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SORT

SAFELY OPTIMISED RUNWAY THROUGHPUT

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Abstract

This document constitutes the DEMO Report-Part II Safety Assessment Report for WP3, hence is part of the contractual deliverable D1.4 (DEMOR). This document specifies the safety assessment activities that have been carried out in SESAR 2020 Wave 2 by Project VLD3-W2-SORT in Work Package 03 exercise (EXE-VLD-03-002) Wake Decay Enhancing Devices.

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1 Executive Summary

This document provides a summary of the VLD safety assurance activities conducted in accordance with the VLD3-W2-SORT DEMO Plan Part I (Core) and II (Safety Plan), including the VLD safety demonstration with regards to the suitability of the SESAR Solution for the deployment and the safety acceptability of the VLD impact on current operations.

2 Introduction

2.1 VLD Objectives, Justification and Scope

The objectives of WP3 exercise number EXE-VLD-03-002 are provided in Section 5.3.3 of the VLD3-W2-SORT DEMOP Part I [1]. The installation of plate lines at runway ends shall mitigate encounter risks during final approach. The concept aims at increasing the safety level of this critical phase of flight which will also reduce the number of go-arounds triggered by wake vortex encounters. WP3 demonstration objective number OBJ-VLD-03-002-001 comprises as first part the quantification of the reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines for different environmental conditions and aircraft types. The statistical significance of these results shall be demonstrated. Second, potential capacity gains via synergies with other measures for the optimization of aircraft separations shall be assessed as well.

2.2 Scope of the VLD Safety Assessment

The objective of this WP3 demonstration was to industrialize the plate line concept into an authority-approved prototype of the plate and its installation, which is suitable for permanent deployment.

The concept '*wake decay enhancing devices*' is classified as a technological solution. Plate lines constitute passive devices that accelerate wake vortex decay and thereby increase safety without the involvement of digital or human interference. The functionalities and performance characteristics of the concept are described by the dimensions and locations of the plates and the plate design as well as the quantification of the accelerated wake vortex decay and its exploitation to potentially reduce aircraft separations. In case accelerated wake vortex decay may also allow reducing aircraft separations, the corresponding ATS operational solutions like for example RECAT-EU have to be adjusted accordingly. Being a technology solution, the concept aims at reaching technology readiness level TRL 7 (system prototype demonstration in operational environment) for deployment by interested airports at the end of WAVE-2.

According to WP3- Safety Assessment Plan [2] the scope of the safety assessment can be divided in two main parts.

First, the safety gains that can be achieved by the installation of plate lines were quantified based on the measurement data gathered in the field measurement campaign LT10 conducted in Wave 1 at Vienna airport. These safety gains are achieved by the acceleration of wake vortex decay during final approach, the phase of flight with most encounters. The acceleration of wake vortex decay was quantified in two ways: On one hand, by the determination of the reduction of the lifetime of the long-lived wake vortices, and, on the other hand, by the reduction of circulation strength at relevant vortex ages.

Second, the plate design for permanent installation at an airport was conducted such that it complies with airport requirements set forth by ICAO and EASA. All material required for authority approval like expert opinions on statics etc. for the installation of plate lines at an airport location has been prepared. For this purpose, a three-stage design process was carried out consisting of i) the development and prioritisation of requirements, ii) the development of 15 potential designs and

selection of four most promising ones, and iii) the detailed design and strength analysis of the four remaining concepts enabling the selection of the best design.

Furthermore, the achievable reductions of separation minima employing the rationale developed for RECAT-EU and RECAT2-EU (static pairwise separations) as well as for dynamic pairwise separations have been assessed.

The WP3 work has been structured by the following activities (tasks):

1. Elaborate a technical plate line design as well as the design for its installation for permanent deployment at an airport
2. Prepare all material for authority approval like expert opinions on statics etc. for the installation of plate lines at an airport location
3. Installation of the plate prototype in a suitable environment, e.g. at Vienna airport considering legal, and stakeholders' requirements
4. Thorough quantification of the acceleration of wake vortex decay by plate lines based on the validation results stemming from WAVE-1
5. Assessment of achievable reductions of separation minima
6. Conducting a demonstration/visitor's day in order to demonstrate that all required qualifications for the installation of plate lines at airports have been fulfilled within VLD3

Of these the tasks 1, 2, 3 and 4 directly relate to safety work performed.

3 VLD safety argument and assurance activities

The WP3 objective number OBJ-VLD-03-002-001 comprises the “Reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines for different environmental conditions and aircraft types” and the “Assessment of achievable reductions of separation minima”. Additionally, we report here on the “Technical plate line design for permanent deployment at an airport” including the “Material needed for authority approval for the installation of plate lines at an airport location” and “The installation of the plate prototype in a suitable environment” as several requirements established for the plate design (e.g. stability against storms and frangibility) are also safety relevant. While the following achievements are also described in section 4.2.2 of the VLD3-W2-SORT DEMOR Part I, the description provided here focuses on the respective safety aspects.

Reduction of wake vortex lifetime and circulation strength that can be achieved by the installation of plate lines.

The analysis was based on a measurement campaign that has been accomplished from 6 May 2019 until 28 November 2019 at Vienna International Airport in the SESAR Joint Undertaking “Increased Runway and Airport Throughput” project (PJ.02 EARTH). The following analysis has been described in detail in Ref. [8]. During the campaign at Vienna airport two temporary plate lines were erected below the glide path to runway 16 and wake vortex behavior was gathered employing three wind lidars complemented by a suite of meteorological instrumentation (see Figure 1 and Figure 2).

