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Improved pairwise aircraft separation minima applying Plate Lines

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Abstract

An analysis of the potential aircraft separation benefits that could be enabled by the installation of wake vortex decay enhancing Plate Lines has been performed. Because Plate Lines are only effective close to the ground, a special focus was on the analysis of the results when applying the reduced separations out of ground effect as well. It has been shown that substantial separation benefits can be enabled by the installation of Plate Lines without compromising safety in ground effect and out of ground effect.

Keywords Wake turbulence · Wake vortices · Plate Line · Pair-wise separations

Abbreviations

Abbreviations

B739	Boeing 737-900
BADA	Base of Aircraft Data
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EASA	European Union Aviation Safety Agency
EU	European Union
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
IGE	In-ground effect
LJ35	Learjet 35
LORD	Leading Optimized Runway Delivery
MLM	Maximum landing mass
MRS	Minimum radar separation
MTOM	Maximum take-off mass
OGE	Out-of-ground effect
P2P	Probabilistic Two-Phase wake vortex decay and transport model
PL	Plate Line
PWS	Pair-wise separation
RECAT	Re-categorisation
RMC	Rolling moment coefficient
SESAR	Single European Sky ATM Research
SORT	Safely optimized runway throughput
TAS	True airspeed
VLD	Very large demonstration

List of symbols

a :	Core parameter of the wake vortex (−)
A_R :	Wing aspect ratio (−)
b :	Vortex spacing (m)
b_f :	Wing span of the follower aircraft (m)
b_l :	Wing span of the leader aircraft (m)
N :	Brunt-Väisälä frequency (1/s)
t :	Time (s)
V :	True airspeed (m/s)
Γ :	Vortex circulation (m2/s)
ε :	Energy dissipation rate (m2/s3)
ρ :	Air density (kg/m3)

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1 Introduction

Wake vortices are an unavoidable result of the lift generation of aircraft. Because encountering wake vortices can be hazardous especially for smaller aircraft, minimum separations have been defined that aircraft following each other are not allowed to undershoot. The most prominent minimum separation schemes, such as the ones defined by ICAO [1] or FAA, have been proven over the last decades to be sufficiently safe [2]. On the other hand, minimum aircraft separations due to wake vortices may limit the airport capacity because these can be larger than the separations due to collision avoidance or the runway occupancy time. For this reason and due to the again continuously increasing air traffic, there is a demand for an optimisation of those minimum separations. Any change in the prescribed minimum separations must not affect the flight safety. However, it is widely accepted that the common minimum separation schemes (e.g., ICAO or FAA) are overly conservative for a variety of aircraft pairings [2].

To redefine minimum separation schemes without compromising safety, a huge effort has been undertaken in the past. For example, RECAT-EU, a re-categorisation effort performed by EUROCONTROL [3, 4], introduces a bigger number of aircraft categories (six categories instead of the four categories as defined by ICAO) considering besides the aircraft weight the approach speed, wing characteristics and in parts also the rolling moment exerted on following aircraft. The lowered minimum separations for many aircraft types lead to an overall airport capacity gain, while maintaining acceptable levels of safety. RECAT-EU is already in operation at several European airports [11].

Although RECAT-EU is able to increase the airport capacity, it is assumed to be still overly conservative for many aircraft pairings. Still the safety is benchmarked for the most vulnerable aircraft of the follower's category and the aircraft of the leader's category generating the most critical wake vortices. Any pairing of a bigger follower aircraft in the same follower's category and/or a smaller wake generator in the same leader's category would be at least slightly overly conservative. As simply increasing the number of categories is not necessarily efficient, the consequent next step towards a further optimised use of the airport capacity is the introduction of pairwise minimum separations. Minimum separations defined for each combination of leader and follower aircraft can distribute the level of safety over all types of aircraft more evenly. This approach improves the use of the airport capacity significantly without compromising safety. In Europe, it is realised by the RECAT-EU-PWS [2] initiative for the introduction of pairwise minimum separations by EUROCONTROL which is expected to be approved by EASA in the near future.

Further reductions of the minimum separations could be achieved either by employing dynamic pairwise wake vortex separations that consider the involved aircraft type pairing, the prevailing weather conditions, and the resulting wake vortex behaviour [5] (RECAT phase III) or by introducing appropriate means that alleviate the wake's impact on a following aircraft as for example investigated in [6]. Surveys on further procedural modifications meant to increase airport capacity and on wake-vortex advisory systems are available in [7].

One method to accelerate the decay of wake vortices in ground proximity is the introduction of so-called Plate Lines. A Plate Line is a line of vertical plates installed in a row in front of the runway. The effects of Plate Lines have been thoroughly investigated in the past with towing tank experiments, numerical fluid dynamic simulations, and field measurement campaigns [8, 9]. Along the edges of the plates, Ω-shaped secondary vortices are generated which wrap around the primary vortices and thus accelerate wake vortex decay in the final approach shortly before landing, which is the flightphase with most wake vortex encounters [10]. Lidar measurements at Vienna airport showed that a Plate Line is able to effectively reduce the wake vortex lifetime [11], especially of the longest-living vortices. Also, a flight simulator study revealed that the faster decayed vortices reduce the severity of a wake encounter and increase the pilot acceptance of such disturbances [12]. Hence, the previous investigations showed the effectiveness of the plates to lower the risk of hazardous wake encounters in ground proximity and thus increase flight safety.

The Plate Line concept enables five use cases as outlined in the Plate Line White Paper [13]. As a first use case, the installation of a Plate Line could be used for a pure safety gain. Especially airports that show a higher low-level encounter rate at least under certain weather conditions could make use of Plate Lines to reduce the encounter frequency. Use case II suggests the simultaneous introduction of RECAT-EU(-PWS) together with a Plate Line, which could increase both runway throughput capacity and safety. Here, the Plate Line shall compensate the expected increase of uncritical encounters of 60% as estimated in the RECAT-EU-PWS safety case [2].

