# IMPACT OF INDIVIDUAL AND DYNAMIC WAKE VORTEX SEPARATIONS ON AIRPORT CAPACITY

**Carsten Schwarz, Klaus-Uwe Hahn**
**German Aerospace Center, Institute of Flight Systems**
**Lilienthalplatz 7, 38108 Braunschweig, Germany**

**Keywords**: *wake vortex, hazard area, wake vortex separations, dynamic wake vortex separations, single/ parallel runway*

## Abstract

*For many airports the capacity is limited by minimum separation distances especially for approach and landing due to the possible hazard generated by wake vortices. In order to alleviate capacity limitations, separation rules have to be improved without reducing safety. Based on simplified hazard areas dynamic wake vortex separations can be derived taking into account atmospheric conditions and actual aircraft pairing. This concept is applied to parallel runways in comparison to the single runway case for cross wind and headwind conditions.*

## Nomenclature

| | |
|---|---|
| C | aerodynamic coefficient |
| δ | control surface deflection |
| Δ | difference |
| γ | (flight-) path inclination angle |
| Γ | circulation (vortex strength) |
| hh | ICAO pairing heavy-heavy |
| hm | ICAO pairing heavy-medium |
| ST | separation time |
| t | time |
| u | velocity x-component |
| v | velocity y-component |
| V | airspeed |
| x | longitudinal coordinate |
| z | vertical coordinate |

### subscripts

| | |
|---|---|
| a | aileron, air-path |
| g | geodetic/ earth-fixed |
| K | flight-path |
| l | rolling moment |
| L | leader/ generator aircraft |
| nom | nominal |
| req | required |
| W | wind |
| WV | wake vortex |

### abbreviations

| | |
|---|---|
| A/C | aircraft |
| ATTAS | Advanced Technologies Testing Aircraft System |
| CSPR | closely spaced parallel runways |
| DoF | degrees of freedom |
| DLR | German Aerospace Center *(Deutsches Zentrum für Luft- und Raumfahrt)* |
| ICAO | International Civil Aviation Organization |
| ILS | instrument landing system |
| MTOW | maximum takeoff weight |
| P2P | probabilistic two phase model |
| PR | parallel runway |
| RCR | roll control ratio |
| ROT | runway occupancy time |
| RWY | runway |
| SHA | simplified hazard area |
| SHAPe | simplified hazard area prediction |
| SR | single runway |

## 1 Introduction

Due to the wake vortex phenomenon minimum separation distances are enforced especially for approach and landing [1], which can be a limiting factor for airport capacity. In order to increase airport terminal area capacity it is desirable to enhance separation rules without compromising safety. This could be accomplished for example by taking into account the actual aircraft pairing and/ or atmospheric conditions. Dynamic wake vortex separations require a definition of an area around the vortices which has to be avoided. This area is provided by the concept of simplified hazard areas (SHA), which is presented in this paper.

## 2 Fixed Wake Vortex Separations

The present wake vortex separations are defined by ICAO based on 3 weight categories [1], although national exceptions exist. For non-radar operation the minimum separation is 3 minutes for light behind heavy or medium and 2 minutes for medium behind heavy (no non-radar minimum exists for heavy behind heavy). In any case the absolute separation minimum as defined by ICAO is 3 nm for sufficient radar capability and 2.5 nm if the runway occupancy time (ROT) is proven not to exceed 50 s. Depending on the approach speed the minimum separation time can generally assumed to be around 60 s. For radar operation the separation minima are specified as distances by the well known wake vortex separation matrix, e.g. 4 nm for heavy behind heavy and 5 nm for medium behind heavy.

The subdivision into aircraft classes influences the capacity. Simply by increasing the number of aircraft classes from three to four or five the landing capacity is significantly improved [11], [17].