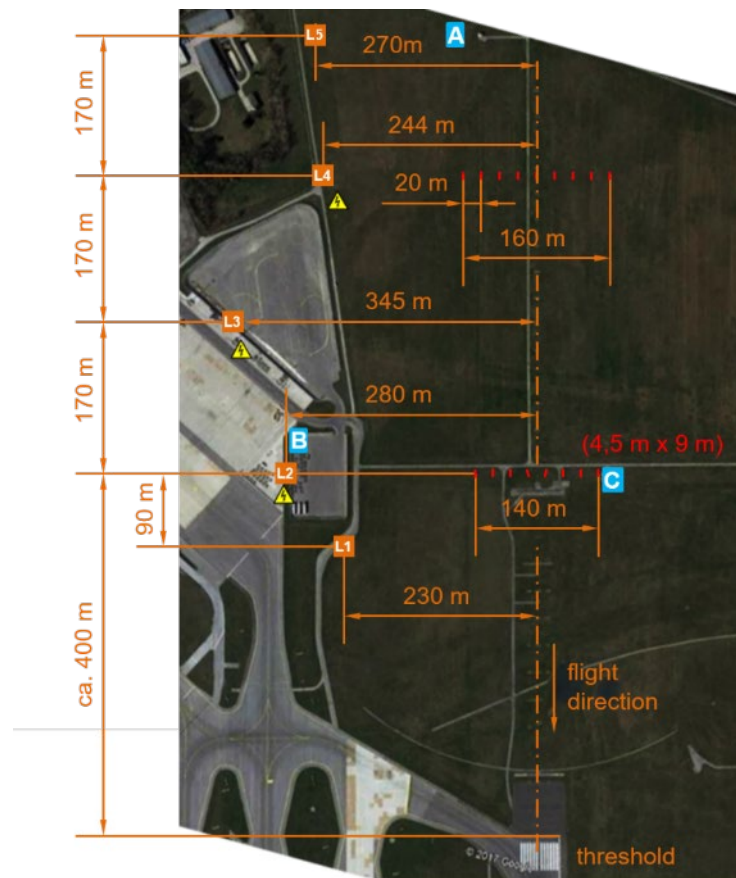


Figure 1: Positioning of plate lines (red dashes) and lidar measurement positions L1 to L5 (© Google 2017).



Figure 2: Overflight of A380 of plate line 1 next to the localiser.

Wake vortex behavior of about 9,500 approaches has been collected in five different lidar measurement planes L1 to L5 (see Figure 1) covering the area in which wake vortices may rebound to the approach path corridor. From these over 1000 wake vortex evolutions with and without plate lines have been processed and used for the current analysis.

The developed evaluation strategy focused on safety aspects:

- The conducted analysis employs an aircraft safety corridor extending ± 50 m from the runway centerline. Vortex measurements outside that safety area are neglected for the analysis of the lifetime reduction by the plates. However, circulation reduction can only be evaluated if the vortices are considered throughout their entire lifetime. This requirement is met by

considering only vortices where the last measured location is situated within the safety corridor. The sensitivity to the width of the safety corridor turned out to be weak. A larger safety corridor slightly decreases the measured plate line effectiveness, because additional plates ahead of a vortex strengthen the plate-induced vortex decay.

- The data indicates that vortex decay is correlated with headwind speed. Because strong headwinds support the transport of end effects (occurring during touchdown and accelerating vortex decay) into the measurement planes, cases with headwinds stronger than 2 m/s are excluded for the further analysis. Encounter frequencies and go-around rates are highest at weak headwinds or even tailwinds [9].
- The analysis combines data of all the available lidar measurement planes, because the accelerated vortex decay should be effective all along the stretch where rebounding vortices may reach up to the flight corridor. Given the large scatter of wake vortex lidar data, the data samples collected in the five individual lidar planes appeared too small to support conclusive results for each individual plane.
- To enable the comparison of wake vortices generated by different aircraft types, the data characterizing vortex decay is partly normalized employing aircraft parameters retrieved from the Mode-S protocol and aircraft masses provided by Austrian Airlines.
- The analysis evaluates the above median lifetime reduction of wake vortices at an advanced state of decay. For vortices at an advanced state of decay (circulation bins below 150 m²/s and normalized circulation bins below 40% of the initial circulation) the median, the 75th percentile, and the 95th percentile of the vortex lifetime are considered. To condense the results to a single percentage of lifetime reduction, the 18 values resulting from three dimensional circulation bins and three normalized circulation bins with three percentiles, respectively, are averaged.
- The circulation reduction is considered for vortex lifetimes around 60 s for Medium vortex generating aircraft and around 120 s for Heavies. Again, the relative circulation reductions achieved for the three selected percentiles are averaged into a single value.
- Finally, the Wilcoxon rank-sum test is used to assess whether the differences of the lifetime distributions with and without plate lines are statistically significant or not. Further, margins of uncertainty of the median lifetime reductions are determined with 95% confidences.

As an example of the measurement results **Figure 3** depicts probability density distributions (PDD) of the vortex lifetimes for different circulation ranges. The PDDs for circulations above 250 m²/s with and without plate lines are almost identical indicating that the statistical basis for their further development is sound. With decreasing circulation strength, the PDDs with and without plate lines diverge evermore which is also seen in the median values of the PDDs indicated by vertical lines. The Wilcoxon rank-sum test indicates that the PDDs for circulations below 200 m²/s differ with extremely high statistical significances with and without plate lines. Similar characteristics are also observed for the individual aircraft types.

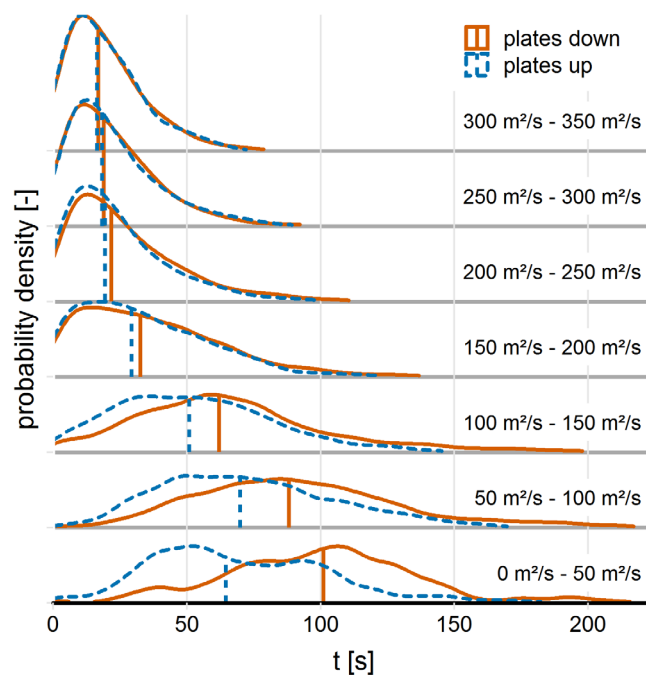


Figure 3: Probability density distributions of vortex lifetimes for different circulation bins for different aircraft of weight classes J, H, M employing the ± 50 m safety corridor for headwinds lower than 2 m/s. Vertical lines indicate the median values.