The current manuscript deals with use case III, which applies the RECAT-EU(-PWS) methodology to convert the accelerated wake vortex decay facilitated by the Plate Line into some potential for an additional reduction of the aircraft separations without compromising safety. In contrast to the previous investigations of use case III [14, 15], which were focusing on the effects in ground proximity, the current analysis investigates to which extent the reduced separations in ground proximity can also be safely applied along the glide slope. This previous work is summarized in section 2 together with other pre-requisits that have been used for the current investigations. Section 3 describes the methodology of the analysis in this work; the results of this analysis are shown in section 4 thereafter. A conclusion and a brief outlook towards future work are given in section 5.

2 Models and measurements

For the work described here, some pre-requisits need to be explained aforehand. This concerns on one hand a comprehensive measurement campaign at Vienna airport, where the vortex decay was measured with and without Plate Lines. On the other hand, some simulation tools are required for the presented study. Here, the well-established Probabilistic Two-Phase wake vortex decay and transport model (P2P) for prediction of the vortex decay under different atmospheric conditions is used. The Plate Line effects on the vortex decay and the resulting possible gain in minimum aircraft separations in ground effect was analysed in a previous study. The results of that previous study shall only be recapitulated as far as required to understand the combined analysis in and out of ground effect as presented in section 3. Details on the previous study can be found in references [14] and [15].

2.1 Plate Line measurement campaign

DLR and Austro Control partnered to accomplish a comprehensive Plate Line demonstration campaign at Vienna International Airport between 6 May and 28 November 2019 as described in detail in [11]. Two Plate Lines consisting of eight and nine plates, respectively, with dimensions of 4.5 m height and 9 m length separated by 20 m were temporarily installed at runway 16 (see Fig. 1 and Fig. 2). Three lidars alternatingly situated in measurement positions L1–L5 captured the evolution of vortex position and strength (i.e., circulation).

From the recorded landings, 589 individual vortex pair evolutions with Plate Lines were processed. Without Plate Lines, 637 individual vortex pair evolutions were processed. The analysis of the data suggests that the lifetime of wake vortices in ground proximity can be reduced between 22% for medium weight class aircraft and up to 37% for Heavies [11]. This corresponds to a reduction of vortex circulation at 5 NM behind heavy aircraft (minimum ICAO separation to medium followers) by about 50%.

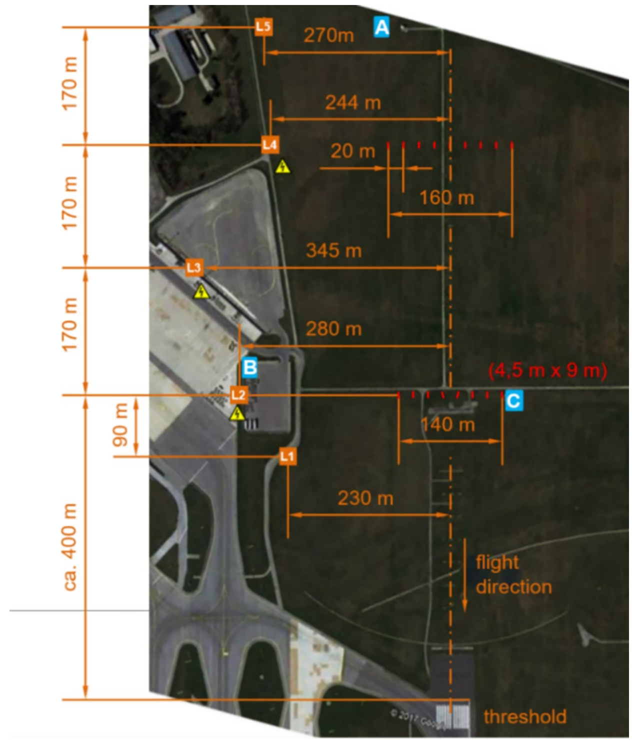

Fig. 1 Positioning of Plate Lines (red dashes) and measurement instrumentation on the apron at runway 16 at Vienna International Airport (© Google 2017) [11]

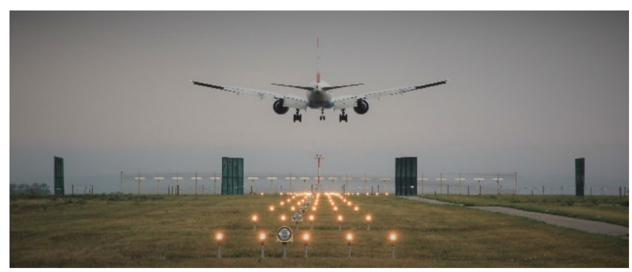

Fig. 2 Landing aircraft with Plate Line at Vienna International Airport [11]

2.2 Wake vortex prediction model P2P

Reducing separations in ground proximity with a Plate Line raises the question whether the reduced separations at higher altitudes along the glide slope are still safe. To model wake vortex decay out of ground effect, the deterministic version of the Probabilistic Two-Phase wake vortex decay and transport model (P2P) is used. A detailed description of this model can be found in the references [16] and [17]. P2P considers the aircraft parameters wing span, weight, velocity, and attitude angles and the meteorological parameters air density, wind (crosswind and headwind components), wind shear, turbulence, thermal stratification, and ground proximity. P2P has been validated against in-ground effect and out-of-ground effect measurement data of four US and 10 European field measurement campaigns comprising about 16,000 individual wake vortex evolutions.

Fig. 3 illustrates the two-phase circulation decay characteristics consisting of a diffusion phase followed by rapid decay as observed in numerical simulations and in lidar measurements [16]. The aircraft are flying at an airspeed of 160 kts descending along the glideslope in a weakly stably stratified atmosphere with a Brunt-Väisälä frequency of

