly higher than the ideal required RCR_{req} (red curve)

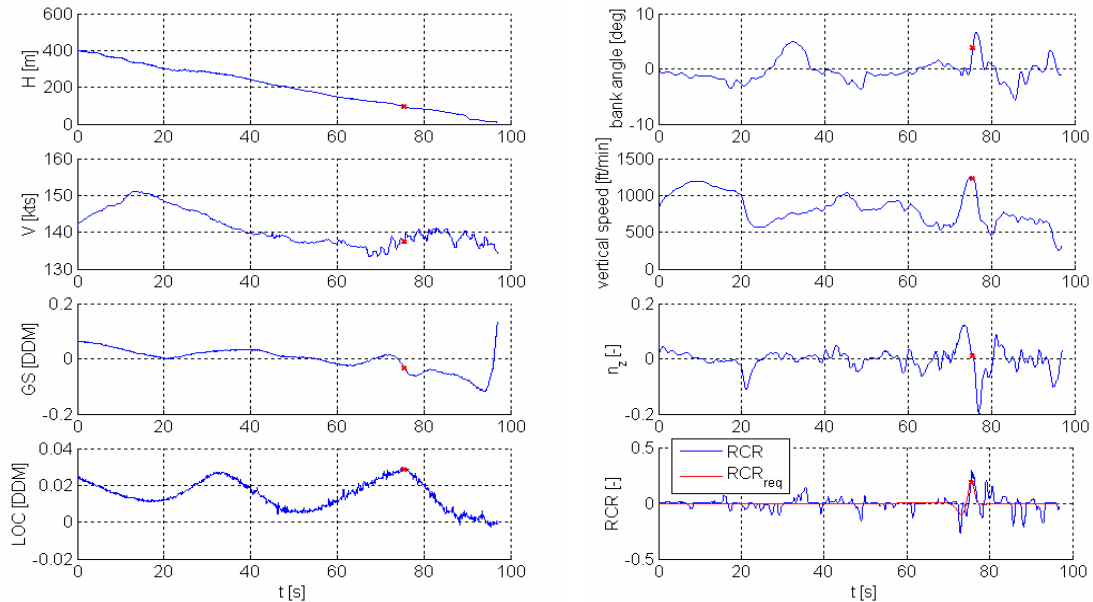


Figure 17. Flight test results from an in-flight simulation of a wake vortex encounter ($RCR_{req} = 0.2$)

a safe limit. The blue colored bars represent the mean values for all approaches and the black lines indicate the maximum and minimum ratings, respectively.

Within the DLR wake vortex project *Wirbelschlepe II*, there are additional in-flight simulation flight tests for 2006 in preparation, with the goal to investigate hazard area limits in a continuous process. It should be pointed out that there is a general need for a reliable and well defined safety criterion. To solve this problem extensive pilot-in-the-loop wake vortex encounter studies have to be executed. For the following investigations $RCR_{nom} = 0.2$ is assumed to provide safe flight operations especially without any wake vortex caused go-around.³⁴

