Reduced Wake Turbulence Separation Minima between Departures from Closely Spaced Runway Entry Taxiways

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***Abstract*—This paper showcases how to define safe reduction of wake turbulence separation minima applicable in case of intersection departure, when involving closely spaced runway entries. Current separation provision indeed imposes an additional minute of time separation when follower uses an intermediate runway entry, irrespective of the distance between the two entries. The local definition of the reduced minima depends on the local runway entries' layout. The associated safety risk assessment relies on local traffic and meteorological data analysis. The paper describes the concept, the principles of the safety assessment methodology and provides an example of application to Palma de Mallorca airport, for departures from runway 06R. The proposed solution provides significant operational benefits (up to 30% separation reduction) on all concerned pairs, providing environmental and capacity benefits and increasing flexibility in departure traffic management during peak periods. It shows potential for many other European airports having closely spaced runway entries.**

Keywords-air traffic management; wake turbulence separation; departures; runway performances.

I. INTRODUCTION

As global air traffic continues to grow, the performance of airport runways remains a critical bottleneck in achieving a more efficient, resilient, and sustainable Air Traffic Management (ATM) system. This challenge is particularly acute at high-density airports, where infrastructure expansion is often limited by physical, environmental, or regulatory constraints. In this context, optimising departure operations is essential, yet inherently complex due to the interplay of dynamic factors such as aircraft performance variability, wake turbulence separation requirements, runway occupancy time (ROT), and surface traffic interactions.

Wake turbulence, generated by the lift of departing aircraft, poses a significant hazard to following aircraft, especially during take-off and initial climb [1][2]. To mitigate this risk, separation minima have traditionally been defined conservatively, often leading to underutilized runway capacity. However, recent advances in wake turbulence separation optimisation such as RECAT schemes [3][4], or more recently evolved to pairwise separation (PWS) [5] and Time-Based Separation (TBS) [6][7] – both developed under SESAR, have enabled more refined separation strategies.

A specific operational constraint arises when two aircraft depart from different runway entry points. According to ICAO PANS-ATM Doc 4444 [8], an additional one-minute time separation is required if the follower uses an intermediate runway entry located downstream of the lead aircraft's entry point. This rule applies regardless of the actual distance between the entry points, potentially leading to unnecessary delays and inefficiencies for wake-constrained aircraft pairs.

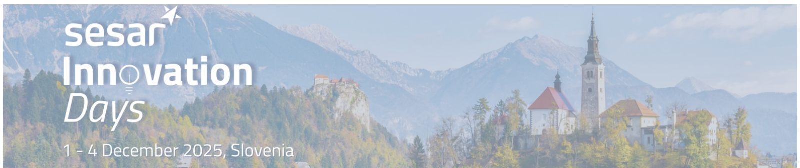
This paper introduces the BRETSEP (coming from 'Bretelle', meaning taxiway in French, and Separation) concept, which aims to enhance departure capacity by reducing wake turbulence separation minima between aircraft departing from Closely Spaced Runway Entry Taxiways. The concept is locally defined and supported by a safety assessment methodology based in wake encounter risk modelling fed by local traffic and wind data analyses.

The remainder of the paper is structured as follows: Section II presents the BRETSEP concept in detail; Section III outlines the safety assessment methodology; and Section IV illustrates the application of the concept through a case study at Palma de Mallorca Airport (LEPA/PMI).

II. BRETSEP CONCEPT DESCRIPTION

According to ICAO PANS-ATM Doc 4444 [8], for wake constrained pairs (i.e., HEAVY aircraft when taking off behind a SUPER aircraft, LIGHT or MEDIUM aircraft when taking off behind a HEAVY or a SUPER aircraft, or LIGHT aircraft when taking off behind a MEDIUM aircraft), an additional minute of separation is required when the follower is taking off from an intermediate part of the same runway. This additional separation aims to mitigate the increased Wake Turbulence (WT) encounter risk experienced by the follower when using intermediate runway entry point as this could lead to the follower flying below the leader wake and possibly crossing it hence enhancing WT risk probability, as illustrated in Figure 1.

However, this rule applies irrespective of the distance between the runway entries used by the leader and follower.