Following all the above listed criteria, the lifetime of the vortices in the safety corridor is reduced on average by 22% for 420 landings comprising Medium, Heavy, and Super weight class aircraft. For this 456 vortex pair evolution measurements with plate lines and 472 vortex pair evolutions without plates have been considered. The median lifetime reductions according to the Wilcoxon test range from 21% to 30%. The average circulation reduction around vortex ages of 120 s, corresponding to the ICAO separation for Mediums behind Heavies, amounts to 66% (32% for the 95th percentile).

It is found that increased environmental turbulence reduces wake vortex lifetimes by the same order of magnitude as the lifetime reductions achieved by the plate lines. The circulation and lifetime reduction potentials of plate lines appear to be similar in low and high-turbulence conditions. So, the highest potential for the mitigation of wake vortex risks lies within low wind and low turbulence conditions where without plate lines the longest-lived vortices occur and are leading to the highest encounter risks - just those reasonable worst-case environmental conditions for which the plate-line concept was developed in the first place.

The mitigation potential of wake turbulence risks via plate lines is considered for the most frequent aircraft at Vienna airport for three different weight categories of the RECAT-EU scheme. As representative of the ICAO weight category Medium and category D "Upper Medium" of the RECAT-EU scheme, 348 approaches of the A320 aircraft corresponding to 337 vortex pair evolutions with plate lines and 388 vortex pair evolutions without plates have been assessed. For this smaller aircraft type circulation and lifetime reductions are less pronounced than for larger aircraft, because the interaction of the smaller vortices with the plates sets in later, leading to an overall reduced plate effect. The circulation of the A320 vortices is reduced on average by 8% at vortex ages around 60 s corresponding to radar separation. The vortex lifetimes are reduced on average by 18%, whereas the medians of the lifetime reductions vary according to the Wilcoxon rank-sum test between 17% and 27%. Considering

only those measurement planes where intense vortices might rebound to the flight corridor, the average lifetime reduction is increased to 22%.

Within the weight category Heavy and category C “Lower Heavy” of the RECAT-EU scheme the B767-300ER was the most frequently captured aircraft type with 39 approaches. Based on 54 vortex pair evolutions with and 52 vortex pair evolutions without plate lines the reduced vortex lifetimes average to 23% with a confidence interval of the median of 18% to 36%. Within the ICAO separation relevant vortex age bins centered around 120 s the circulation is reduced on average by 53%.

The B777-200ER with 30 landings is the most frequent representative of the RECAT-EU scheme B “Upper Heavy”. For this aircraft type 41 vortex pair evolutions with plate lines are compared to 38 vortex pair evolutions without plates. The longest-lived B777-200ER vortex reaches a lifetime of 315 s. The average circulation reduction of 48% and the average lifetime reduction of 37% are quite high and backed up by the Wilcoxon test notwithstanding the relatively small sample size.

Despite the relatively high scatter of individual lidar circulation measurements, the presented statistics appear sound. So initially, the percentiles for the cases with and without plate lines proceed almost identically, demonstrating that random fluctuations stemming from varying environmental conditions and stochastic vortex behavior as well as measurement uncertainties have smoothed out. Then the curves deviate from each other and split up into λ -shaped legs when the plate induced decay comes into effect. This instant coincides with the time when the Wilcoxon test attests the transition from statistically similar vortex age distributions to distinctly different distributions with high confidences transitioning from p-values like 0.7 to 10^{-10} .

In summary, it can be concluded that the plate lines substantially reduce both the lifetime of wake vortices as well as their circulation at vortex ages relevant for aircraft separations in a safety corridor along the final approach path. The above median lifetime reductions increase with aircraft size from 18% for the A320 to 37% for the B777-200ER. If we exclude flight altitudes not impaired by energetic rebounding wake vortices, the A320 vortices experience almost the same lifetime reduction of 22% as the vortices shed by B767 aircraft with 23%. For the two investigated Heavy aircraft types the mean circulation reduction amounts to 50% assuming a 120 s separation to following Medium weight class aircraft.

Assessment of achievable reductions of separation minima

Now the Vienna data base is analysed in order to assess the potential for reducing minimum aircraft separations facilitated by plate lines during approach and landing following the RECAT-EU and RECAT-EU-PWS methodologies for revised wake turbulence categorization. In the following, these two complementary methods are mostly considered together and are termed RECAT-EU(-PWS) for simplicity.

For this purpose, the RECAT-EU(-PWS) methodology is adopted as close as possible in order to estimate most realistic potential capacity gains that already meet to a large extent the requirements for future approval by the authorities and operational implementation. The method to estimate the potential for reduced separations with plate lines in ground proximity with respect to RECAT-EU(-PWS) is described in detail in Refs. [10], [12]. Wake vortex risks along higher parts of the glide path, where plate lines have no effect on the wake vortices, are considered as well. The final separation reduction potential results from the maximum separations found either in ground proximity with the plate line or out of ground effect on the glide slope without plate line effects.

In order to ensure that the analysis of the aircraft separation reduction potential is valid, it is verified that other parameters controlling wake vortex decay like wind speed, atmospheric turbulence, thermal stratification, and flight altitude above ground reside in similar ranges with and without the plates [12]. It is shown that wind and turbulence conditions both would even support slightly faster decay without

the plates such that the environmental conditions for the assessment of the separation reduction potential may be clearly rated conservative.

Prior to the very analysis, the measured single vortex evolutions were screened by excluding cases with headwinds above 2 m/s, featuring premature vortex decay caused by so-called end effects triggered during touchdown. Further, those vortices were excluded that are quickly and irrevocably advected out of a safety corridor around the glide path, because these are irrelevant for the encounter risks of following aircraft.

Next, the analysis follows the steps of the RECAT-EU(-PWS) method to generate the so-called reasonable worst-case (RWC) decay curve (see Figure 4). First, the vortex age of the considered vortex evolutions is adjusted such that the vortex evolutions commence at a height of one wing span of the vortex generator aircraft above ground. Then, the measured circulation evolutions are fitted by a two-phase decay model in order to smoothen the scatter of the lidar data and to enable extrapolation to low circulation values. In order to combine the data originating from 12 different aircraft types, the two-phase decay curves are normalised based on the estimated initial values of the circulation and the vortex separation.