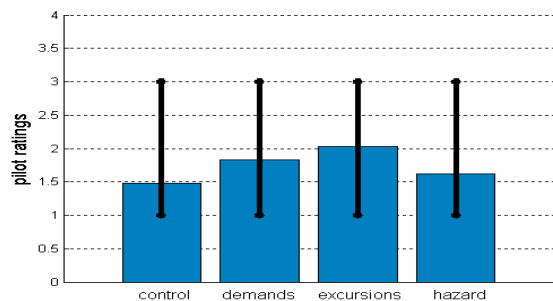


Figure 18. Pilot ratings from IFS flight tests for $RCR_{req} \leq 0.2$

C. Simplified Hazard Area Prediction

For a specific ξ_{nom}^* respectively RCR_{nom} the dimension of the Simplified Hazard Area can be predicted dependent on the aircraft pairing of vortex generator follower. Since the required relevant aircraft data for this calculation are not always available for any aircraft a more general approach is needed. Based on a database of existing aircraft a functional relationship has been established between the relevant aircraft parameters and the MTOW. These functions are used for a "Simplified Hazard Area Prediction" (SHApe) independent of specific aircraft.^{3,5} To account for data scatter and uncertainties only worst case parameter combinations are used. For example for a certain aircraft category the roll control power provided by the respective function shows a bandwidth with upper and lower limit. The SHApe tool uses for the determination of the hazard area dimension only the minimum roll control power since this presents the worst case situation. This way a conservative hazard area calculation can be executed for any conventional transport aircraft (see Fig. 19). For each specific aircraft pairing or combination of aircraft category (e.g. H-M) the SHApe can be run in a pre-process to generate the respective hazard area dimensions in advance. Then the size of SHA can be calculated from a function or look-up table depending on the actual (time and weather dependent) circulation strength of the generator.

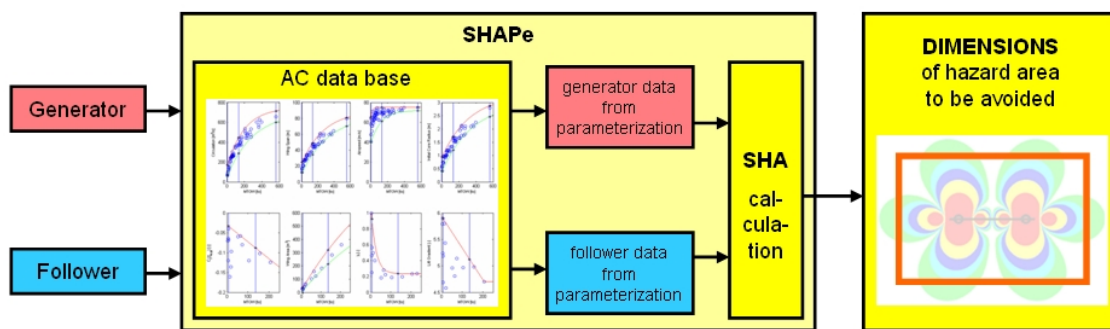


Figure 19. Principle of SHApe

D. Concept for dynamic wake vortex separation

The wake vortex hazard during approach depends on vortex strength and its length of stay within the approach corridor. Thus vortex decay and transport play an important role for safe wake vortex separation minima. Implementing this into a dynamic wake vortex separation concept is the goal of the Wake Vortex Prediction and Monitoring System (WSVBS) within the DLR project *Wirbelschlepppe II*.²⁸

The underlying idea is sketched in Fig. 20 which shows a cross section at a certain distance before the RWY threshold. For IFR approaches the aircraft will fly within the approach corridor around the nominal ILS path. For certain likelihood²⁹ for aircraft not leaving a definite region around ILS the approach corridor can be approximated by a simple rectangle. Within this approach corridor wake vortices are generated. They are located in their probable

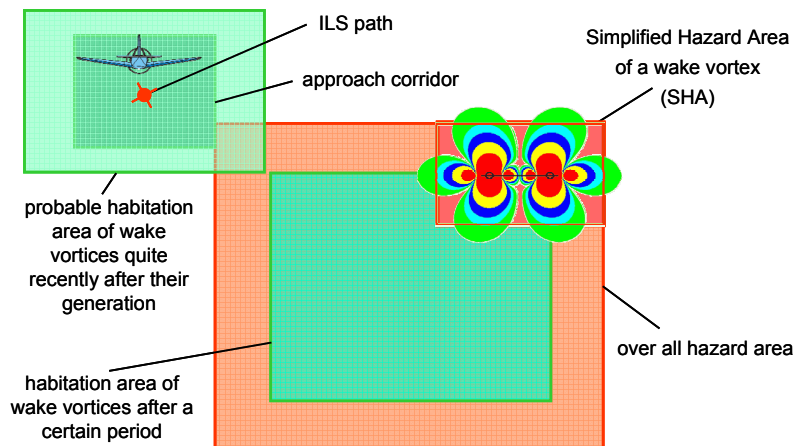


Figure 20. Cross section of approach corridor and hazard areas

habitation area which has to be enlarged due to position uncertainties. After a period the probable wake vortex habitation area has moved away from the ILS path by the vortex self induced sink rate and by wind effects. The habitation area increases due to uncertainties in prediction which increase with forecast horizon. All along the boundaries of the so developed vortex habitation area the Simplified Hazard Area (SHA) has to be superimposed to cover the sphere of influence of a wake vortex. The resulting outer limits frame the complete hazard area to be avoided by following aircraft. Or the other way round: If this overall hazard area after