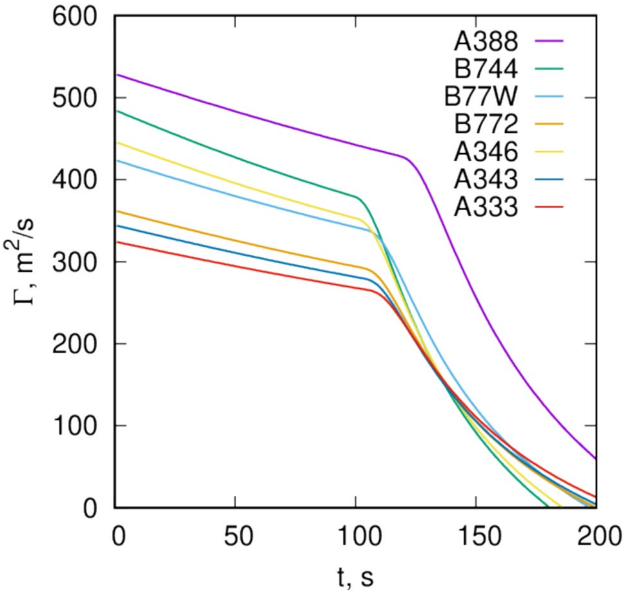

Fig. 3 P2P prediction of circulation evolution for a number of heavy aircraft types under reasonable worst-case conditions

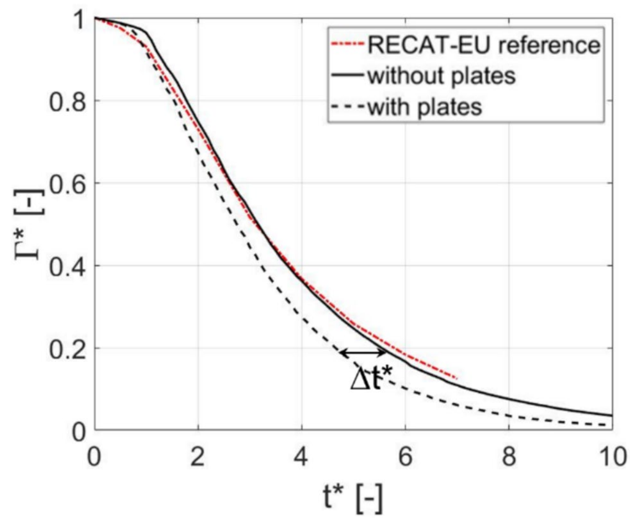

Fig. 4 The generic reasonable worst-case decay curves with and without Plate Line and the reference generic decay curve from RECAT-EU [15]

N = 0.01 1/s and weak turbulence with an energy dissipation rate of $\varepsilon = 4 \cdot 10^{-4}$ m^2/s^3. These atmospheric conditions are considered reasonable worst-case conditions as specified in the RECAT-EU-PWS safety case [2].

2.3 Analysis considering IGE only

Based on the Vienna Lidar measurements in a first step, the possible reduction of minimum aircraft separations enabled by the Plate Lines was assessed in ground effect only. The results of that analysis shall only be summarised here. Detailed descriptions can be found in the references [14] and [15]. In that assessment, the method as described in the RECAT-EU-PWS safety case report [2] was followed as closely as possible to be most compliant with the RECAT-EU-PWS method.

This means that only those vortex evolutions measured by Lidar in Vienna that remain within a flight corridor of ± 50 m for at least 29 s were considered. The width of the corridor was chosen because of the lateral range, within which the plates are effective. By applying this data selection process, it was guaranteed that only those vortices were considered that remain within the effectiveness range of the plates for a sufficiently long time. If a vortex is drifted outside this corridor by crosswind, it is not affected by the plates anymore. However, those vortices are not relevant anymore for the design of minimum separations anyway.

In analogy to the RECAT-EU-PWS safety case, the time axis of the vortex evolutions was shifted in such a way that the aircraft's height above ground at $t = 0$ is always at one generator's wing span. This should allow a proper comparison between the vortices of different aircraft types. The initial vortex circulation Γ_0 and the initial vortex spacing b_0 are estimated from the Lidar measurements.

For the further evaluation, the circulation measurements are not used directly but the vortex decay is modelled by a two-phase fit according to equation (4) in [18] as done in the RECAT-EU-PWS safety case report. By fitting this two-phase decay model to the vortex measurements, a generic decay curve was generated. For those measurements without plates, only the longest-lived vortices are used, for which the lifetime is larger than $5 \bullet t_0$ [19]. The generic decay curve is the median of all those longest-living vortices. By selecting the longest-lived vortices only, the resulting decay curve can be considered as a generic reasonable worst-case decay curve. For the measurements with the Plate Line a generic reasonable worst-case decay curve was evaluated in analogy to the measurements without the Plate Line. However, as the lifetime of vortices with plates is much shorter, it makes no sense to use the same lifetime criterion as without plates. For this reason, the same percental number of longest-lived vortices was used for the measurements with plates as without plates, while it was assured that the relevant parameters controlling wake vortex decay, such as aircraft mix, wind speed, atmospheric turbulence, thermal stratification and flight altitude above ground, reside in similar ranges for both cases [15].

This way, two similar generic decay curves were generated for reasonable worst-case conditions: one for conditions with a Plate Line and one for those without (Fig. 4). The difference in vortex age between the two curves for a given circulation can be translated into a difference in aircraft separation given the aircraft specific final approach speed and the actual mass of the aircraft.

For the evaluation of the final approach speed, the BADA database (Base of Aircraft Data) [20] was used here. The aircraft mass during approach is estimated to be 85% of the maximum landing mass (MLM) as found in measurements conducted at the airports Memphis and Dallas Fort Worth [21] and as also assumed in the RECAT-EU safety case [4] if no aircraft type specific data were available. Another method to estimate the landing masses of aircraft is given in [22] yielding slightly higher landing masses between 85 and 93%. However, for simplicity and comparability, the value of 85% MLM is used here.

As a short recap of the previous work in [14], the absolute and percental reductions of the minimum aircraft separations for each considered aircraft pair are shown again here in Figs. 5 and 6.

As a depiction of each aircraft name would make the figures barely readable, only an index number of each aircraft is depicted (as defined in [14]) with increasing number for decreasing maximum take-off mass (MTOM). Additionally, to give the reader a better overview, the six RECAT-EU aircraft categories *Super heavy*, *Upper heavy*, *Lower heavy*, *Upper medium*, *Lower medium* and *Light* are separated by dashed lines, even though these categories are not used in RECAT-EU-PWS.