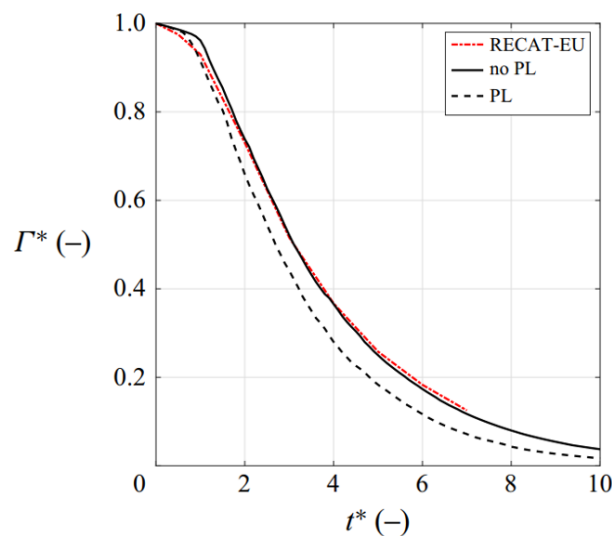


Figure 4: Normalised reasonable worst-case circulation decay curves from RECAT-EU(-PWS) and the corresponding decay curves established from the Vienna data without and with plate lines.

The resulting median decay curve is fitted to the RECAT-EU(-PWS) reasonable worst-case curve by selecting the cases with measured lifetimes extending beyond 3.5 vortex timescales. As reasonable worst-case atmospheric conditions were given preference already for both execution and processing of the Vienna measurements, the selected vortices correspond to 72% of the Vienna data; a much higher fraction compared to the top 2% of the longest-lived measurements resulting from a lifetime threshold of five vortex timescales applied to the over 100,000 tracks collected at London Heathrow airport for RECAT-EU(-PWS). While the number of the individual circulation decay curves generated by Heavy category aircraft types is lower here than that considered in the RECAT-EU(-PWS) safety case [11], the lidar data also allowed establishing decay curves for a Medium category aircraft type. Nonetheless, the good agreement of the reasonable worst-case decay curves made up of the different data sets provides good confidence that the applied methods are actually equivalent.

The time-based separation reduction potential enabled by the plate lines is established in analogy by selecting the top 72% of the longest-lived vortex evolutions with upright plates. It is translated into spatial minimum separations of the RECAT-EU(-PWS) categories using typical parameters of the leading and following aircraft within the respective categories of the separation matrix. The sensitivity

of the resulting minimum separations to the required parameters aircraft gross mass, air density, initial vortex separation, and approach speed turns out to be minor and not critical for the robust assessment of the aircraft separation reduction potential.

Leader / Follower		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
		A	B	C	D	E	F
Super Heavy	A	2.6 NM	3.4 NM	4.4 NM	4.4 NM	5.2 NM	6.9 NM
		-0.4 NM	-0.6 NM	-0.6 NM	-0.6 NM	-0.8 NM	-1.1 NM
		-13.3 %	-15.0 %	-12.0 %	-12.0 %	-13.3 %	-13.8 %
Upper Heavy	B		2.6 NM	3.5 NM	3.5 NM	4.4 NM	6.0 NM
			-0.4 NM	-0.5 NM	-0.5 NM	-0.6 NM	-1.0 NM
			-13.3 %	-12.5 %	-12.5 %	-12.0 %	-14.3 %
Lower Heavy	C			2.6 NM	2.6 NM	3.5 NM	5.2 NM
				-0.4 NM	-0.4 NM	-0.5 NM	-0.8 NM
				-13.3 %	-13.3 %	-12.5 %	-13.3 %
Upper Medium	D						4.3 NM
							-0.7 NM
							-14.0 %
Lower Medium	E						3.4 NM
							-0.6 NM
							-15.0 %
Light	F						2.6 NM
							-0.4 NM
							-13.3 %

Table 1: Distanced-based aircraft separation minima with plate lines and differences to RECAT-EU scheme.
Empty fields indicate minimum radar separation.

Table 1 outlines the resulting distanced-based separation minima with plate lines in nautical miles within the RECAT-EU separation matrix in bold face. Listed below the minimum separations are the differences to the respective RECAT-EU minimum separations as absolute values in NM and as percentages. The aircraft separation reduction potential varies between 12% and 15% depending on the respective aircraft category combination.

As the efficacy of the plate lines appears to be higher for larger leading aircraft, the aircraft separation reduction potential based on the reasonable worst-case decay curve established from measurements of the B772, taken as representative of the RECAT-EU(-PWS) leader category Upper Heavy, would amount up to 20% (not shown). Focusing in any future lidar measurement campaign on Heavy aircraft, as done within the RECAT-EU(-PWS) safety cases [11], may presumably increase the separation reduction potential of the plate lines.

Applying the same methodology as described above, the potential for reduction of minimum separations is evaluated for the RECAT-EU-PWS separations. Figure 5 depicts the absolute and relative separation reduction potential for the 86 considered aircraft types. The aircraft types are depicted only by their index as a labeling with the exact name would be barely readable. Low numbers indicate heavy aircraft and high numbers indicate light aircraft. However, in order to give a better overview, the boundaries of the RECAT-EU aircraft categories are shown by the dashed lines.

Figure 5 shows an absolute reduction potential of circa 0.4 NM to 1.3 NM, which corresponds to approximately 12% to 24%. The average over all aircraft pairings is 14.8%. Hence, the reduction potential shown here is on the order of magnitude of the reduction potential evaluated for RECAT-EU (Table 1) and even higher for some aircraft pairings.