a certain period of time Δt_s does not overlap anymore the approach corridor, a save approach is possible for the next aircraft. This way the required minimum separation time is derived. The procedure can be repeated for different gates along the approach corridor, to obtain a minimum separation for the entire approach (see Fig. 21). Since this process accounts for the actual aircraft pairing and the atmospheric conditions, dynamic time based separation minima are achieved.¹⁸

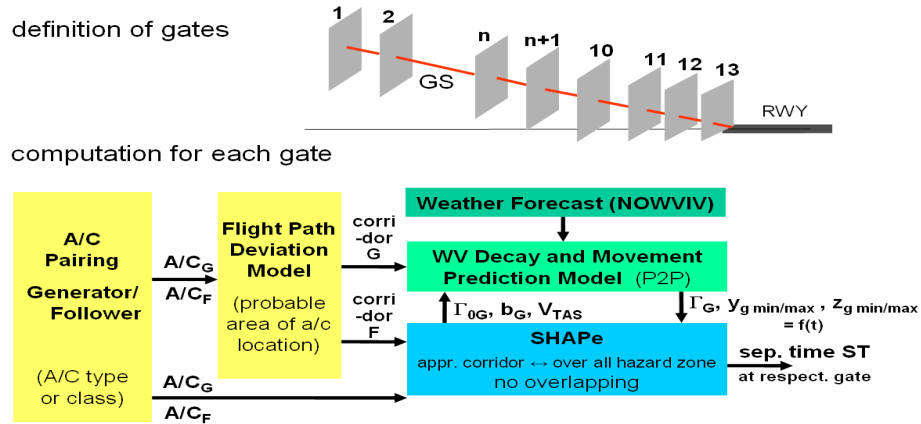


Figure 21. Dynamic wake vortex separation concept

For its application within DLR's Wake Vortex Prediction and Monitoring System SHAPE does not only predict the SHA (as illustrated in Fig. 19) but also checks the overlapping of approach corridor and overall hazard area. From Fig. 21 it is clear that the reliability of the whole concept strongly depends on the consistency of the weather and wake vortex decay and movement prediction.³⁰ The presented concept is using DLR's sophisticated NOWVIV³¹ weather forecast tool and Probabilistic Two-Phase (P2P)^{6,32} wake vortex transportation and development model. The latter has been successfully matched against many different wake vortex data bases.

E. Effect of wind

1. No wind. Since worst case combinations and uncertainty margins are taken into account the above described concept is considered to provide conservative separation minima. This can be demonstrated in calm air conditions. But independent from the actual mean wind two meteorological cases for different turbulence conditions stimulating the vortex decay are considered.

met_1: no atmospheric turbulence

met_2: light turbulence ($\epsilon = 6.6 \cdot 10^{-5} \text{ m}^2/\text{s}^3$, $\text{TKE} = 0.1 \text{ m}^2/\text{s}^2$)

The respective probable wake vortex habitation areas for met 1 and 2 were calculated by the P2P model. As a reference separation times for H-M: 120s and H-H: 90s are chosen being representative for nowadays average separations for single runway.

Applying the above described dynamic separation concept for no wind condition no capacity gain is calculated independent of aircraft combination or turbulence level. The only accountable factors to clear the gates along the approach corridor behind a vortex generating aircraft are decay and sinking of the vortices. The overall hazard area stays in the approach corridor for a longer period than for the above given reference cases which does not allow a separation reduction below the present standards.