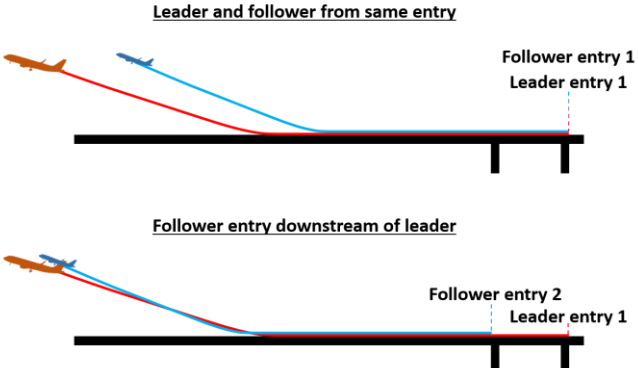


Figure 1. Illustrations of wake exposure risk for departures using same runway entry points or with intermediate runway entry.

Therefore, since one additional minute of separation is proven, by operational experience, to be safe for runway entries separated by, e.g., about one kilometre and no additional separation is safe for same runway entry utilization, a reduction of the additional separation shall be possible for runway entries separated by few tens or hundreds of meters.

The objective of the BRETSEP concept (coming from 'Bretelle', meaning taxiway in French, and Separation), is to tailor additional separation depending on actual distance between the runway entries with a particular focus on closely spaced runway entries. Note that in the USA, a FAA ORDER (JO 7110.65Z, §3−9−7. b. 2) already suppresses additional separation for runway entries spaced by less than 500ft (~152m). However, nothing similar is currently existing in EASA or ICAO rules.

III. ASSESSMENT METHODOLOGY

To define safe BRETSEP separation between departures, the risk assessment methodology relies on a relative comparison, for wake constrained pairs, between the wake vortex encounter risks observed in today's operations and those modelled with reduced extra time separations. The baseline for risk assessment is thus twofold: i) successive departures using same runway entry point at WT separation minimum (i.e., without the additional minute of separation) ii) successive departures with follower using intermediate runway entry located far from leader's one at WT separation minimum (i.e. with the additional minute of separation). The methodology relies on previous work performed in the framework of the CREDOS EU project [9] and the Wake Independent Departure and Arrival Operations (WIDAO) project for Paris-CDG airport [10][11].

To characterize local baseline and test case wake encounter risk, an analysis of the operational data is needed in the first place. This allows the characterization of all relevant take-off information (in terms of mean but also variability) for all frequently observed aircraft types. It also allows characterization of local wind conditions. Those characteristics are then used to model wake behaviour using a wake prediction software and follower aircraft flight behaviour.

The WT encounter risks are assessed for the test cases with different extra time separations, to find, for a given runway entry pair configuration, the equivalent encounter risks as today's operations.

A. Wake encounter risks comparison

The wake encounter risk comparison between baseline and test case scenarios is assessed through comparisons of complementary cumulative probability density functions (CCDF) curves of the induced rolling moment coefficient (RMC) used as severity metric. Work on WVE severity criteria has been on-going for several decades (e.g. [12][13][14]). The severity metric used here is the same as that used in RECAT-EU[3] and RECAT-PWS[5] Safety Cases and has been validated compared to wake encounter flight test campaign[15].

A test case is considered as acceptably safe if, compared to the baseline, the probability of occurrence of a wake encounter event of a given severity or higher is not higher than that of the baseline case. In terms of CCDF, it corresponds to the case where the baseline CCDF curve is above the test case CCDF curve for all severity values (see Figure 2. (top)). On the contrary, if the CCDF curve of the test case is significantly above the baseline CCDF curve for high severity values, the probability to observe events of high severity is significantly increased for the test case compared to the baseline and the concept is hence considered as not acceptably safe (see Figure 2. (middle)). Finally, if the test case CCDF curve is above the baseline CCDF curve only for the lower severity values, the probability to observe events of low associated severity is increased but the probability to observe events of high severity is decreased or unchanged for the test case. The concept can then still be considered as acceptably safe provided that the crossing point of the CCDF curves is sufficiently low (see Figure 2. (bottom)).

When reducing separation, an increase of the wake encounter risk is to be expected. However, for some scenarios, this increase might be marginal and in the order of magnitude of the variability in wake encounter severity observed in today's operations due, e.g., to delivery inaccuracy. In RECAT-PWS wake separation definition and related Safety Case [5], the analyses showed that some obtained wake minima led to a wake risk severity slightly larger than the severity obtained for the reference "pivot" pair defining the reference level of wake encounter severity for wake separation design. However, for those pairs, it was shown that the wake encounter severity was not exceeding the wake severity of the reference pivot pair if for the latter, the separation was reduced by 0.1 NM (corresponding to the typical resolution of Controller Working Position separation measurement and monitoring tool). This thus led to the definition of a "tolerance" of wake encounter severity increase compared to the reference. This tolerance corresponding to 0.1NM separation reduction was estimated to an increase in RMC of 0.002. This tolerance is used here to define the "acceptable" increase of severity when applying BRETSEP compared to a baseline for a given probability level.