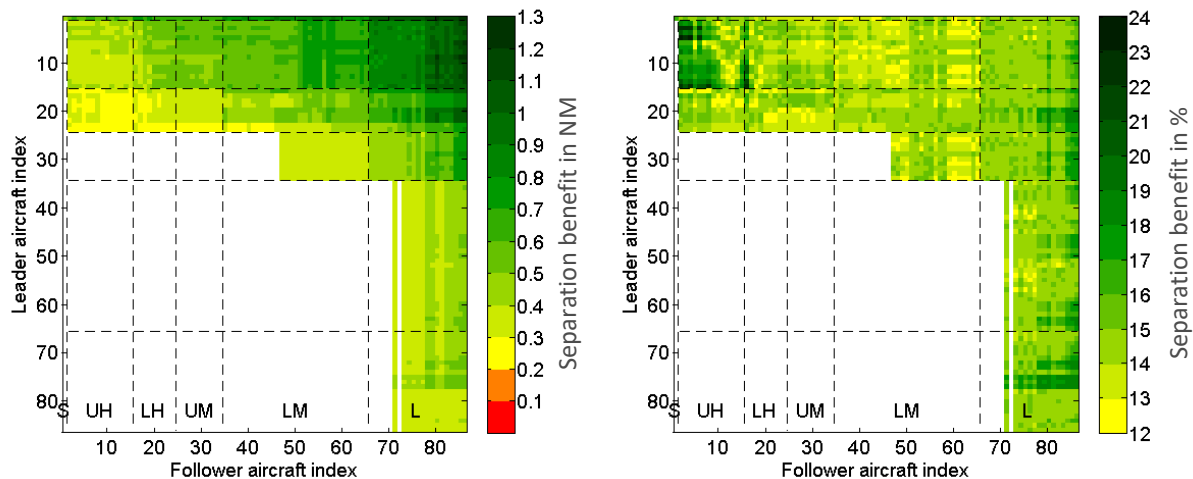


Figure 5: Separation reduction potential with plate line for RECAT-EU-PWS separation minima; left absolute in NM, right relative in percent.

With a risk assessment employing the rolling moment coefficient RMC to characterize encounter severity and the traffic mix from the top 25 ECAC airports to characterize the frequency of occurrence, the risk of the separation schemes under worst-case conditions was investigated following the method employed for the RECAT safety cases. It was found that the installation of plate lines could substantially reduce wake vortex encounter risks for all three considered separation schemes (ICAO, RECAT-EU, RECAT-EU-PWS), bringing the encounter risk of RECAT-EU-PWS down to a risk level even below that of RECAT-EU (and that of RECAT-EU for the greater part down below that of ICAO).

Also, the out-of-ground effect (OGE) analysis, representing the flight situation at 4 NM before threshold, follows the RECAT-EU-PWS safety case report [11]. Circulation decay is computed for all 86 considered aircraft using the deterministic version of the P2P wake vortex prediction model [12] for RWC atmospheric conditions represented by a turbulence eddy dissipation rate $EDR = 4 \cdot 10^{-4} \text{ m}^2/\text{s}^3$ and a thermal stratification in terms of the Brunt-Väisälä frequency of $N = 10^{-2} \text{ 1/s}$. For every follower aircraft the minimum separation distance OGE between the aircraft pairings is adjusted such that the highest rolling moment coefficient (RMC) occurring under RECAT-EU-PWS is not exceeded using an airspeed of 160 kts. Then an additional separation of 0.5 NM is added to all separations as a buffer to consider the “compression effect” occurring on the way to the runway threshold.

For the RECAT-EU aircraft categories the respective worst-case pairings within one category define the minimum separation for the complete category. The final separation reduction potential with plate line shown in Table 2 corresponds to the maximum separation found in ground proximity and out-of-ground effect along the glide path. Depending on the particular RECAT-EU category combination, the aircraft separation reduction potential now ranges between 0% and 14%. The average benefit for the operationally relevant Heavy-Heavy and Heavy-Medium pairings amounts to 7.5%.

Leader / Follower		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
		A	B	C	D	E	F
Super Heavy	A	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	B		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	C			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	D						4.3 NM -0.7 NM -14.0 %
Lower Medium	E						3.6 NM -0.4 NM -10.0 %
Light	F						2.6 NM -0.4 NM -13.3 %

Table 2: Distanced-based aircraft separation minima with plate lines and differences to RECAT-EU scheme considering OGE limitations of separation reduction. Empty fields indicate minimum radar separation.

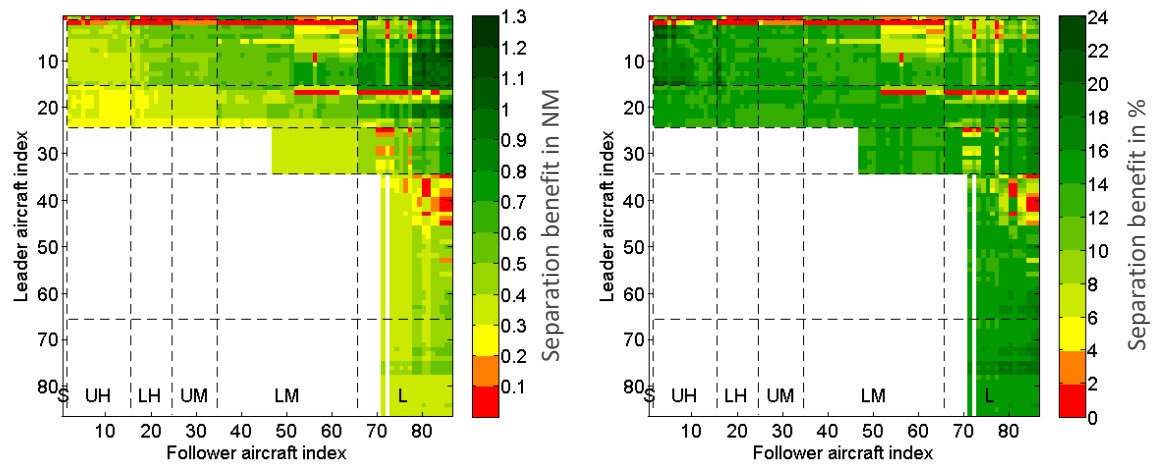


Figure 6: Separation reduction potential with plate line for RECAT-EU-PWS separation minima considering OGE limitations of separation reduction; left absolute in NM, right relative in percent.

Figure 6 depicts the separation reduction potential with plate line for the RECAT-EU-PWS separation minima considering the restrictions of the OGE analysis. The absolute separation benefits on the left are ranging from 0 NM to 1.22 NM with an average 0.45 NM corresponding to relative separation benefits on the right ranging from 0% to 23.8% with an average of 13.1%. The OGE analysis restricts the plate benefits obviously much less for RECAT-EU-PWS than for RECAT-EU as only a few

leading aircraft types (see red or orange pairings in Figure 6) restrict some of the category combinations listed in Table 2.

It can be concluded 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. For most aircraft pairings, the in-ground-effect (IGE) case is dimensioning the wake vortex separation, which allows a potential reduction of the separation even for the out-of-ground-effect (OGE) case without compromising safety. When using RECAT-EU as reference, substantial benefits can only be gained for some – albeit relevant – aircraft category combinations. When using RECAT-EU-PWS as reference, for most aircraft pairings, benefits of about 0.5 NM separation reduction seem to be possible when using plate lines. As OGE wake vortex transport is the relevant mechanism guaranteeing safe separations, further OGE separation analysis may be needed for a safety case that will make this separation reduction potential available at congested airports.