2. Lateral wind. Calm air conditions are no standard situations. Normally there is mean wind very often resulting in a crosswind component related to the runway. Compared to the no wind situation there is the additional effect of a lateral wake vortex movement out of the approach corridor. Fig. 22 illustrates the movement of the overall hazard area during the approach of a H-M aircraft pairing in a $v_W = 3 \text{ m/s}$ pure crosswind (wind from the left) in met_1 condition. The applicable minimum separation time ST is defined by the maximum length of stay of the wake vortex at any gate. From the executed studies it was observed that the relevant gates are those which are very close to the runway threshold.

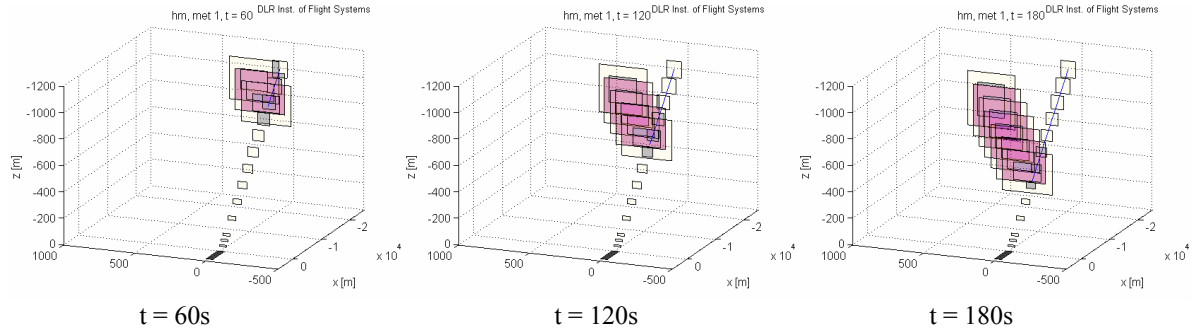


Figure 22. Example for the development of the hazard areas along the approach corridor (H-M, $v_W = 3\text{m/s}$, met_1 , $\text{RCR}_{\text{max}} = 0.2$)

Fig. 23 shows the influence of level of turbulence and the aircraft combination on the crosswind magnitude when a separation reduction below the above reference separation intervals is possible and a capacity increase is feasible. It can be seen that the minimum crosswind for a H-H combination has to be stronger than for H-M. Assuming that for any aircraft combination $\text{ROT} \geq 60\text{s}$ the maximum achievable capacity increase of course is higher for H-M pairings than for H-H. Although the met_2 condition yields the higher level of turbulence and thus the faster vortex decay the minimum crosswind for separation reduction is stronger than for met_1 . This is due to the fact that there is an increasing uncertainty in the prediction of the wake vortex habitation area with higher turbulence levels. The maximum capacity gain for H-H is 50% since the difference between the minimum separation time limited by ROT and the currently applied minimum separation of 90s is only 30s. For H-M the capacity can theoretically be doubled if the separation time can be reduced from 120s to ROT.

It can be noted that there is only a very small bandwidth of crosswind components in which the capacity gain reaches from zero to its maximum. A capacity gain is possible if the approach corridor is free of wake vortices for a specific minimum crosswind. But then very soon for higher cross winds wake vortices do no longer play a role for separation due to the limiting effect of ROT. For example, for a crosswind of 5m/s a wake vortex has already been moved laterally 300m off the nominal flight path before the next a/c follows.

The positive effect of crosswind on capacity can be shifted to weaker crosswinds when the overall hazard area is reduced. Such a reduction can be achieved for example by a more precise wake vortex transport prediction (reduction of uncertainty margin) and/or an improved nominal flight path tracking (smaller flight path deviations). The latter can be achieved using automatic flight controllers enhancing flight path tracking. Another possibility for the overall hazard area reduction is the acceptance of higher RCR values for the hazard area determination. Higher RCR values can be handled by special controllers designed to cope with vortices. Fig. 24 illustrates the improvement of a/c response if a specific wake vortex controller based on feed-forward disturbance compensation is active [5]. The presented results in Fig. 24 are valid for $\text{RCR}_{\text{nom}} = 0.4$. But even much stronger wake vortices up to $\text{RCR}_{\text{nom}} < 1$ can be passed successfully using specific a wake vortex controller.