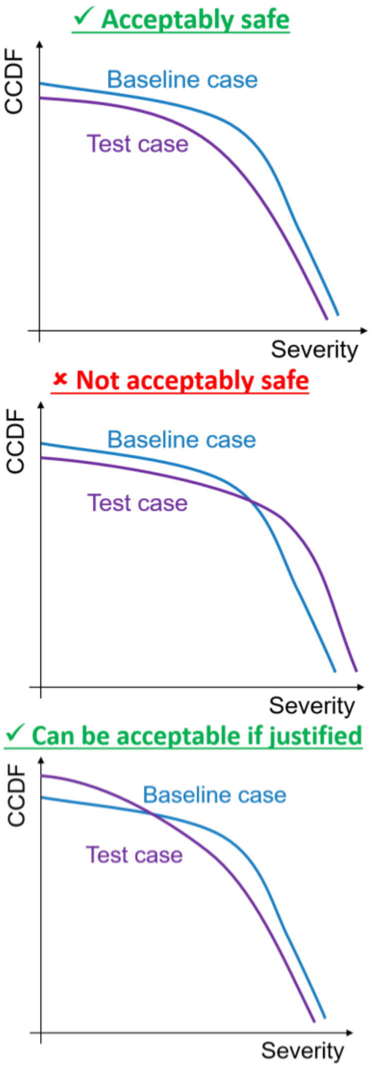


Figure 2. Illustrations of CCDF comparison for three scenarios: (top) test case acceptably safe compared to baseline; (middle) test case not acceptably safe compared to baseline and (bottom) test case acceptably safe provided that the intersection point between baseline and test case is at a sufficiently low severity value.

In other words, as illustrated in Figure 3, for each point of the test case severity curve, the test case severity is compared to that of one of the baseline curves (the RMC corresponding to the same probability level). The increase in severity for each severity level is then calculated and compared to the tolerance. A test case is finally considered as acceptably safe if, for severity levels larger than RMC= 0.03 (value established as threshold for wake encounter to be significant), the severity increase does not exceed the defined tolerance. Note that for very low probability levels, the risk curves might not be statistically converged and the results hence not reliable.

B. Local data analysis

The BRETSEP concept local development and related safety assessment initially relies on local surveillance and wind data analysis. The surveillance database shall cover representative local traffic for envisaged departure runway and cover seasonal effects.

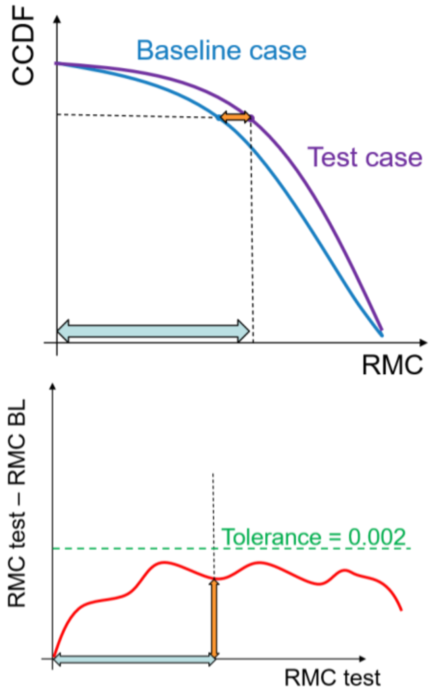


Figure 3. Illustrative representation of risk CCDF curves comparison to tolerance

It shall provide aircraft 3-D position and speed for each flight from runway entry until initial climb phase. The corresponding wind data (e.g., METAR or surface wind anemometer) shall also be available. A data processing is first performed to extract relevant departure parameters following five steps.

First, the departure runway is detected from the surveillance data by comparison of the latitude/longitude track positions to the opposite runway threshold latitude/longitude. The runway leading to minimum difference is selected as departure runway. If the minimum distance between the track and opposite runway threshold is larger than 1 km, the track is discarded.