In order to assess the potential of plate lines for dynamic pairwise separations (RECAT III) the Wake Vortex Prediction System (WSVS) developed by DLR has been used. The study employs twelve months of traffic and weather prediction data collected at Vienna International Airport as described in [14]. The meteorological conditions were taken from operational predictions of the Integrated Forecasting System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) with a model output interval of three hours. The considered arrival traffic consists of 106,293 approaches and landings of 94 different aircraft types on the runways 11/29 and 16/34 during the months November 2017 to October 2018. With these input parameters the P2P probabilistic wake vortex model predicts wake vortex evolution within 16 gates (WSVS prediction planes) along the final approach.

The distance between the gates is 1 NM along the glidepath and is reduced in ground proximity first to 1/3 NM and then to 1/6 NM to properly resolve the interaction of wake vortices with the ground. The probabilistic bounds of vortex position and strength predicted by P2P are expanded by the safety area around a vortex that must be avoided by follower aircraft for safe and undisturbed flight employing the simplified hazard area prediction model SHAPe. The instant when all the resulting safety ellipses along the glideslope do not overlap anymore with the elliptical approach corridor defines the temporal minimum wake-vortex separation between an individual aircraft pairing. For operational purposes, the maximum of three time thresholds, the WSVS separation, the minimum radar separation, and the runway occupancy time, would then constitute the applicable separation.

For this study a parametrization of the plate line effects has been developed using the wake vortex measurement data collected at Vienna airport. The plate line parametrization uses a differential extension of the two-phase circulation decay model [13] with an earlier onset of rapid decay (rapid decay without plates is initiated at an altitude of one vortex separation above ground, with plate lines it starts already 10 m higher) and a by 48% increased turbulent viscosity determining the vortex decay rate. The plate disturbances propagate at a speed of 8.0 m/s and the probabilistic envelopes for vortex circulation are widened by 2%.

Figure 7 shows exemplarily normalized circulation decay of wake vortices generated by B763 aircraft without (left) and with plate lines (right), where symbols denote lidar measurements (dark blue circles indicate the starboard vortex, red crosses the port vortex) and lines the P2P predictions. The yellow marks indicate that at a relevant vortex age of 4 vortex time units (vortex age around 100 s) the upper probabilistic envelope for circulation used by the WSV (light blue line) is reduced by about 30% compared to the case without plates.

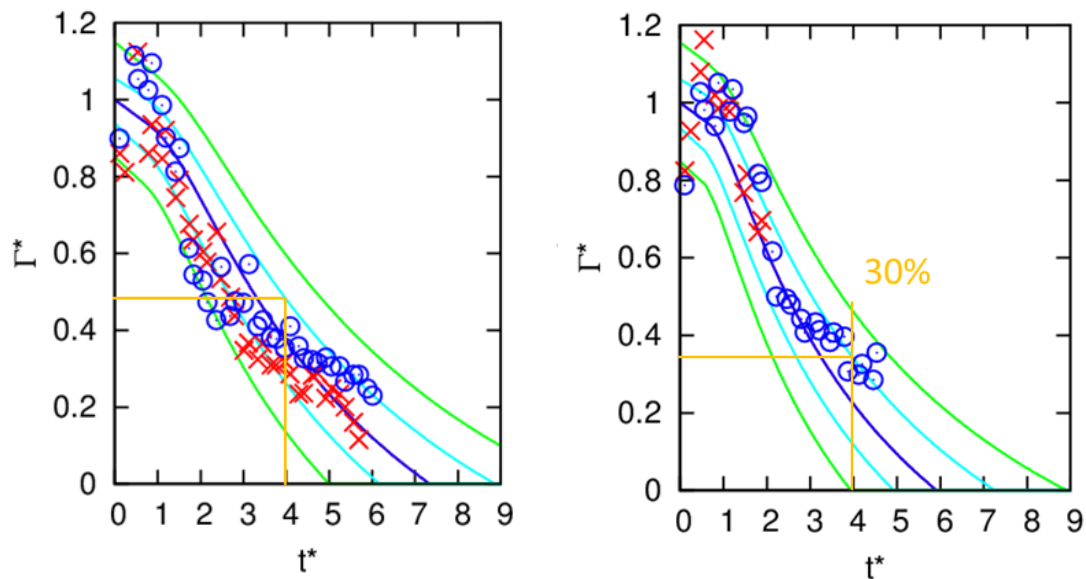


Figure 7: Probabilistic P2P predictions of normalized circulation decay of B763 aircraft without plates (left) and with plates (right) in a measurement plane at 170 m upstream of plate line 1. Symbols denote lidar measurements, dark blue lines the deterministic predictions and the light blue (green) lines denote the probabilistic 1- σ (2- σ) envelopes.

The WSV analysis shows that plate lines reduce the longest-lived wake vortices under RWC conditions in ground proximity that are not blown out of the glide path corridor by crosswinds with a strength below 2 m/s. As RWC conditions in terms of turbulence and thermal stratification occur only in about 2% of the time, the corresponding separation gains for pairwise dynamic separations by plate lines are also quite limited and amount to about 2%.

Technical plate line design for permanent deployment at an airport

To develop a technical design of the plate lines for the permanent installation at airports, a three-stage design process was carried out consisting of i) the development and prioritisation of requirements, ii) the development of 15 potential designs and selection of four most promising ones, and iii) the detailed design and strength analysis of the four remaining concepts enabling the selection of the best design. This design process is detailed in deliverable PMP.006 [15].

In the first design phase, requirements were gathered in several exchanges between DLR and selected experts of ACG. Figure 8 depicts the resulting requirements ranked according to their relevance rated by the experts from ACG.