The measures mentioned above will help to reduce the overall hazard area. Fig. 25 shows the positive effect of 30% dimension reduction of the overall hazard area on the capacity gain versus crosswind. Fig. 24 also shows the consequence of an additional separation of the MEDIUM aircraft category. H-M2 represents the possible capacity gain of an upper MEDIUM aircraft category with 64.5to < MTOW < 136to behind a HEAVY aircraft as a function of crosswind. The respective separation reductions for the expected capacity gains can only be applied on condition that the real crosswind at any time during the approach of the following aircraft is always equal or higher than the required coming from the presented concept.

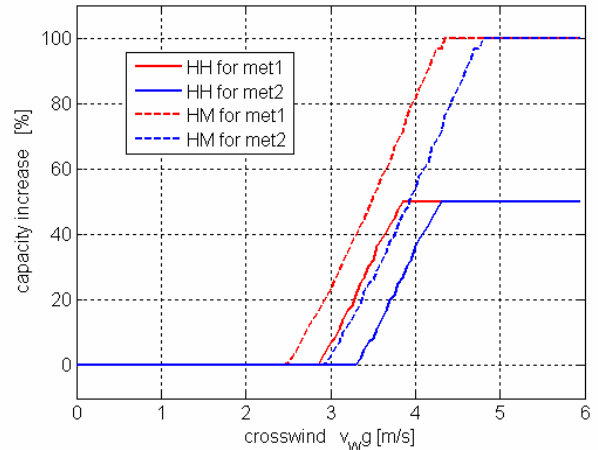


Figure 23. Capacity gain due to crosswind ($\text{RCR}_{\text{max}} = 0.2$)

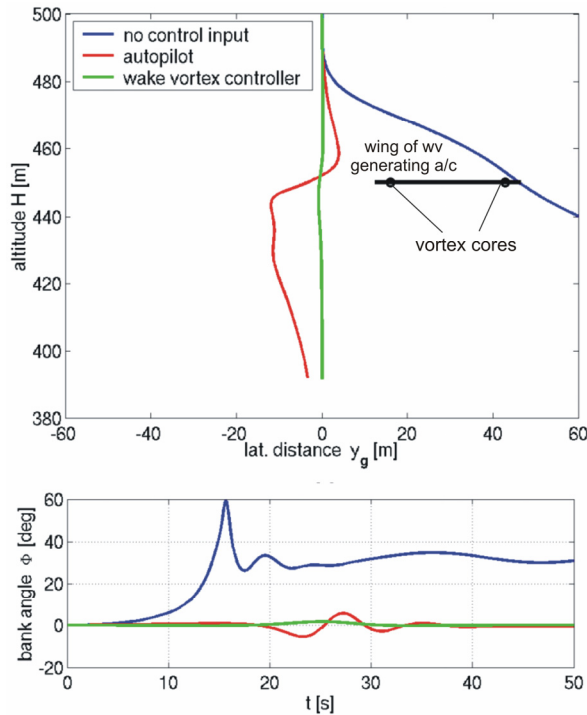


Figure 24. Comparison of aircraft response for wake vortex encounters on ILS (3deg) using different levels of control

3. Longitudinal wind. The principle influence of headwind on capacity is illustrated in Fig. 26. Without headwind ($u_W = 0$ m/s) the wake vortex descends for increasing time. When a headwind ($u_W < 0$ m/s) occurs the wake vortex not only descends but moves longitudinally away from the nominal ILS path towards the following aircraft. Thus, in a potential encounter the vortices will be younger than for the calm air situation (see chapter III). In principle DLR's Wake Vortex Prediction and Monitoring System (WSVBS) shows positive effect of headwind situations. Compared to approaches in calm wind the reference gates described above are cleared earlier. But a separation reduction (compared to reference separation times for H-M: 120s and H-H: 90s) can only be observed for very high and unrealistic headwinds. This can mainly be assigned to the current conservative assumptions for WSVBS. If the uncertainty margins can be reduced in the future due to improved knowledge the effect of headwind on capacity may become a topic.