Due to the accelerated decay stemming from the plates, a follower aircraft would experience the same circulation at the reduced separation as with RECAT-EU-PWS minimum separations without plates. For this reason, within the range

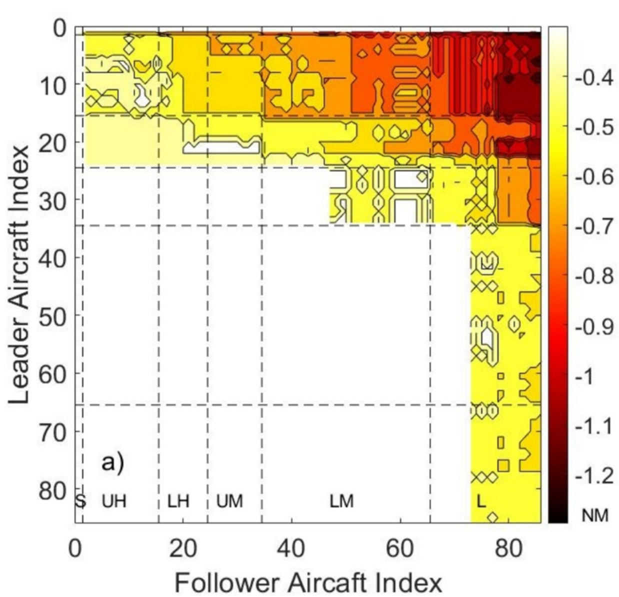

Fig. 5 Absolute reduction of minimum separations due to the Plate Line based on RECAT-EU-PWS separations (IGE consideration only) [14]

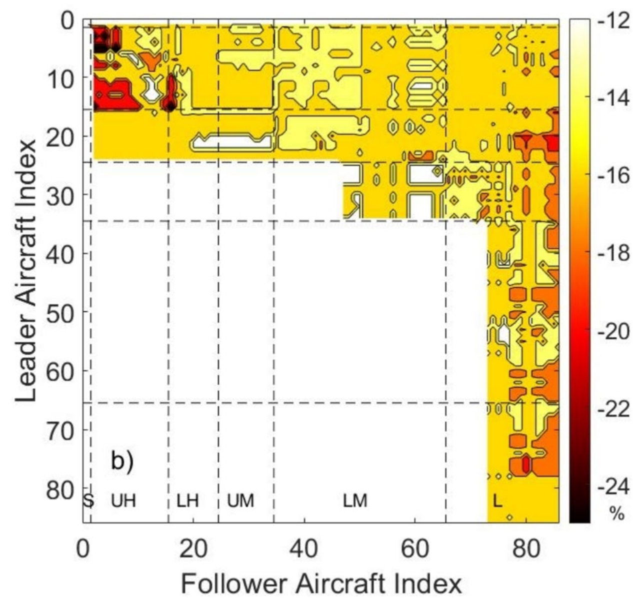

Fig. 6 Percental reduction of minimum separations due to the Plate Line based on RECAT-EU-PWS separations (IGE consideration only) [14]

where the plates are effective, the reduced separations with plates can be considered just as safe as the RECAT-EU-PWS separation without plates.

Fig. 5 shows an absolute reduction potential of 0.4 NM to 1.3 NM, which corresponds to approximately 12 to 24% in Fig. 6. The average over all aircraft pairings amounts to 14.8%. One can clearly observe in Fig. 5 that the largest absolute gain is for the light aircraft behind heavy leaders. This can be explained by the increasing plate effect with increasing vortex age. The relative gain shown in Fig. 6 shows a wide region of aircraft pairings with a benefit close to the average of 15%. This means that the relative benefit is similar for most aircraft pairings. The only aircraft pairs with larger relative benefits are some of the heaviest followers behind upper heavy leaders and some light followers behind leaders of different categories. The first ones can be explained by the already very low separation distance, for which even a small absolute gain is already a large percental gain. The latter ones can be explained again by the large vortex age for light followers, hence the larger plate effect connected to it.

As the Plate Line's effect of reducing the wake vortex strength and lifetime is only effective close to the ground (the maximum rebound height of wake vortices generated by large aircraft amounts to approximately 300 ft [9, 11]), the results depicted in Figs. 5 and 6 could only be applied for the in-ground effect (IGE) case without any further safety analysis. This means that for the out-of-ground effect (OGE) case, aircraft would need to follow the unchanged minimum spearations as prescribed by RECAT-EU-PWS. A reduction of the minimum aircraft separations close to the ground along the glideslope can practically not be applied because the aircraft fly at their respective landing speed already from an altitude of mostly 1,000 ft above ground. Therefore, the separations cannot be changed along the glideslope at such low altitudes.

Having said this, it is evident that the potential to further reduce the minimum aircraft separations even out of ground effect needs to be investigated as well.

3 Methodology of the analysis considering IGE and OGE

For many aircraft pairings the dimensioning case for the assessment of minimum aircraft separations is IGE. In those cases, the aircraft separations could theoretically be even further reduced OGE, but then safety would be violated IGE. For this reason, a safe reduction of the minimum aircraft separations IGE justified by the presence of a Plate Line could be applied along the whole glidepath. Only in cases where the OGE situation is the dimensioning case, the benefit from the plates cannot be fully used as a separation reduction. To evaluate the potential benefit when considering the glide slope as well, a combined analysis considering both situations IGE and OGE has been performed.

In the same way as it has been done already for the IGE analysis, this combined analysis for IGE and OGE followed the method developed for the RECAT-EU-PWS safety case report [2] as close as possible. The combined analysis has not only been performed using RECAT-EU-PWS as reference but also using RECAT-EU as reference to allow a comparison between these two reference cases. In the following description, the methodology will be explained using RECAT-EU-PWS as reference first; the results for both reference cases are shown thereafter.

As already mentioned in the previous section, landing aircraft typically fly at their respective landing speed from an altitude of mostly 1,000 ft above ground. Above this altitude, aircraft are typically starting their approach at a higher airspeed and then reduce their airspeed while descending along the glidepath. Because of this deceleration, the separation between the aircraft during approach is decreasing until the aircraft reach their landing speed. This reduction of the separation while descending along the glidepath is commonly called “compression effect” and needs to be considered by air traffic control because the necessary separation needs to be ensured all the way down to the threshold of the runway. Thus, a slightly higher separation is applied by air traffic control initially to reach the target separation at the runway threshold. To deal with this compression effect, in the RECAT-EU-PWS safety case report [2], an additional separation of 0.5 NM has been added to all OGE separations and it has been identified that this additional buffer, when applied to all separations, has no significant influence on the resulting target separations. In the analysis presented in this section, an additional buffer of 0.5 NM to deal with the compression effect has been applied as well and, similar to the results in the safety case report, the influence on the resulting target separations has been negligible.