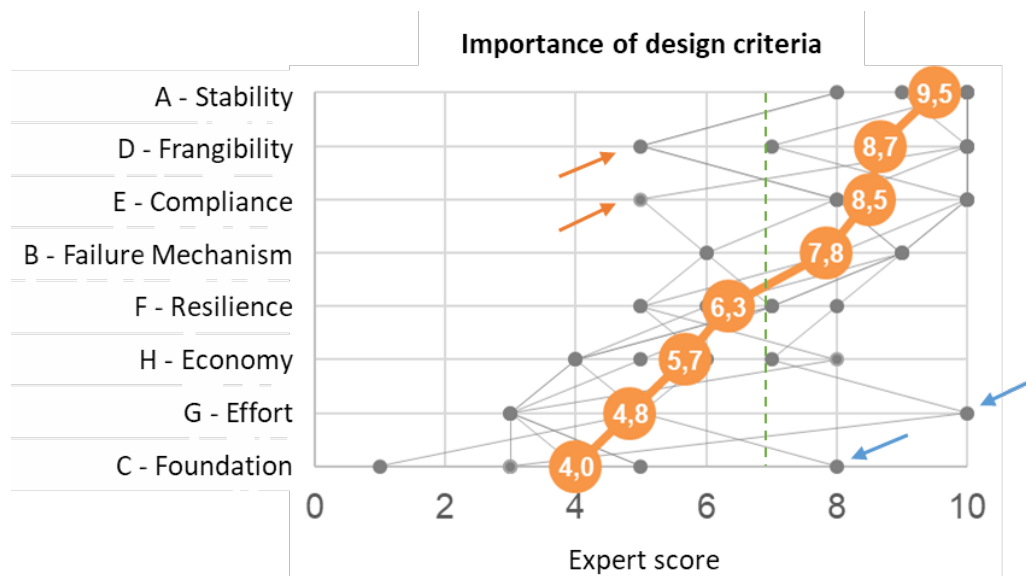


Figure 8: Plate design criteria ranked according to relevance.

Second, based on a morphological analysis a longlist of 27 plate design ideas was developed and characterised by a fact sheet. Simplified analytical stress calculations considering the wind loads defined by different norms (ÖNORM EN 1991-1-4:2013, ÖNORM B 1991-1-4:2013, ICAO Doc 9157 Part 6, Ch. 3.2) reduced the number of design ideas to 15 potential designs shown in Figure 9. The 15 viable shortlisted designs were discussed in detail and rated in a formalized voting process by experts based on the design criteria with their respective weights. The resulting scores are listed in Figure 9 below the designs.

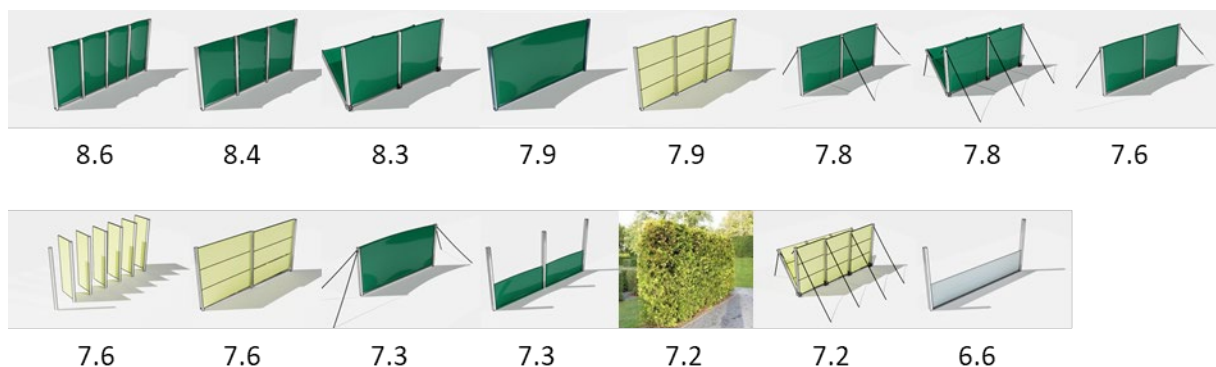


Figure 9: Fifteen plate line designs on the shortlist with expert scores.

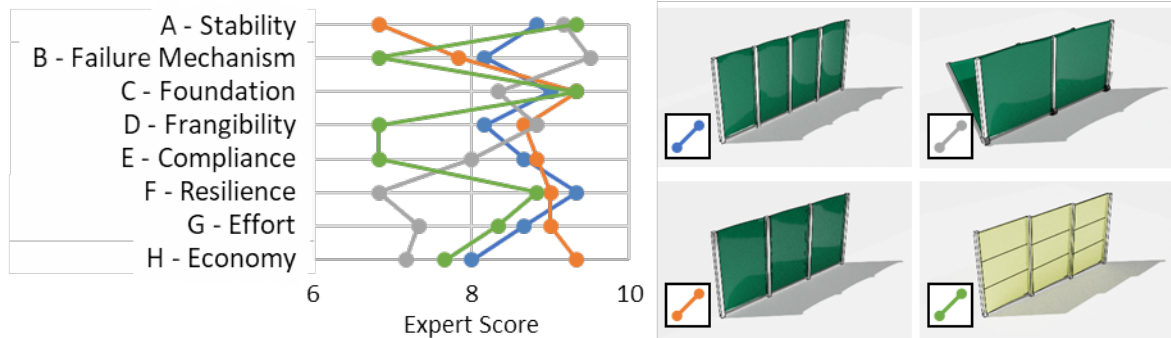


Figure 10: Expert scores for the four selected designs.

The four most promising designs, which are shown in Figure 10 together with the respective unweighted ratings of the eight requirements, were selected for further development. These remaining designs are: five masts covered with truck tarpaulin (blue scores), four masts with tarpaulin (orange), movable three-mast system with reset device and tarpaulin (grey), and four masts with panels (green).

In the third step, the four selected designs were matured into technical solutions and modelled in detail using finite element methods (FEM). As the design with four masts with tarpaulin turned out not to be stable enough, three technical design solutions for the plate lines remained. The elaborated solutions were presented in another expert workshop with DLR and ACG, where two final designs were deemed suitable for installation at an airport: five masts with tarpaulin and four masts with panels.

In a next step, a consultation with the mast manufacturer Lattix (Sweden) provided guidance for the choice of the final design leading to the selection of the four-mast solution with panels. Figure 11 shows the plate prototype installed at the antenna test centre Rauchenwarth close to Vienna airport in January 2023. The plate design consists of four aluminum lattice masts 4430 with a side length of 300 mm which are passively safe and certified for frangibility. Lattix masts are used at numerous airports worldwide and are installed even with plates for visual cover at Shanghai Hongqiao International Airport. Nine ALUCORE aluminum honeycomb composite panels are hooked in to the mast connectors. To guarantee frangibility the plates don't stiffen the plate construction but would release from the connectors easily and fall to the ground once an airplane would hit a mast.