Normally, landing in tailwind situations are avoided. From the view point of capacity tailwind produces a positive effect if standard distance separation is applied and wake vortex transport and development is ignored (see Fig. 9a). Considering these important effects a different situation is present. Since the ILS track is earth fixed a tailwind will move a wake vortex towards the nominal flight path while the vortices descend. Assuming a wake vortex sink rate of about $w_{VV} \approx 2$ m/s the wake will move roughly along a 3deg glide slope for a tailwind of $u_W = +38.2$ m/s. But now the wake vortices are older (compared with no wind situation) when the follower aircraft passes a specific position on the glide path. The corresponding reduced

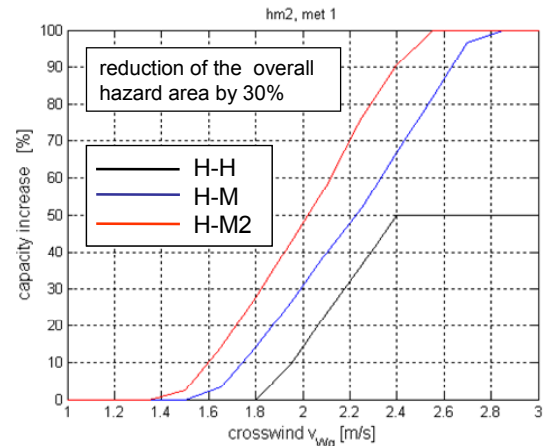


Figure 25. Effect of reduced overall hazard area on capacity gain versus crosswind

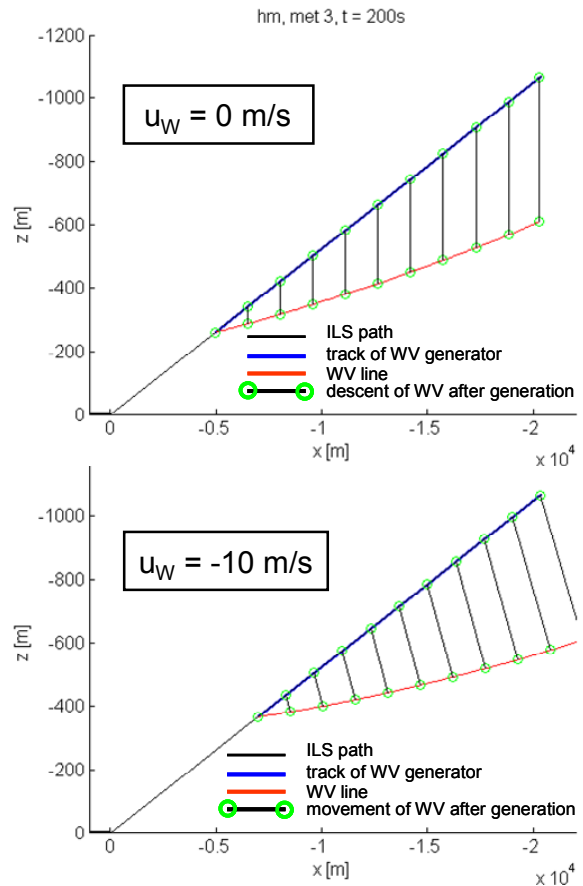


Figure 26. Effect of headwind on WV movement

vortex circulation has only minor effects. As already mentioned DLR's Wake Vortex Prediction and Monitoring System gives no separation reduction in calm air. Therefore, at least in the range between $0\text{m/s} < u_w < +38.2\text{m/s}$ no separation reduction and capacity increase can be expected. To blow the vortex above the ILS path much higher (unrealistic and unacceptable for landing) tailwinds are necessary. This is confirmed by the WSVBS. But it can be expected that due to the very high turbulent airflow vortex movement is no longer important compared with the rapid vortex decay. Thus, longitudinal wind does not seem to become a big factor when looking for capacity margins. This may change when the current conservative assumptions for WSVBS can be improved. But due to real world effects those safety margins will always be a part of the game.