## 3 Dynamic Separations based on the Hazard Area Concept

Wake vortex behavior (ageing and transport) is strongly influenced by atmospheric conditions like wind and turbulence. The severity of a wake vortex encounter significantly depends on the involved aircraft. Therefore, dynamic wake vortex separations considering these factors seem to be an appropriate approach. The idea is to define so called hazard areas around the vortices which have to be avoided.

### 3.1 Simplified Hazard Areas (SHA)

The concept of simplified hazard areas (SHA) is described in detail in [2] and [3]. It is based on the commonly accepted position regarding wake vortices that "no planned wake vortex penetration is permitted" [4]. In other words it has to be ensured that flight operations are safe and undisturbed so that the wake vortex effect is not distinguishable from other acceptable atmospheric phenomena. Therefore an area around a wake vortex is defined <u>outside</u> which the vortex flow is definitely not hazardous to an aircraft. However not every penetration of that zone results in an unsafe situation (conservative approach). Different approaches exist to identify the safety relevant parameters [5]. Considering the context of approach separation minima, safety is not the only requirement. In addition, passenger comfort as well as undisturbed operations have to be ensured. The latter means that there must be no go-arounds due to wake vortex encounters.

As described in more detail in [2] and [3] SHA are defined based on the wake vortex induced rolling moment $C_{l,WV}$ related to the maximum roll control power of the encountering aircraft $C_l(\delta_{a,max})$. This defines the required roll control power $RCR_{req}$.

$$RCR_{req} = \frac{C_{l,WV}}{C_l\left(\delta_{a,\max}\right)} \tag{1}$$

By choosing a maximum value for the required roll control ratio (i.e. nominal roll control ratio)

$$RCR_{req} \overset{!}{<} RCR_{nom} \tag{2}$$

the hazard area is defined, (conservatively) approximated by a rectangle (Fig. 1). The nominal roll control ratio is the maximum theoretical value for quasi-stationary flight outside the simplified hazard area. If this value is sufficiently small, the resulting hazard area covers also the other risks posed by the wake vortex. The suitability of this approach is discussed in [6] and [7].

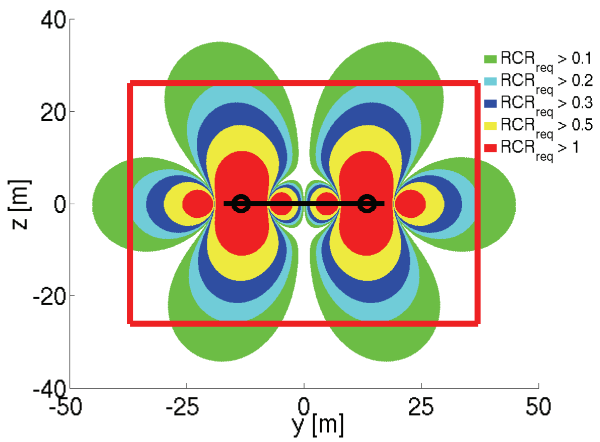


**Fig. 1 Wake vortex induced required roll control power and simplified hazard area (SHA, for $RCR_{nom} = 20\%$, $t_{age} = 50$ s, example ICAO pairing 'light' behind 'medium', no turbulence) in the cross section behind the vortex generating aircraft (with indicated generator wing and vortex cores)**

The main parts of the hazard area calculation are the description of the vortex generation and aging, the representation of the wake vortex induced velocity distribution and the modeling of the encounter aircraft reaction. Basically the same components are used for the 6 DoF simulation of wake vortex encounters and are described in [3] and [8] including their validation.

### 3.2 Hazard Area Boundaries

The applicability of the quasi-stationary required roll control ratio for the definition of hazard areas is investigated by means of offline simulation, full flight simulation and in-flight simulation. The final goal is to set up a roll control limit to guarantee safe and undisturbed flight operations.

Offline 6 DoF simulations with autopilot [8] along the hazard area boundaries suggest that the SHA concept is appropriate for wake vortex hazard avoidance [7], [3]. Furthermore a nominal roll control ratio of $RCR_{nom} = 30\%$ seems to be adequate for automatically controlled flights to prevent hazardous situations [9].