The same 86 aircraft types as for the IGE analysis have been considered in this combined analysis as well. The methodology will be explained here based on Fig. 7 using the Learjet 35 (LJ35) as an exemplary follower aircraft. An aircraft of the RECAT-EU category *Light* has been chosen because for larger follower aircraft types, no wake vortex separation is defined by RECAT-EU(-PWS) when flying behind relatively small leader aircraft and thus the number of exemplary data points in Fig. 7 would be much less. On the horizontal axis, the different leader aircraft types are indicated by their index number. These are roughly sorted by their size with the Airbus A380 being the first aircraft type and the Piper PA-34 being the last aircraft type with the index number 86. On the vertical axis, the separation in nautical miles and the rolling moment coefficient (RMC) that is induced by the wake vortex are shown.

For many combinations of aircraft types, the wake turbulence separation is not dimensioning the separation, but instead minimum radar separation (MRS) is applied. That means that the required separation is depending primarily on the precision of the radar systems in use, but there is no wake turbulence separation defined. Thus, no further analysis about the wake turbulence separation is required in that case. For all other combinations of aircraft types, a further analysis has been performed according to the methodology that is described in the following paragraphs.

As a first step, for each individual combination of leader and follower aircraft types, the RMC that is induced by the wake vortex at RECAT-EU-PWS separation has been calculated. For this purpose, the previously introduced P2P model has been used to predict the remaining circulation at the RECAT-EU-PWS separation (see Fig. 3). Assuming a true airspeed (TAS) of 160 kts as in the RECAT-EU-PWS safety case report [2], the vortex age at the respective separation distance can be calculated and then used to estimate the corresponding vortex circulation under reasonable worst-case conditions with the P2P model. As defined in the safety case report, the RMC for each individual aircraft pairing at RECAT-EU-PWS separation has been calculated using the following equation:

$$\mathrm{RMC} = \frac{\Gamma}{V \cdot b_f} \cdot \frac{A_\mathrm{R}}{A_\mathrm{R} + 4} \cdot F\left(\frac{b_l}{b_f}\right) \tag{1}$$

with

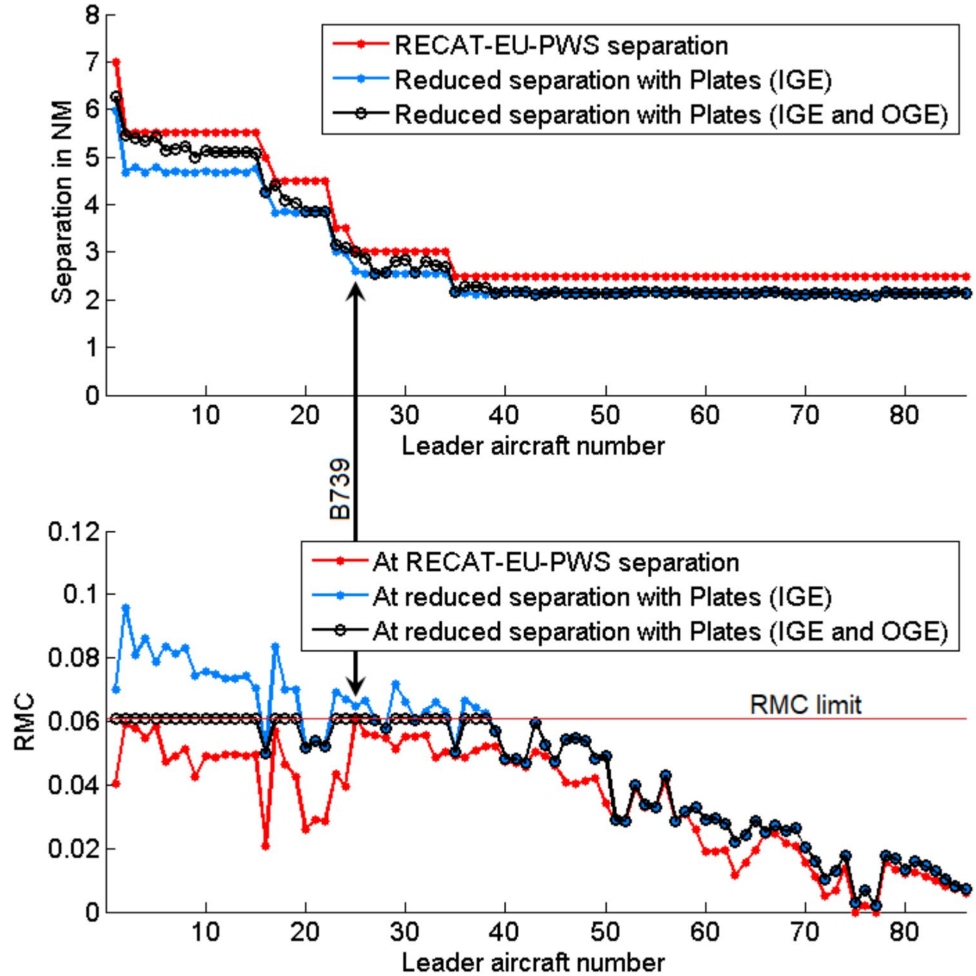

Fig. 7 Separations and RMCs for the Learjet 35 as an exemplary follower aircraft

$$F\left(\frac{b_l}{b_f}\right) = 1 - 2 \cdot \left(2a\frac{b_l}{b_f}\right) cdot \left(\sqrt{1 + \left(2a\frac{b_l}{b_f}\right)^2} - \left(2a\frac{b_l}{b_f}\right)\right)$$

and

$a = 0.035$ (core parameter of the wake vortex).