Second, the runway entry point is detected by comparison of the latitude/longitude track positions to the latitude/longitude of a point located in the middle of the runway entry taxiway. The runway entry leading to minimum difference is selected as Entry Point. If the minimum distance is larger than 200 m, the track is discarded.

Third, after a smoothing of the groundspeed, the start of rolling time is selected as the time at which an increase of at least 14 kts over the next 5 seconds is observed. The groundspeed 4 seconds after start of rolling is denoted GS_{accel} and is recorded. However, if a ground speed lower than GS_{accel} is found later on for at least four consecutive measurement points, a new start of rolling time is searched starting from that new time.

Forth, the rolling time and rolling distance are found by fitting on the altitude profile a simple model

$$alt = alt_0 \; for \; x \le R_d,$$
$$alt = alt_0 + Climb_{rate} \; (x - R_d) \; for \; x > R_d,$$

where R_d, $Climb_{rate}$ and alt_0 are the three parameters to be fitted and correspond to rolling distance, climb rate after take-off and altitude on the ground. The rolling distance is imposed to range between 100 m and the distance between start of roll and opposite runway threshold. If the fit fails, the track is discarded. The time and speed at take-off point are also recorded.

Finally, the wind data is associated to each track, by selecting the latest wind data available prior to take-off. In case, this message date is earlier than the updated rate of the wind data (e.g. 30 minutes for METAR data) prior to the take-off time, the track is discarded. The true airspeed at take-off is deduced from the groundspeed and the headwind computed from wind info.

After full data processing, two additional filters are applied to exclude outliers. Tracks with climb angles deduced from vertical profile lower than 3 deg or larger than 20 deg are discarded. Tracks performing a rolling take-off (detected from the distance from runway entry at which the aircraft starts to accelerate imposed to be lower than 150 m and the initial GS_{accel} that shall be lower than 30 kts) are discarded as not representative of wake constrained pairs.

From this extensive data analysis, the statistics (in terms of mean, median, standard deviation 2.5% and 97.5% quantiles) of the take-off parameters are extracted for each aircraft type:

- Runway entry usage,
- Rolling time R_t,
- Rolling distance R_d,
- True air speed at take-off TAS_{TO},
- Initial climb rate V_{z0}.

The distribution frequencies of head- and crosswind conditions for each runway operations are also established.

C. *Meteorological data modelling*

1) *Wind profile*

To limit the number of simulations to be made, from the map of wind established in Section III.B, only wind conditions (i.e., combination head- and crosswind) for which the frequency of occurrences is equal or above a given threshold (e.g., 0.025%) are selected.

For all those surface wind conditions, wind profile inputs are derived assuming that the surface wind is following a uniform distribution ranging within mean value +/- 2.5 kts. In the absence of a wind profiler, the headwind and crosswind vertical profiles are then rebuilt using a classical logarithmic profile, reading:

$$u(z) = \frac{u_\tau}{\kappa} \log\left(\frac{z}{z_0} + 1\right)$$

with $\kappa = 0.40$ the von Karman constant, $z_0 = 0.01\,m$ the roughness height (typical value for grass) and u_τ the friction velocity, determined from the 10 m height wind.

2) *Turbulence, stratification and air density profiles*

Over a certain range of eddy sizes, following the similarity hypothesis of Kolmogorov, all the statistical properties of atmospheric turbulence can be related to one parameter, the eddy dissipation rate (EDR) ϵ, a dissipation rate of turbulent energy. We here assume that away from the ground, the EDR vertical profile is uniform. The considered EDR values follow a Uniform distribution on the exponent 10^{-4} (weak turbulence) and 10^{-2} m^3/s^3 (strong turbulence).

Within the surface boundary layer, the EDR profile can be related to the wind to account for the influence of ground atmospheric turbulence. In ground vicinity we then use the Prandtl law for the EDR profile:

$$\epsilon = \frac{u_\tau^3}{\kappa\, z},$$

where u_τ is the friction velocity fitted on the total wind velocity profile using the classical log profile law for a boundary layer:

$$V(z) = \frac{u_\tau}{\kappa} \log\left(\frac{z}{z_0} + 1\right).$$

This model is used until it reaches a value lower than the value considered in the region away from the ground.

As no temperature measurement are available, the standard vertical temperature profile is assumed for the different simulations. It is expressed through:

$$T = T_0\left(1 + \frac{\Delta \mathrm{T}\, \mathrm{z}}{\mathrm{T}_0}\right),$$

with:

- T_0 the surface temperature = 15°C,
- ΔT the adiabatic temperature gradient = -6.5 K/km.