For full flight simulator investigations a value of $RCR_{nom} = 20\%$ yields acceptable results for manual control [7], [6], [10]. Recent results from real flight test using DLR's fly-by-wire in-flight simulator ATTAS seem to support this conclusion [18], [11], [6].

### 3.3 Simplified Hazard Area Prediction (SHAPe)

The determination of the simplified hazard areas requires a number of input parameters and aircraft data, mainly for the encountering aircraft. In order to allow a broad applicability independent of available specific aircraft data, a "Simplified Hazard Area Prediction" (SHAPe) can be applied [2], [3]. In a first step of simplification only the wing of the encountering aircraft is considered for hazard area determination (no tails), which greatly reduces the number of required parameters, but has minor influence on the results. For the highest level of abstraction the parameterization of aircraft data is related to only one quantity, the maximum takeoff weight (MTOW). Based on a database of existing aircraft a functional relationship is established between the relevant aircraft parameters and the MTOW. In order to account for statistical uncertainties a worst case approach is applied. For example lower encounter aircraft airspeed results in a larger hazard area because the wake vortex induced angles of attack are higher. So the lowest airspeed for a certain aircraft category within the database represents the respective worst case. This way the hazard area calculation can be executed for any (generic) conventional transport aircraft.

### 3.4 Concept of Dynamic Separation

Implementing dynamic wake vortex separation minima considering decay, sinking, and wind drift of the vortices while retaining at least the same level of safety is the goal of the wake vortex prediction and monitoring system within the DLR project Wirbelschleppe II [12].

For ILS approaches the approach corridor can be determined (conservatively approximated by a rectangle), which covers the positions of the approaching aircraft with a certain likelihood [13] (Fig. 2). The wake vortex behavior prediction model P2P yields the actual vortex strength for both vortices and their probable propagation area [14], [15]. For the worst case one or both vortices are exactly on the border of that area. For this case the simplified hazard area is superimposed with the wake vortex habitation area which yields the overall hazard area. If this overall hazard area after a certain period of time ST 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 windows along the approach corridor to obtain a minimum separation for the entire approach. Since this process accounts for the actual aircraft pairing and the atmospheric conditions, dynamic separation minima are achieved.

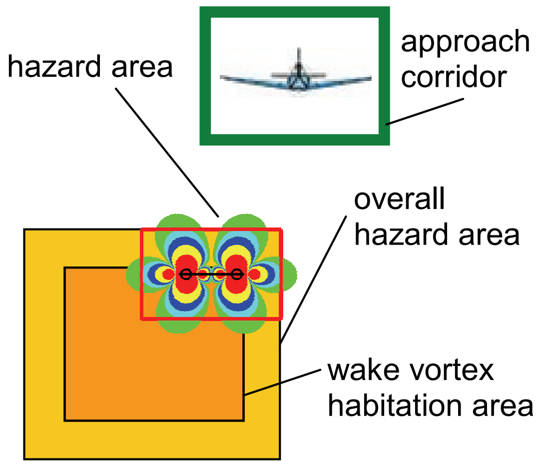


**Fig. 2 Approach corridor and hazard areas**

## 3.5 Influence of Wind for Parallel Runways

The concept of dynamic wake vortex separations is applied to parallel runways (PR), in comparison to a single runway (SR). The spacing between the parallel runways is $\Delta y_{RWY} = 500$ m, which makes them CSPR (closely spaced parallel runways) which is a common scenario for today's airports. The current treatment of CSPR is as follows [16]:

"Two parallel runways are treated as a single runway, when they are separated less than 2500 ft when visual approaches are not employed."

This means aircraft approaching the different runways have to obey the separation rules for a single runway which greatly reduces the capacity of such a runway system.