The RMC is a function of the circulation Γ (provided by the P2P model), the true airspeed V of the follower aircraft and some geometry parameters of the leader and follower aircraft that have been extracted from the BADA database [20]: the wing aspect ratio A_R of the follower aircraft and the wingspans b_l and b_f of of the leader and follower aircraft respectively. The core parameter a of the wake vortex is defined as the ratio between the vortex core radius to the wingspan of the leader aircraft and is assumed to be 3.5%. Further details about the underlying assumptions of this RMC definition can be found in [2]. The results of this calculation are shown in Fig. 7 in red colour for the RECAT-EU-PWS separations behind the considered leader aircraft types with the Learjet 35 as follower. In the upper half of the figure, the red dots show the corresponding RECAT-EU-PWS separations.

Relatively low RMC values occur for the leader aircraft numbers 16 and 20–22 which correspond to the aircraft types MD11, A306, A30B, and A310. These aircraft types feature relatively small wing spans in relation to their landing masses. Accordingly, they have relatively high initial circulations but also small vortex times scales [16] on the order of 20 s leading to relatively rapid vortex decay and thus relatively low RMC values at the considered separations.

After calculating the RMC for each individual aircraft pairing, the leader aircraft that induces the highest RMC at RECAT-EU-PWS separation for the specified follower aircraft can be identified. For the Learjet 35 as exemplary follower aircraft, when using the P2P model and applying the mentioned assumptions, the Boeing 737-900 (B739) is the leader aircraft that induces the highest RMC at RECAT-EU-PWS separation as indicated in Fig. 7. This RMC is considered the highest acceptable RMC for the respective follower aircraft and thus defines the RMC limit that is shown in Fig. 7 below as a red line. This definition of an RMC limit is aligned to the method used in the RECAT-EU-PWS safety case report [2] in which in section "7.1 OGE wake turbulence risk acceptability criteria" as one of several possible alternatives, the separation is defined to be acceptably safe when the RMC is "below the maximum RMC obtained for the considered follower behind any leader at ICAO separation in OGE situation." In the safety case, the maximum RMC behind any leader at ICAO separation is used as a reference for defining the RECAT-EU-PWS separation. Thus, it is here considered as a reasonable method to use the maximum RMC behind any leader at RECAT-EU-PWS separation for defining a reduced separation when using Plate Lines.

In the next step, for each individual combination of leader and follower aircraft type, the RMC is calculated that would result OGE when applying the reduced IGE separation with Plate Lines also for OGE. The reduced IGE separation when using Plate Lines (IGE-PL separation) had been calculated previously as published in [14] and described in section 2. This IGE-PL separation and the resulting RMC for the OGE case are shown in Fig. 7 with blue dots. Obviously, there are a number of leaders where the RMC limit would be exceeded for the LJ35 if the IGE-PL separations would be applied without consideration of the situation along the glide slope.

Then, it is checked whether the resulting RMC is below the previously defined RMC limit for the specified follower aircraft. If this RMC is below the limit, then the reduced IGE-PL separation can be considered as a safe separation for OGE as well because the IGE case is dimensioning the separation without interfering with the safe limits OGE. In that case, the possible IGE-PL separation reduction can be fully used OGE without compromising safety. Thus, the reduced separation when using plates for IGE and OGE that is shown in the upper part of Fig. 7 as black circles is the same as the IGE-PL separation, which is shown as blue dots. This is typically the case for relatively light leader aircraft types as it is visible in Fig. 7 on the right-hand side where the black circles exactly match the blue dots, but it is also visible for some heavier leader aircraft types on the left-hand side. These black circles can be considered as the finally resulting separation that is reasonably safe when using Plate Lines without inducing a higher RMC than at RECAT-EU-PWS separation for this follower aircraft behind any leader aircraft.

However, if the RMC that would result from applying the IGE-PL separation for OGE as well is above the limit, then the possible IGE-PL separation reduction cannot be fully used for OGE. In that case, starting at the reduced IGE-PL separation, the separation is increased until the resulting RMC is at or below its limit. For the worst-case leader aircraft type (in this example the B739), the finally resulting separation corresponds exactly to the RECAT-EU-PWS separation because the RMC corresponds exactly to the RMC limit for this leader aircraft type per definition. Thus, for this specific combination of aircraft types (in this case LJ35 behind B739), the IGE-PL separation reduction cannot be used at all because for this combination, the OGE case is dimensioning the separation where the Plate Lines are not effective and the RMC is already at the limit for the OGE case without any possible reduction margins without exceeding this limit.

For all other aircraft combinations, the RMC limit is reached at a separation that is somewhere between the RECAT-EU-PWS separation and the IGE-PL separation. In that case, the possible IGE-PL separation reduction can be used partially OGE as well. This is visible in Fig. 7 for many leader aircraft types on the left-hand side where the black circles that represent the finally resulting separation for IGE and OGE lie somewhere between the red and the blue dots. For these aircraft combinations, the IGE case is dimensioning the separation without Plate Lines and thus the Plate Lines enable a separation reduction. Now the IGE-PL separation reduction potential can only be partially used because the OGE case becomes dimensioning first before the full potential of the Plate Lines is reached. However, in many cases (even for relatively heavy leader aircraft types), the finally resulting separation reduction that is defined as the difference between the red dots and the black circles in Fig. 7 is still in the order of about half a mile which can be a significant benefit for airports that operate near their capacity limit.

To sum up this methodology, four different cases are possible for each individual combination of leader and follower aircraft type:

1. Minimum radar separation is applied and no further analysis is performed because the wake turbulence separation is not dimensioning the separation anyway. Not present for the example follower aircraft type in Fig. 7 because for this follower aircraft type, a wake vortex separation is defined for every leader aircraft type.
2. The RMC that would result OGE when applying the IGE-PL separation OGE as well is below the RMC limit. Thus, the possible IGE-PL separation reduction can be fully used for OGE as well. Black circles match the blue dots in Fig. 7.
3. The RMC has already reached its limit at the RECAT-EU-PWS separation. Thus, the possible IGE-PL separation reduction cannot be used for OGE at all. Only present for the worst-case leader aircraft type. Black circles match the red dots in Fig. 7.
4. The RMC that would result OGE when applying the reduced IGE-PL separation also OGE is above the limit, but the RMC at RECAT-EU-PWS separation is below the limit. Thus, the possible IGE-PL separation reduction can be used partially for OGE. Black circles are somewhere between the red dots and the blue dots in Fig. 7.