The Brunt-Väisälä frequency that characterizes the atmospheric stratification is defined by:

$$N^2 = \frac{g}{\Theta}\frac{d\Theta}{dz},$$

with:

$$\Theta = T_0\left(1 + \frac{\Delta T\, z}{T_0}\right)^{\frac{g}{\Delta T\, c_p}+1},$$

with:

- g is the gravity acceleration = 9.81 m/s²,
- c_p is the heat capacity = 1005 J/kg/K.

Hence, for the ICAO standard atmosphere, we have:

$$N^2 = \frac{g}{T_0}\left(\frac{g}{c_p} + \Delta T\right)\left(1 + \frac{\Delta T\, z}{T_0}\right)^{-1}.$$

The considered atmosphere is hence weakly stably stratified ($N = .0106\, s^{-1}$).

The air density profile also corresponds to the ICAO standard atmosphere, reading:

$$\rho(z) = \rho_0 \left(1 + \frac{\Delta T\, z}{T_0}\right)^{-\frac{g}{R\,\Delta T}-1},$$

with:

- $\rho_0 = 1.225$ kg/m³,

$R = 287.05$ J/kg/K.

D. Aircraft trajectory modelling

The assessment considers typical frequent leader and follower aircraft types showing different flight performances based on data analysis described in Section III.B.

For each considered aircraft type, 50 different take-off trajectories are built as inputs for the simulations and the encounter analysis. The number of sample trajectories set to 50 was empirically chosen as a compromise ensuring good coverage of the aircraft position distribution while limiting the number of simulation runs. To build those trajectories as precisely as possible, a model is developed based on extensive local data analysis.

The model establishes a relationship between, the various take-off parameters based on a single aircraft characteristic: the take-off mass. Indeed, a higher take-off mass should, for instance, result in a larger rolling distance and time, as well as a larger take-off speed. The correlations of each of those four parameters to the take-off mass are as follows:

- The rolling time is considered to vary linearly with the take-off mass,
- The rolling distance is considered to vary linearly with the take-off mass,
- The true airspeed at take-off is considered to vary with the square root of the take-off mass,
- The initial climb rate is not seen to be correlated with the take-off mass but seems to be more dependent on airlines' procedures (and thrust setting); it is thus considered to be independent.

In order to be realistic, the range of operational take-off masses has to be determined, avoiding too small values, which are not representative of real operations. The upper bound of this range is considered as the maximum take-off weight (MTOW), whereas the minimum bound is specifically computed for each aircraft type and runway entry. In fact, as take-off mass values are not available in the given database, they have to be retrieved through calculations involving the true airspeed values.

The MTOW is defined as the upper bound of the take-off mass values range ($= mass_{\mathrm{sup}}$) and corresponds to the 97.5% quantile value of all observed take-off true airspeeds:

$$mass_{\mathrm{sup}} = MTOW \leftrightarrow TAS_{TO,sup} = TAS_{TO,p\,97.5}.$$

The lower bound of the take-off mass values range ($= mass_{\mathrm{inf}}$) is defined such that it corresponds to the 2.5% quantile value of all observed take-off true airspeeds:

$$mass_{\mathrm{inf}} \leftrightarrow TAS_{TO,inf} = TAS_{TO,p2.5}.$$

The lower bound of the take-off mass values range is then obtained through the ratio of the two true airspeed values as follows:

$$\left(\frac{TAS_{TO,inf}}{TAS_{TO,sup}}\right)^2 = \frac{mass_{\mathrm{inf}}}{mass_{\mathrm{sup}}} = \frac{mass_{\mathrm{inf}}}{MTOW}$$

$$mass_{\mathrm{inf}} = MTOW * \left(\frac{TAS_{TO,inf}}{TAS_{TO,sup}}\right)^2$$

Finally, for each of the 50 trajectories, one take-off mass value is randomly assigned from the values range defined here above, and the different take-off parameters are then assigned following their dependencies:

$$R_d = R_{d,p2.5} + \frac{\left(R_{d,p97.5} - R_{d,p2.5}\right)}{\left(MTOW - mass_{inf}\right)}\left(mass - mass_{\mathrm{inf}}\right)$$

$$R_t = R_{t,p2.5} + \frac{\left(R_{t,p97.5} - R_{t,p2.5}\right)}{\left(MTOW - mass_{inf}\right)}\left(mass - mass_{\mathrm{inf}}\right)$$

$$TAS_{TO} = TAS_{TO,sup}\sqrt{\frac{mass}{MTOW}},$$

with:

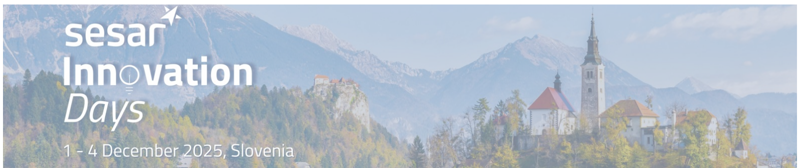
- $mass$ the assigned mass in the $[mass_{\mathrm{inf}} - MTOW]$ range,
- $R_{t,p2.5}$ (resp. $R_{t,p97.5}$) the 2.5% (resp. 97.5%) quantile of rolling time established from local data analysis for the considered aircraft type,
- $R_{d,p2.5}$ (resp. $R_{d,p97.5}$) the 2.5% (resp. 97.5%) quantile of rolling distance established from local data analysis for the considered aircraft type,

As mentioned above, as no correlation between the take-off mass and initial climb rate is established, a value is taken in the range from 2.5 to 97.5 quantiles of the experimental distribution ($[V_{z_0,p2.5},\ V_{z_0,p97.5}]$) for the considered aircraft type.

Once all those 4 parameters are assigned, the final trajectory is computed for all selected wind profiles. It is important to note here that all trajectories do not deviate from the runway centreline and are generated until 3000 ft.

E. Wake prediction software

The WT position and strength evolution is based on the analysis of wake behaviour model results using the WAKE4D software. The WAKE4D platform is a software that predicts, in fast-time, the 3-D spatial and 1-D temporal (hence 4-D)



evolution of the wake vortices generated by a given aircraft flying in provided atmospheric conditions. The software can provide both deterministic and probabilistic forecasts. In the WAKE4D, the computational domain is divided in several computational gates, separated by a constant time. Each time the aircraft crosses one of the gates, it generates a pair of vortices. In each gate, the wake vortex evolution (transport and decay) is then predicted. A description of the WAKE4D platform including examples of applications can be found in[16].

The deterministic prediction model used in each computational gate integrates in time Ordinary Differential Equations (ODEs) representing various physical models forecasting the transport and decay of the wake vortices generated by a given aircraft under given meteorological conditions. It accounts for the effects on circulation decay and wake transport of the aircraft characteristics, the vertical profile of the meteorological conditions (wind turbulence and stratification) and the ground proximity. Those models have been developed, calibrated, and assessed using the results of advanced numerical simulations and of field measurements. The description of the models, their calibration and assessment compared to experimental and numerical data can be found in [17] and [18].

To obtain stochastic prediction, the WAKE4D perform several deterministic runs, in a Monte-Carlo approach, with variations on the input impact parameters (aircraft flight and meteorological inputs but also coefficients of the physical models). Those variations model both the uncertainties and the "natural" variations of the quantities. The probabilistic results hence provide the statistical evolution of the temporal evolutions of 3-D wakes generated by the considered aircraft evolving in the considered meteorological conditions and that accounts for the variations/uncertainties on the inputs (as calibrated based on local traffic data).

The WAKE4D software is used to simulate for each aircraft type, each wind condition, and each of the 50 considered trajectories, the probabilistic evolution of the wakes using 20 deterministic runs. The number of deterministic runs set to 20 was empirically chosen as a compromise ensuring good coverage of the distributions of wind and WAKE4D model coefficients (that have small variations) while limiting the number of simulation runs. For each leader in each wind condition, the evolution of a total of 20x50 = 1000 3-D vortex pairs are obtained.

F. Follower aircraft modelling and wake encounter detection

Frequent wake constrained followers are considered covering various aircraft size and performances. As for the leaders, for each follower aircraft type, 50 different trajectories are modelled based on the same process used for the wake generators (see Section III.D). Those 50 trajectories are then used to characterize the probability, in both the Y (lateral) and Z (altitude) axis, and severity of the encounter in several control gates located in 2-D scanning planes along the follower flight path (hence covering the full range of altitude from ground to 3000 ft).