This scenario is investigated for the ICAO aircraft pairings medium behind heavy (hm) and heavy behind heavy (hh) to show principal effects for the present wake vortex aircraft categories; however the same concept can be applied for differently defined aircraft classes or specific aircraft types.

The following atmospheric conditions are considered according to the wake vortex behavior prediction model P2P (which includes the ground effect):

met 1: no atmospheric turbulence

met 2: light turbulence

The separation time ST is calculated for the different parameter combinations and is in any case limited to 180 s as this is presently the maximum imposed wake vortex separation (see section 2).

The reference separation times according to the current rules are depending on the airspeed if separation distances are applied (see section 2). Approach speeds for commercial aircraft range from approximately V = 65 m/s to V = 75 m/s [2]. The approximate corresponding separation times are shown in Table 1 (no time based separation minimum is defined for hh for non-radar operation).

| separation distance | distance based (for approach speed) | | time based |
|---|---|---|---|
| | 65 m/s | 75 m/s | |
| hh: 4 nm | 115 s | 100 s | N/A |
| hm: 5 nm | 140 s | 120 s | 120 s |

**Table 1 Approximate separation times**

### *3.5.1 Calm Air*

For conditions with zero wind the dynamic wake vortex separations yield no capacity gain as can be seen on the figures in the following subsection for $v_W = 0$. This is due to the fact that the uncertainty margins and worst case combinations result in conservative separation predictions. Specifically close to the runway threshold in the lower part of the approach corridor the wake vortices can remain in the flight corridor for a long time due to the ground effect.

Fig. 3 shows whether the approach corridor and overall hazard area for 13 gates along the flight path are overlapping (overlap = gate number) or not (overlap = zero) depending on the separation time ST. Gate 1 is 11 nm from the runway threshold and gates 2 to 11 are at 10 nm to 1 nm. The last two gates are at a distance of 2/3 nm and 1/3 nm. The gates out of ground effect are cleared after ST = 90 s to 117 s, but the lowest three gates are not cleared during the investigated period. Gate 10 shows the rebound effect where the vortices are first sinking below the approach corridor and then rebound. Only the higher gates 1 to 9 are high enough to be not affected by the rebound effect.

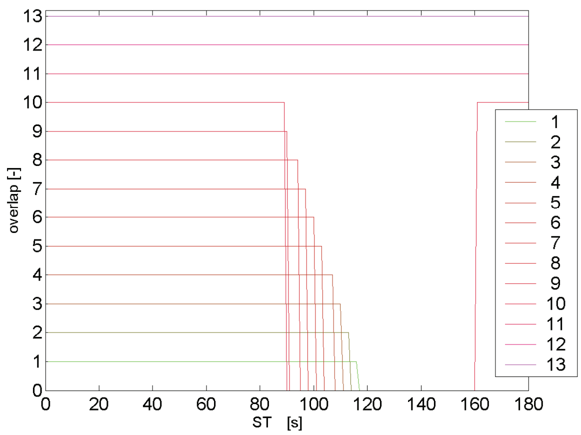


**Fig. 3 Overlapping of approach corridor and overall hazard area for gates along the glide path for calm air**

### *3.5.2 Cross Wind*

The situation for parallel runways with cross wind is depicted in Fig. 4. The overall hazard area is drifted away from the first runway by the cross wind and eventually reaches the second runway.

For the single runway case and for no atmospheric turbulence cross wind of $v_W > 3$ m/s allows smaller separation times than the reference scenario described above (Fig. 5). No additional capacity gain is possible for $v_W > 4$ m/s due to the ROT.