4 Results

The methodology described in the previous section has been applied for all possible combinations of the 86 considered aircraft types as leader and follower aircraft for which a wake turbulence separation is defined according to RECAT-EU-PWS instead of minimum radar separation. As mentioned previously, the potential benefits have been analyzed not only for RECAT-EU-PWS as reference but also for RECAT-EU as reference. When using RECAT-EU as reference, the aircraft are grouped in six categories and the highest required separation for all combinations of aircraft types in the respective combination of aircraft categories defines the finally resulting separation. The results refering to RECAT-EU are shown first, the results for the detailed analysis refering to RECAT-EU-PWS are shown thereafter.

Table 1 shows the results of the combined analysis for IGE and OGE when using RECAT-EU as reference. The separations are rounded up to increments of 0.1 NM to enhance the clarity. Because the achievable precision of the separation by the air traffic controllers is limited, the RECAT-EU-PWS separations are defined in increments of 0.5 NM. However, when applying pairwise separations for each individual aircraft pairing instead of grouping the aircraft types in only a few categories, it cannot be demanded that the air traffic controllers can memorize the required separations for all possible aircraft pairings. Thus, some kind of controller assistance system like EUROCONTROL's Leading Optimized Runway Delivery (LORD) tool [23] or the arrival spacing tool Intelligent Approach [24] would be required for applying a pairwise separation scheme and if an assistance system is used, a higher precision than 0.5 NM would possibly be achievable. Because this paper presents a scientific analysis, it has been decided not to round the separations up to increments of 0.5 NM but to calculate and store the numerical values in the full precision that is defined by the software. Just for reasons of clarity, the separations in Table 1 are rounded up to increments of 0.1 NM. For some combinations of aircraft categories, only minimum radar separation is applied but no wake turbulence separation is defined. Thus, for these combinations, the respective cells in Table 1 are kept empty.

When using RECAT-EU as reference, the worst case for each respective combination of leader and follower aircraft category defines the separation for the entire category, even though for some combinations of aircraft types, lower separations and thus higher benefits could be possible. Thus, the separation reductions are generally lower than for RECAT-EU-PWS as reference.

For many follower aircraft types, the Airbus A380 is the leader aircraft type that induces the highest RMC at RECAT-EU separation and thus for most aircraft categories as follower behind the Airbus A380, which is the only aircraft type of the *Super heavy* category, no separation reduction is safely possible under the mentioned assumptions. However, for the worst-case pairings with follower aircraft of the categories *Lower medium* and *Light*, a leader aircraft type of the category *Upper heavy* induces the highest RMC at RECAT-EU separation. Thus, for these two combinations of aircraft categories, no separation reduction is safely possible under the mentioned assumptions while for aircraft of the categories *Lower medium* and *Light* behind the category *Super heavy*, a small separation reduction of about 0.1 NM would be safely possible under the mentioned assumptions.

Table 1 Results of the combined IGE/OGE analysis for RECAT-EU as reference (upper rows in each cell show the finally resulting separation, middle rows show the absolute separation reduction compared to RECAT-EU, bottom rows show the percental separation reduction compared to RECAT-EU)

Leader/follower	Super heavy	Upper heavy	Lower heavy	Upper medium	Lower medium	Light
Super heavy	3.0 NM −0.0 NM −0.0%	4.0 NM −0.0 NM −0.0%	5.0 NM −0.0 NM −0.0%	5.0 NM −0.0 NM −0.0%	5.9 NM −0.1 NM −1.7%	7.9 NM −0.1 NM −1.3%
Upper heavy		2.6 NM −0.4 NM −13.3%	3.8 NM −0.2 NM −5.0%	3.9 NM −0.1 NM −2.5%	5.0 NM −0.0 NM −0.0%	7.0 NM −0.0 NM −0.0%
Lower heavy			2.6 NM −0.4 NM −13.3%	2.6 NM −0.4 NM −13.3%	3.8 NM −0.2 NM −5.0%	5.6 NM −0.4 NM −6.7%
Upper medium						4.3 NM −0.7 NM −14.0%
Lower medium						3.6 NM −0.4 NM −10.0%
Light						2.6 NM −0.4 NM −13.3%

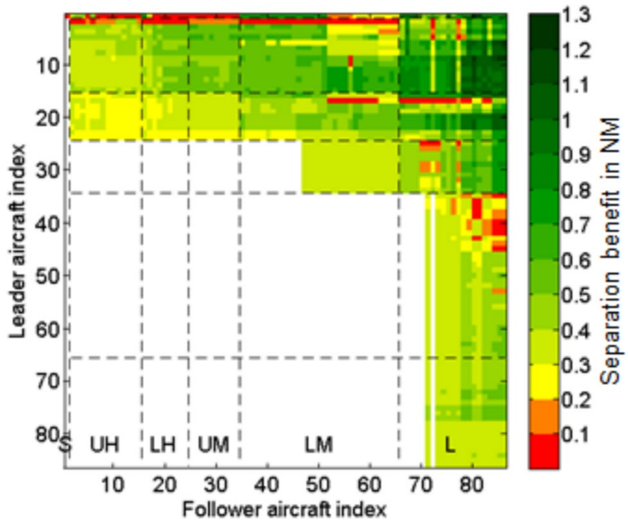

Fig. 8 Results of the combined analysis for IGE-PL and OGE when using RECAT-EU-PWS as reference (absolute values)