1) Probability of encounter in the Z-axis

The probability of encounter in the Z-axis is assumed to follow a Normal probability density function, reading:

$$P_z = \frac{1}{\sigma_z\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{z-\mu_z}{\sigma_z}\right)^2}\text{, with}$$

- z the altitude of a vortex predicted by WAKE4D
- $\mu_z = \frac{z_{\mathrm{sup}}+z_{\mathrm{inf}}}{2}$,
- $\sigma_z = \frac{z_{\mathrm{sup}}-z_{\mathrm{inf}}}{4}$,
- $z_{\mathrm{sup}} = \max\left(z_{follower}\right) + \frac{\pi}{4}\frac{b_{lead}}{2} + 0.2\, b_{foll}$, the maximum altitude value of all 50 follower trajectories in the considered control gate increased by an estimate of the wake vortex radius ($\frac{\pi}{4}\frac{b_{lead}}{2}$, with b_{lead} the leader wingspan) and a fraction of the follower wingspan (b_{foll}) accounting for the wing of the follower being not vertically centred on the fuselage.
- $z_{\mathrm{inf}} = \min\left(z_{follower}\right) - \frac{\pi}{4}\frac{b_{lead}}{2}$, the minimum altitude value of all 50 follower trajectories in the considered control gate decreased by an estimate of the wake vortex radius (capped to zero if negative).

2) Probability of encounter in the Y-axis

The probability of encounter in the Y-axis is also assumed to follow a Normal probability density function, reading:

$$P_y = \frac{1}{\sigma_y\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2}\text{, with}$$

- y the lateral position of a vortex predicted by WAKE4D in the control gate
- $\mu_y = \frac{y_{\mathrm{sup}}+y_{\mathrm{inf}}}{2}$,
- $\sigma_y = \frac{y_{\mathrm{sup}}-y_{\mathrm{inf}}}{4}$,
- $y_{\mathrm{sup}} = \frac{runway\ width}{2} + \frac{\pi}{4}\frac{b_{lead}}{2} + \frac{b_{foll}}{2}$,
- $y_{\mathrm{inf}} = -\frac{runway\ width}{2} - \frac{\pi}{4}\frac{b_{lead}}{2} - \frac{b_{foll}}{2}$.

3) Final probability of encounter

The final probability of encounter is equal to the multiplication of probabilities of encounter in both the Y and Z axis, times the probability of headwind conditions. This method accounts for spatial probabilities for every calculated vortex, even if some are far away from follower trajectories.

4) Wake encounter severity

The severity of the potential wake encounter is calculated from the wake circulation of a vortex predicted by WAKE4D, the span of the follower, its airspeed in the control gates using the rolling moment coefficient (RMC) as severity metric [15]. This metric assumed 'centred' wake encounter hence providing an upper bound of what can be expected.

Figure 4. Plan view of Palma de Mallorca airport. Runway 06R is located at the South of the runway

Figure 5. Zoom on runway 06R entries

IV. EXAMPLE OF APPLICATION TO PALMA DE MALLOWRCA

A. Airport layout description

Palma de Mallorca airport operates two parallel runways, see Figure 4. The present study focuses on the South runway when operating facing East (06R) that has four holding points: H6, H7, H8 and S3, see Figure 5. Holding points H6, H7 and H8 are closely spaced.

According to the take-off distances reported in PMI AIP[19], the distance differences between the different entries are as reported in TABLE I. The objective is to allow for separation reductions for H6-H7 and H7-H8 departures and possibly also for H6-H8. Ignoring S3 (as not closely spaced from another entry), the maximum distance between two consecutive runway entries is observed between H6 and H7 with 188 m, whereas 320 m separates H6 from H8.

TABLE I. TORA AND TODA FOR RUNWAY 06R AND DISTANCES BETWEEN SUCCESSIVE ENTRY POINTS

Entry point	***TORA [m]***	***TODA [m]***	***Distance to previous HP [m]***
06R H6	3000	3060	
06R INT H7	2812	2872	188
06R INT H8	2680	2740	132
06R INT S3	2390	2450	290

When the follower is using one of the intermediate runway entries, the separation minima are increased by one minute as defined in TABLE II.