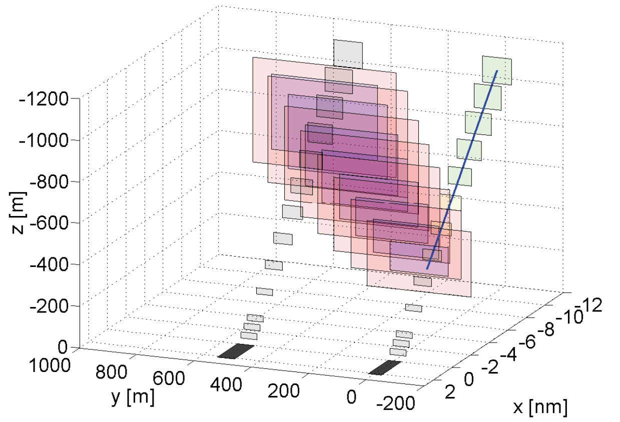


**Fig. 4 Parallel runway scenario with wake vortex habitation area and overall hazard area for cross wind $v_w = 3$ m/s (hm, met 2, $RCR_{nom} = 20\%$)**

The parallel runway on the downwind side is affected for cross wind of $v_W = 1$ m/s or higher. Separation improvements can be observed for $v_W > 6$ m/s for medium behind heavy and for $v_W > 7$ m/s for the hh case respectively. In any case is the upwind runway not affected at all by the wake vortex!

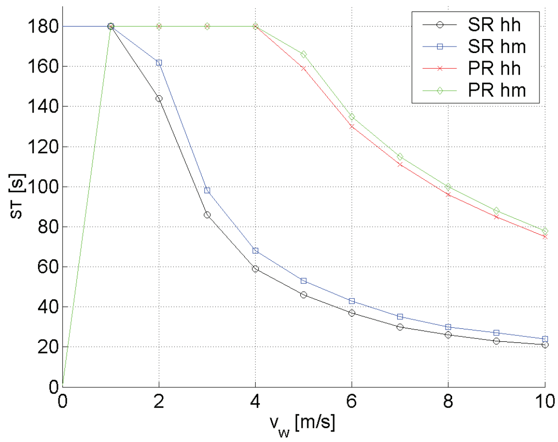


**Fig. 5 Comparison of separation times for different A/C classes (met 1, $RCR_{nom} = 20\%$)**

The atmospheric turbulence level does have considerable effect on the separation times. On the one hand, higher turbulence results in higher uncertainties for the wake vortex position and hence in higher probable wake vortex habitation areas. However the vortex decay is accelerated by higher turbulence. The first effect is dominating as can be seen from Fig. 6. Light turbulence increases the separation times by

10 s and more for small cross wind speeds (both for single and parallel runways).

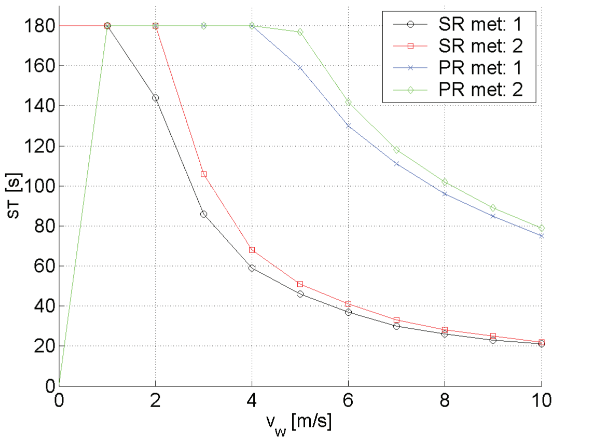


**Fig. 6 Comparison of separation times for different meteorological conditions (hh, $RCR_{nom}$ = 20%)**

The hazard area dimensions (depending on $RCR_{nom}$) can influence the separation times in the order of 10% (Fig. 7). The determination of the valid $RCR_{nom}$ value for the hazard area boundaries is described in section 3.2. However the final value for manually controlled flight can only be determined based on a sufficient statistical basis which requires pilot-in-the-loop experiments.

Possibilities to reduce the overall hazard area include wake vortex predictions with reduced uncertainties as well as pilot assistance systems like automatic flight controllers [11].