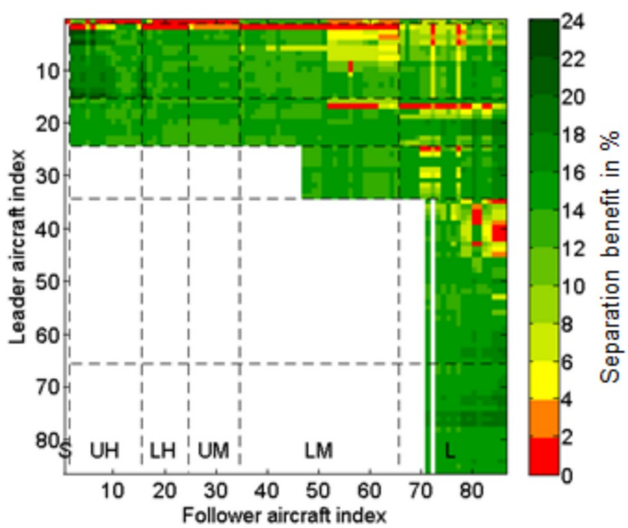

Fig. 9 Results of the combined analysis for IGE-PL and OGE when using RECAT-EU-PWS as reference (percental values)

The absolute benefit relative to RECAT-EU ranges between 0 NM and 0.7 NM while the relative benefit ranges between 0 and 14%. For the combinations with a leader aircraft of the category *Upper heavy* or *Lower heavy* and a follower aircraft of the category *Upper heavy*, *Lower heavy*, *Upper medium* or *Lower medium* that are most relevant for many airports, the average benefit is at about 7.5% which can be a significant benefit for airports that operate near their capacity limit.

When using RECAT-EU-PWS instead of RECAT-EU as reference and thus considering the individual aircraft types instead of grouping the aircraft in categories, even higher benefits can be achieved. Figures 8 and 9 show the corresponding results of the combined analysis for IGE-PL and OGE separations when using RECAT-EU-PWS as reference in absolute values and in percental values respectively. As a depiction of each aircraft name would make the figures barely readable, only an index number of each aircraft is depicted with increasing number for decreasing maximum take-off mass (MTOM). Additionally, to give the reader a better overview, the six RECAT-EU aircraft categories *Super heavy*, *Upper heavy*, *Lower heavy*, *Upper medium*, *Lower medium* and *Light* are separated by dashed lines, even though these categories are not used in RECAT-EU-PWS.

For the aircraft pairings for which minimum radar separation is applied, the respective areas in the figures are kept white because for these aircraft pairings, the wake turbulence separation is not dimensioning the separation anyway and thus no further analysis has been performed. For the other aircraft pairings, the results of the analysis show absolute separation benefits enabled by Plate Lines ranging from 0 NM for the previously defined worst-case leader aircraft up to 1.22 NM with an average benefit of 0.45 NM. The percental separation benefits are ranging from 0 to 23.8% with an average benefit of 13.1%. The red areas in Figs. 8 and 9 without any separation reduction potential correspond to cases where the accelerated vortex decay facilitated by the Plate Line cannot be translated into capacity gains as the RMC limits are already reached OGE. The absolute benefit reaches the highest values for light aircraft types behind heavy aircraft types while the relative benefit reaches the highest values for heavy aircraft types behind heavy aircraft types.

Overall, it is clearly visible that for most aircraft pairings, substantial separation benefits are possible according to this combined analysis for IGE-PL and OGE. The benefits are significantly higher when using RECAT-EU-PWS instead of RECAT-EU as reference because the full benefits for the individual aircraft pairings can be applied instead of capping the benefits at the values of the worst-case aircraft combination in each category.

Depending on the traffic mix at a specific airport, the actual benefits are varying, but the results of this combined analysis for IGE-PL and OGE show that not only for a small range of aircraft combinations but for nearly all relevant aircraft combinations, substantial benefits can be achieved when using Plate Lines. These benefits are possible because in most scenarios, the IGE case without Plate Lines is dimensioning the separation and thus the benefit that can be achieved with Plate Lines can be used OGE partially or fully without compromising safety.

5 Conclusions

The potential aircraft separation benefits that could be enabled by the installation of wake vortex decay enhancing Plate Lines have been analysed. It has been shown that even though Plate Lines are only effective close to the ground, they still support a potential reduction of the separation further up on the glideslope because in most scenarios, the wake vortex decay rates in ground proximity without plates are dimensioning the separations. Thus, the accelerated decay brought along by Plate Lines during final approach may enable a separation reduction also along the glide path out of ground effect without compromising safety. In contrast to the final approach in ground proximity, wake vortex transport along the glide slope is not restricted by the ground surface. Thus, wake vortices usually exit the flight corridor of follower aircraft by self-induced vortex descent and not only by advection with the wind. Therefore, not only wake vortex decay as anticipated in this study but also self-induced vortex descent is a relevant mechanism guaranteeing safe separations along the glide slope. Further analysis considering all aspects of wake vortex evolution may be needed for a safety case that will make the additional separation reduction potential of Plate Lines fully available at congested airports.

The analysis described here showed that even without considering wake vortex transport as a relevant safety mechanism, substantial benefits can be gained for some relevant combinations of aircraft categories by the installation of Plate Lines when using RECAT-EU as reference. When using RECAT-EU-PWS as reference, for most aircraft pairings, even higher separation benefits of about 0.5 NM or 13% may be enabled by the installation of Plate Lines, which would be a very significant benefit for airports that operate near their capacity limits. For some aircraft pairings, even higher benefits of more than 1 NM or 20% seem to be possible with Plate Lines. These benefit estimates do not consider yet the limitations brought along by minimum radar separations and runway occupancy times (depending on parameters like the runway exit design, weather conditions, airline and aircraft type) which may occasionally constitute the most constraining factors rather than wake turbulence.

Current exchanges with airports foresee the installation of Plate Lines for use case II which provides for the combination of RECAT-EU-PWS with a Plate Line to exploit enhanced runway capacity without increasing wake vortex encounter rates. The introduction of use case III analysed here may follow as a second step to boost further capacity gains. While the current investigation focuses on single runway operations, Plate Lines can basically also be installed at any location that facilitates the acceleration of the decay of wake vortices that may reach neighbouring runways that cannot be operated independently. Also, this use case is currently discussed with an interested airport.

The approval for reducing the minimum separations could be granted either by national authorities for specific applications or by an international authority like EASA. In any case, it is expected that the operational installation of Plate Lines will be combined at least initially with wake vortex monitoring by lidar to substantiate the expected safe performance in ground proximity.

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Declarations

Conflict of interest The authors declare no competing interests.

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