V. Summary Conclusion

Wake vortex separations are a limiting factor for landing capacity of airports. The increasing air traffic forms the need for more flexible separation procedures taking into account the actual weather situation and the parameters of a more individual aircraft pairing. The present separation standards have to be investigated carefully with the aim to discover possible margins.

Basic considerations and relations determine the absolute limits of traffic throughput and the effect of approach speed on capacity for distance based separations. The subdivision of the existing aircraft classes (based on MTOW) into subclasses have a favourable effect since a specific separation needs not to cover the currently wide range of aircraft masses (e.g. ICAO class M: 7to – 136to). Changing from distance based separation into time based separation will help to cover capacity losses in headwind situations. For time based separations we have to accept that the follower aircraft gets closer to the generating aircraft and the vortices for a potential encounter will be younger. On the other hand the vertical distance to the wake increases in headwind situations. If for a specific trade-off between ΔH gain and vortex age reduction a capacity increase can be achieved without any adverse effect on safety can only be determined by applying a more complex methodology based on a reliable safety criterion.

Separation reductions can also be achieved by wake vortex avoidance using prediction systems for the wake related hazard zones, their development and movement. Avoiding the no-go areas around wake vortices allows safe and undisturbed flight operations. The definition of a reliable and validated safety criterion is the fundamental element for the determination of such hazard zones. During approach and landing phase all aircraft are lined up along the nominal ILS path parallel like wake vortex encounters are prevailing. Therefore, the presented concept of a hazard area determination is based on the normalized required roll control power respectively roll control ratio (RCR). The required RCR represents the roll control demand to compensate for a wake induced rolling moment, normalized by the aircraft's maximum roll control power. For manually controlled aircraft the limit of acceptable RCR can be established using full flight simulator studies and in-flight simulations. Parameterization of the relevant parameters leads to the universally applicable concept of the "Simplified Hazard Area Prediction" method (SHAPE). SHAPE provides the hazard area dimensions for specific approach situations. SHAPE is part of the Wake Vortex Prediction and Monitoring System (German abbreviation: WSVBS) developed within the DLR project *Wirbelschlepe II* for creating safe and reduced landing separations.

Applying the WSVBS for calm air situation no reduction of the current separation distances and no capacity increase are possible. This demonstrates the conservative approach of the WSVBS. The main reason for this result is the applied uncertainty margin in the prediction of the wake vortex habitation area. But it can be shown that for crosswind situations the capacity can be increased due to the effect that the wake vortices are blown off the approach corridor. But there is only a very small bandwidth of crosswinds in which a capacity gain is built up from zero to its maximum. The minimum crosswind for a separation reduction is lowered by a more accurate nominal flight path tracking of the vortex generator aircraft, a precise wake vortex transportation prediction and smaller hazard areas. The latter means that an aircraft is allowed to pass the wake vortex safely at a closer distance. This can be achieved by automatic controllers (pilot assistance systems) supporting the pilot's control task. Thus, only very low crosswinds are required to apply reduced separations and to increase capacity.

In principle a headwind improves the wake vortex situation. But even for very high wind speeds no separation reduction below the presently applied separations is possible due to the current conservative assumptions for WSVBS. Tailwind does not improve the situation at all. Thus, longitudinal wind does not seem to be a factor when looking for capacity margins. But if the uncertainty margins can be reduced in the future due to improved knowledge the effect of headwind on capacity may become a topic. But due to real world effects the safety margins will never be removed completely.

In a next step closely spaced parallel runways and their possible capacity potential due to consideration of the actual wind situation will be investigated.³³ But doubling the capacity of a single runway system to cope with the predicted traffic increase seems to be beyond the possibility of reduced wake vortex separations.

Acknowledgement

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