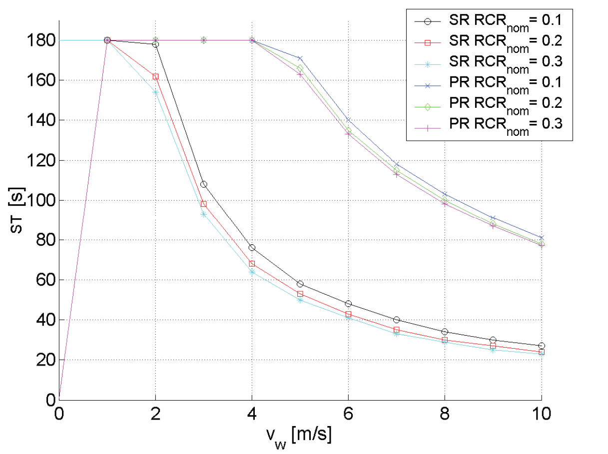


**Fig. 7 Comparison of separation times for different $RCR_{nom}$ values (met 1, hm)**

### *3.5.3 Headwind*

Headwind causes longitudinal transport of the wake vortices towards the following aircraft. (Tailwind is not considered since it is undesired from an operational and safety point of view.) The three effects of headwind are that for the same separation time at the same x-position

(I) the following aircraft is exposed to a younger vortex

(II) which is at a lower position than without headwind

(III) and for the lower gates and for higher separation times no vortices exist at all because the generator is already on the ground.

The generating aircraft passes a given x-position ("gate") at ST = 0 (separation time). In the reference case without wind the vortices are only moving vertically and thus vortex age $t_{age}$ = ST for the respective gate.

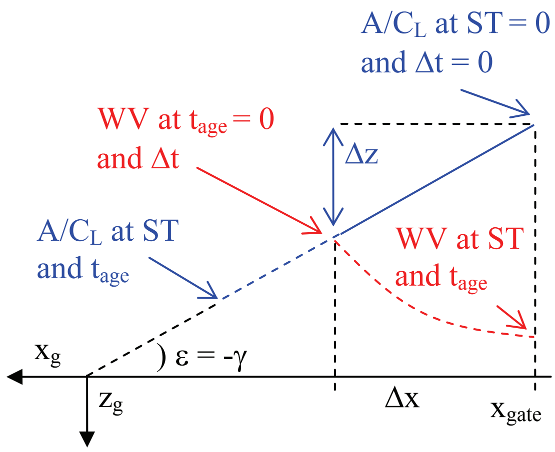


**Fig. 8 Approach situation with headwind**

Fig. 8 depicts the approach situation with headwind for a specific gate (x-position $x_{gate}$) including the approach flight path and the vortex motion. With headwind the generating aircraft is flying a certain distance $\Delta x$ and $\Delta z$ respectively before the vortex is created which reaches the gate at ST.

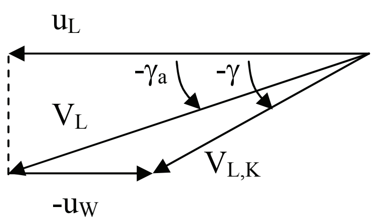


**Fig. 9 Velocities with headwind**

With the horizontal component $u_{L,K}$ of the flight-path velocity (ground speed) of the leading aircraft

$$u_{L,K} = V_L \cos(\gamma_a) + u_W \tag{3}$$

and the air-path inclination angle $\gamma_a$ (Fig. 9)

$$\gamma_a = \gamma + \arcsin\left(\frac{u_W}{V_L}\sin\gamma\right) \tag{4}$$

the separation time ST for the case with headwind $u_W$ (< 0 for headwind) is

$$ST = t_{age} + \Delta t = t_{age} + \frac{\Delta x}{u_{L,K}} \tag{5}$$

Hence with headwind the vortex age at a given x-position for the same separation time is smaller than for the case without headwind (headwind effect I). In other words with headwind the vortices for the same separation time are of higher vortex strength (Fig. 10).