TABLE II. WT SEPARATION MINIMA [S] BETWEEN DEPARTURES WHEN FOLLOWER USES INTERMEDIATE RUNWAY ENTRY

Leader/ Follower	S	H	M	L
SUPER (S)		120+60 s	180+60 s	180+60 s
HEAVY (H)			120+60 s	120+60 s
MEDIUM (M)				120+60 s
LIGHT (L)				

B. *Database description and data processing*

Fifteen months of summer traffic were made available covering the periods 05/2022-10/2022, 05/2023-09/2023 and 05/2024-08/2025. The data contain mostly departures from runway 06R. The corresponding METAR data were extracted from a EUROCONTROL database. The METAR data contain among other, the wind speed and direction provided every 30 minutes. The database contains a total of about 49,000 departure tracks which, after filtering described in Section III.B, led to about 38,000 tracks. The data analysis also shows that about 19% of the Heavy-Medium pairs are operated with Medium departing from intermediate entry point, demonstrating the benefit of being allowed to reduce the extra minute of separation. Note also that this number is expected to grow if separation constraints are relaxed.

C. *Example of results*

Applying the methodology described in Section III for the wake turbulence safety risk assessment relying on Palma de Mallorca operational data, the results concluded that when departing from H7 behind a departure from H6, the extra 60s can be reduced to 10 s for Medium Jets, and to 20 s for Medium Turboprops, as shown in TABLE III. The conservatism to be added on Medium Turbo-propellers comes from their high variability in climb rates, some climbing very slow leading to higher WT risk exposure. Since the distance between H8 and H7 is lower, these minima can conservatively be applied to H7-H8 pairs.

TABLE III. BRETSEP WT SEPARATION MINIMA [S] BETWEEN DEPARTURES WHEN USING CONSECUTIVE RUNWAY ENTRIES H6-H7 OR H7-H8

Leader/ Follower	S	H	M- JET	M- TURBO	L
SUPER (S)		120+10 s	180+10 s	180+20 s	180+60 s
HEAVY (H)			120+10 s	120+20 s	120+60 s
MEDIUM (M)					120+60 s
LIGHT (L)					

The study also showed that when departing from H8 behind a departure from H6, the extra 60s can be reduced to 20 s for Medium Jets and 30 s for Medium Turboprops, as showed in TABLE IV. Note that these 20 and 30 s increases can also conservatively be applied when departing from H7 behind H6 or H8 behind H7.

TABLE IV. BRETSEP WT SEPARATION MINIMA [S] BETWEEN DEPARTURES WHEN USING RUNWAY ENTRIES H6-H8

Leader/ Follower	S	H	M- JET	M- TURBO	L
SUPER (S)		120+20 s	180+20 s	180+30 s	180+60 s
HEAVY (H)			120+20 s	120+30 s	120+60 s
MEDIUM (M)					120+60 s
LIGHT (L)					

Finally, note that the lack of sufficient Light flight data (Light aircraft types indeed represent about 0.5% of the traffic in Palma de Mallorca) did not allow relevant conclusions for those types. The separation minima are thus conservatively maintained for those pairs.

V. CONCLUSIONS

Currently, when departing from an intermediate runway entry, ICAO PANS-ATM Doc 4444 imposes an extra minute to all wake turbulence minima. However, this extra separation does not depend on the distance separating the two used runway entries. The BRETSEP concept detailed in this paper allows for a tailored reduction of these extra separations depending on the local runway entry layout and the aircraft observed departure performances. The local definition and safety assessment of the concept relies on methodology combining local operational data analysis and advanced wake encounter modelling.

The BRETSEP solution can be procedurally applied, provided that the local procedure definition is sufficiently simple for operations, without need for advanced automation support, and the Airspace Users are notified of reduced separation. BRETSEP solution provides significant operational benefits as it allows time separation reduction of up to 50 s (~30% for 180s separation) on all concerned pairs. This results in significant environmental benefits by reduction of holding time at take-off and increased capacity. For Palma de Mallorca airport, considering the current usage of runway entries, this represents up to 2 additional departures per hour for wake constrained pairs (i.e. Heavy-Medium pairs). Furthermore, this relaxation of additional separation constraints enables the Air Traffic Controllers to gain flexibility in their departure traffic management as they can more often use intermediate entries during peak periods without significantly impacting capacity. The BRETSEP solution shows potential for many European airports having closely spaced runway entries.

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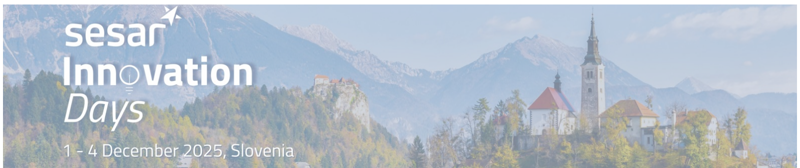

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