Figure 11: The plate prototype installed at antenna test centre Rauchenwarth close to Vienna airport is inspected by international visitors.

Material needed for authority approval for the installation of plate lines at an airport location

The material compiled for authority approval for the installation of plate lines at an airport location comprises the detailed documentation of the development process described briefly in the previous section [16]. In particular, the document details how the design responds to the eight identified requirements. It also describes the computations of plate stability against heavy storms and the measures that guarantee frangibility. This is complemented by technical drawings of all parts and corresponding part lists as well as instructions for the installation of the foundation and the plate. Based on this documentation an external expert opinion [17] was commissioned which led to several minor adjustments of the plate design and the dimensioning of the foundation. Ref. [18] confirms that all expert comments have been considered in the plate design described in Ref. [16].

This comprehensive material corresponds to the documents that the Austrian authorities (BMK, Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology) would have used for approval. With this documentation the approval process for the installation of plate lines at an airport can be brought forward efficiently with relatively small adaptations to the requirements of the individual runway situation.

4 VLD safety Results

4.1 Suitability of the SESAR solution(s) for deployment

The analysis of the measurement data collected at Vienna airport indicates that the installation of plate lines at the runway ends of busy airports will increase the safety and potentially the runway throughput capacity. The passive, low-cost, robust and safe plate lines reduce the lifetime of long-lived vortices by 22% for Medium weight class aircraft to 37% for Heavies. The reduced wake vortex lifetime in turn reduces the frequency of wake vortex encounters and go-arounds. The lifetime reduction corresponds to a circulation reduction by 50% for Mediums behind Heavies.

The analysis of the reduction of wake vortex lifetime and circulation strength by the installation of plate lines provides a clear picture of the benefits with respect to safety gains. However, in order to develop a safety case for reducing aircraft separations more detailed knowledge is needed. So, the limited number of processed measurements in the individual lidar planes didn't allow to derive direct conclusive results regarding the efficiency of the plate effects depending on the distance to the plate lines and the flight height. However, a refined analysis with the P2P wake vortex model allowed to derive a propagation speed of the plate disturbances allowing conclusions on the plate line coverage. Also, at Vienna airport the number of landings of different heavy aircraft types is limited such that only aircraft specific results for the B763 and the B772 aircraft could be derived. A safety case for reduced separations enabled by plate lines will require data of more heavy aircraft types.

Although plate lines are only effective close to the ground, they still support a potential reduction of the separation further up on the glideslope. For most aircraft pairings, the in-ground-effect case is dimensioning the wake vortex separation, which allows a potential reduction of the separation without compromising safety, even though vortices out of ground effect are unaffected by the Plate Lines. When using RECAT-EU as reference, substantial benefits can only be gained for some – albeit relevant – aircraft category combinations. When using RECAT-EU-PWS as reference, for most aircraft pairings, benefits of about 0.5 NM separation reduction seem to be possible when using plate lines. As OGE wake vortex transport is the relevant mechanism guaranteeing safe separations, further OGE separation analysis may be needed for a safety case that will make this separation reduction potential available at congested airports. It is expected that the introduction of capacity gains via the installation of plate lines at an individual airport may require new wake vortex measurements that consider the peculiarities of that specific airport, e.g. with respect to the location of the plates in relation to the runway and the specific aircraft type mix.

The technical plate design is ready for installation. The plate design process was conducted very systematically with an intense exchange with experts leading to excellent results. A prototype plate has been installed near Vienna airport and another one will be installed on DLR premises in Oberpfaffenhofen. Further, the documentation needed for authority approval for the installation of plate lines at an airport location has been produced such that the installation of plate lines at an airport can be brought forward efficiently.

The RECAT-EU scheme or the RECAT-EU-PWS scheme together with the installation of plate lines may advance both, runway throughput for arrivals and safety in terms of the wake vortex encounter risks in the near term.

4.2 Safety impact of the VLD on current operations

In ground proximity vortex descent is restricted and the vortices tend to rebound due to the interaction with the ground surface. Weak crosswinds may compensate the self-induced lateral propagation of the upwind vortex, such that it may hover over the runway directly in the flight path of the following aircraft. As a consequence, aircraft experience wake vortex encounters time after time, even under adherence to separation standards. During final approach, pilots usually respond to encounters by initiating go-arounds, since their options to counteract the imposed rolling moment and re-stabilize the approach are restricted at low heights above ground. So, plate lines may contribute safety gains by reducing the number of encounters in this critical phase of flight where reductions of aircraft separations by the introduction of RECAT separations, time-based separations (TBS) and other measures might rather increase encounter risks.

5 Acronyms and Terminology

Acronym	Definition
ANSP	Air Navigation Service Provider
BADA	Base of Aircraft Data
DEMOP	Demonstration Plan
DEMOR	Demonstration Report
ECMWF	European Centre for Medium-Range Weather Forecasts
EXE	EXercise
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
EASA	European Aviation Safety Agency
EARTH	Increased Runway and Airport Throughput
ICAO	International Civil Aviation Organization
IFS	Integrated Forecasting System
IGE	In-Ground Effect
MRS	Minimum Radar Separation
NLR	Royal Netherlands Aerospace Centre
NM	Nautical Mile
OBJ	OBjective
OGE	Out-of-Ground-Effect
PDD	Probability Density Distributions
PMP	Project Management Plan
PU	PUBlic
PWS	Pair-Wise Separation
RECAT-EU	European Wake Turbulence Re-Categorisation and Separation Minima on Approach and Departure
RECAT-EU-PWS/ RECAT2-EU	European Wake Turbulence Categorisation and Separation Minima on Approach and Departure - Pairwise

Acronym	Definition
RWC	Reasonable Worst-Case Conditions
SAP	Safety Assessment Plan
SAR	Safety Assessment Report
SESAR	Single European Sky ATM Research programme
SHApe	Simplified Hazard Area Prediction model
SORT	Safely Optimised Runway Throughput
TBS	Time-Based Separation
TRL	Technical Readiness Level
VLD	Very Large Demonstration
WSVS	the Wake Vortex Prediction System

Table 3: Acronyms

Term	Definition
RECAT-EU	EU-proposed Wake Turbulence Re-categorisation Scheme
RECAT-EU-PWS	EU-proposed pairwise Wake Turbulence Scheme

Table 4: Glossary of terms

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Safety

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