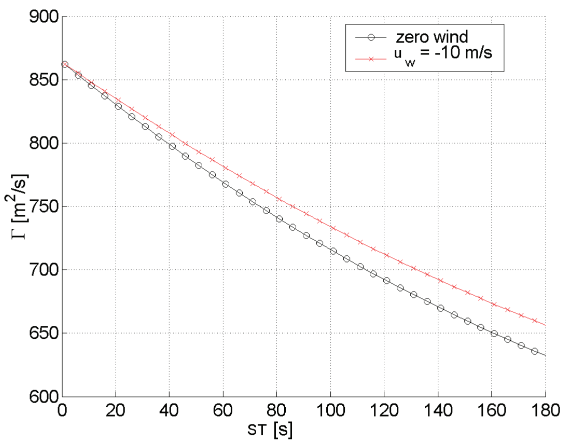


**Fig. 10 Circulation over separation time for zero wind and $u_W$ = -10 m/s at $x_{gate}$ = -11 nm from runway threshold**

The distance Δx (> 0 for headwind) flown by the generator before the specific vortex generation is equal to the distance the vortex is transported laterally during $t_{age}$ until reaching a specific gate at ST.

$$\Delta x = -u_W t_{age} \tag{6}$$

Equations (5) and (6) (and additionally (3)) yield the relationship between the vortex age and the separation time for headwind

$$\frac{t_{age}}{ST} = 1 + \frac{u_W}{u_{L,K} - u_W} = 1 + \frac{u_W}{V_L \cos(\gamma_a)} \tag{7}$$

Since $\cos(\gamma_a) \approx 1$

$$\frac{t_{age}}{ST} \approx 1 + \frac{u_W}{V_L} \tag{8}$$

The difference in height Δz corresponding to Δx can be expressed with the vortex transport and vortex age (6)

$$\Delta z = -u_W t_{age} \tan(\gamma) \tag{9}$$

or with the generator motion between passing the gate ST = 0 and generating the vortex $t_{age} = 0$

$$\begin{aligned}\Delta z &= V_{L,K} \Delta t \sin(\gamma) \\ &= u_{L,K} \Delta t \tan(\gamma)\end{aligned} \tag{10}$$

In the reference case without wind the vortices are sinking at the x-position of their generation during the time $t_{age}$ = ST. With head-wind the vortices which reach the respective gate at ST are created at a height which is lower by the amount Δz. For the period $t_{age}$ the vortices are sinking with the same speed as in the case without wind. But for the first part of the separation time Δt the aircraft sink rate (approximately 3 m/s) is higher than the wake vortex sink rate (approximately between 1.5 m/s and 2 m/s). This is the reason why for headwind the height of the vortices at a given x-position for the same separation time is smaller than for the case without headwind (headwind effect II, Fig. 11).

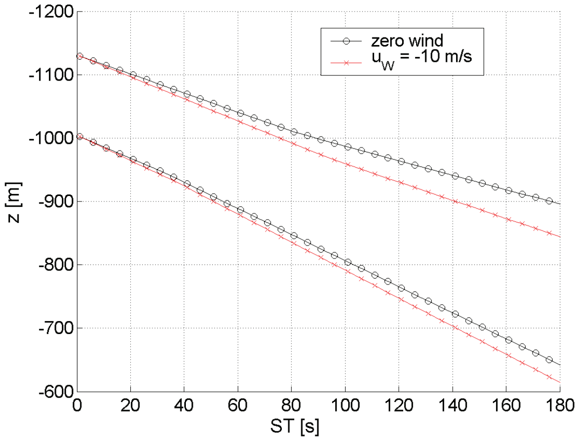


**Fig. 11 Vortex height over separation time for zero wind and $u_W = -10$ m/s at $x_{gate} = -11$ nm from runway threshold**

The two headwind wake vortex effects (younger and lower) are contrary effects and it is not obvious which is the dominating effect with respect to separation times.

Calculations corresponding to section 3.5.2 reveal that there is no capacity gain for head-wind conditions. Fig. 12 depicts the overlapping of approach corridor and overall hazard area for 13 gates along the flight path. The gates out of ground effect are cleared faster than for the case without wind (compare Fig. 3). This means that the effect of lower vortex height (headwind effect II) is outbalancing the effect of stronger vortices (headwind effect I).

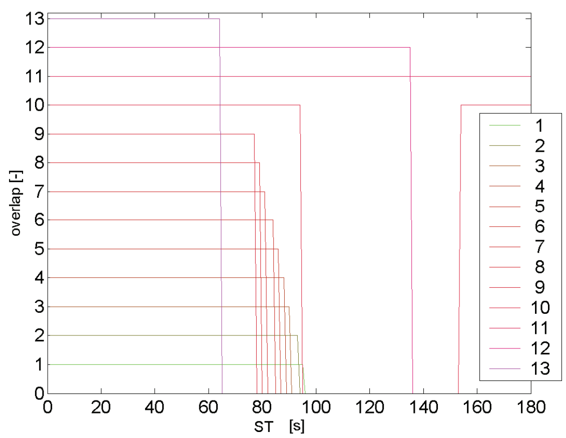


**Fig. 12 Overlapping of approach corridor and overall hazard area for gates along the glide path for headwind $u_W = -10$ m/s**

However gate 11 is blocked throughout the investigated time period and gate 10 is blocked again due to the rebound effect. The latter effect typically but not necessarily occurs for the hh combination for gate 10 for which the rebound effect with and without headwind is shown in Fig. 13.

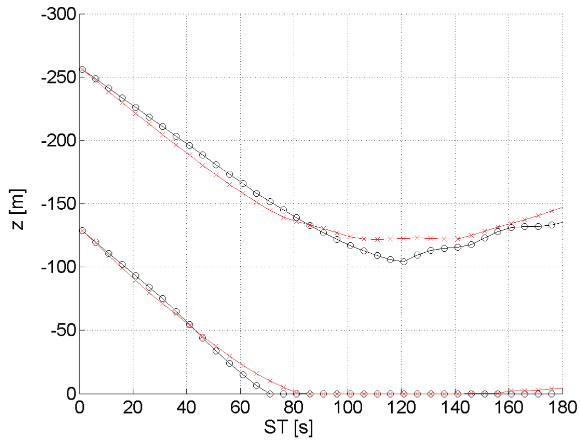


**Fig. 13 Vortex height over separation time for zero wind and $u_W = -10$ m/s at $x_{gate} = -2$ nm from runway threshold (gate 10)**

Gates 12 and 13 are cleared after 65 s and 136 s respectively which is not the case at all without wind. The reason is that for higher separation times the generating aircraft has already landed before the vortices are created which could be transported laterally to reach the respective gate at ST. This is the third headwind effect that for the lower gates and for higher separation times no vortices exist at all.

## 4 Summary

A concept for dynamic wake vortex separations based on simplified hazard areas is presented which allows investigation of safely reduced wake vortex separations depending on atmospheric conditions and aircraft pairing. The concept is applied to parallel runways compared to the single runway case for the present ICAO weight classes heavy and medium behind heavy. Conditions without wind yield no capacity increase due to the conservative approach. For atmospheric conditions with no atmospheric turbulence cross wind speeds of at least 3 m/s allow for capacity increase for the single runway case. The downwind parallel runway can be cleared for cross wind speeds of more than about 6 m/s to 7 m/s.

Three effects of headwind are identified for wake vortex separations. Calculations reveal that there is no capacity gain for headwind conditions due to the rebound effect for vortices in ground effect. However in principle the headwind does have a positive effect on wake vortex separations.

## Acknowledgement

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