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FLIGHT SIMULATION TO SUPPORT SAFETY CASE FOR PAIR-WISE WAKE TURBULENCE SEPARATION ON DEPARTURES

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Abstract

EUROCONTROL has developed a time-based static pair-wise wake separation (S-PWS) scheme for departures. The time-based SPWS minima were defined, based on the distance-based separation reductions/increases allowed by static pair-wise wake scheme compared to the ICAO distance-based separation scheme for arrivals. This methodology is based on the underlying assumption that the derived time-based S-PWS for departures do not lead to a wake turbulence encounter severity increase greater than what has been justified for the S-PWS minima design for arrivals. This paper presents flight simulator trials conducted with two aircraft types and 27 pilots in order to provide further safety evidence for this wake separation design methodology. It details the simulation setup and discusses the major findings in terms of pilot's perception of the severity of the encountered wake turbulence on the final approach and initial departure path. The evidence collected from pilots in this wake impact severity assessment flight simulation will be used to support and finalise the S-PWS safety case. .

Keywords: static pair wise separation, wake vortex, flight simulation

1 Introduction

Runway throughput in peak traffic periods directly depends upon the applicable minimum longitudinal separation between successive aircraft on the final approach or on departure. Aircraft are either separated by Wake Turbulence (WT) separation rules, or by radar separations or runwayor specific spacing minima when aircraft are using same departing routes that apply when WT separations are not required. These WT separations requirements are usually expressed in time between departures and by distance for arrivals on the final approach.

The current ICAO separation minima based on 4 WT categories have been proven to be over-conservative for certain aircraft pairs and under some meteorological conditions. Solutions that allow for a reduction of WT separation minima can provide significant benefits in terms of efficiency, whilst also maintaining an acceptable level of safety.

In 2013, the European Organisation for the Safety of Air Navigation (EUROCONTROL) developed the RECAT-EU scheme, a European separation scheme that re-categorised the ICAO 4 wake turbulence categories into a 6-category scheme which is now deployed at several major European airports [1][2]. RECAT-EU also serves as basis for the recently published ICAO Wake Turbulence (WT) Groups [3].

Following RECAT-EU, a second and further optimisation step consists in the determination of a static "pair-wise" regime, where each aircraft type pair has its appropriate WT separation minima. The work takes place in the framework of Single European Sky ATM Research (SESAR) Programme in Project 06.08.01 and Horizon 2020 SESAR Wave 1 programme solution PJ02 and Wave 2 programme, solutions PJ.02-01-04 and PJ.02-01-06. Wake separation schemes were developed for arrivals and departures respectively based on individual aircraft type/model characteristics as opposed to an aircraft category. These pair-wise wake separation schemes, either referred to as Static Pair-wise Wake Separation (S-PWS) or RECAT-EU-PWS, have been designed on the basis of the RECAT-EU safety case methodology and metrics, with refinements to provide adequate assurance for use in a pair-wise analysis. As the separations are based on aircraft type, the wake separations under S-PWS are tailored per aircraft pair. Under S-PWS, the WT separations will be reduced for most aircraft pairs. However, in minority of cases there will be an increase in WT separation, resulting from an enhanced wake turbulence encounter risk exposure.

For both RECAT-EU and RECAT-EU-PWS schemes, the WT separation minima were initially determined on a distance basis and applicable for Arrival and Departure phases of flight. However, in Europe, wake turbulence separation minima on departure are mostly applied by Tower Controllers based on time. Therefore RECAT-EU and RECAT-EU-PWS time-based separation schemes were also defined.

In order to determine optimised departure time-based separation minima based on wake turbulence risk assessment, a methodology similar to the one used for the determination of distance-based minima on approach would require characterizing the "time-to-fly" on departure and necessary information of take-off speeds and departure speed profiles. Since these are currently not collected and available to support such an analysis, another methodology was proposed. It relies on a transposition of the allowed distance-based separation reductions relative to the ICAO standard (based on 4 WT categories) WT minima to an equivalent proportional time-based separation reduction compared to ICAO standard (based on 4 WT categories) time-based WT minima for departure. This methodology was developed under the RECAT-EU project leading to a 6-category scheme and presented in the RECAT-EU safety case endorsed by European Aviation Safety Agency (EASA). It is then extended in order to build a static pair-wise separation schemed for departure (S-PWS-D).

This methodology is based on the underlying assumption that the derived time-based S-PWS for departures do not lead to a wake turbulence encounter (WTE) severity increase greater than what has been justified for the S-PWS minima design for arrivals.

To complete the S-PWS safety case, the WTE risk analysis was already complemented by a flight simulation campaign focusing on arrival scenarios.

The aim of the flight simulation campaign detailed in this paper, focusing on S-PWS-D, was to validate the risk transfer principle of the safety case that justifies the reduction in departure separations under S-PWS compared to ICAO through "equivalence" to arrival separation minima. In addition, the exercise assessed whether any increase in perceived wake severity was acceptable to pilots.

The paper is organised as follows. In the first part, the static pair-wise scheme for departure and the methodology on how it was derived is detailed. The second part of the paper focuses on the flight simulation campaign conducted to complete the safety case for S-PWS-D providing its set-up, validation and results.

2 Static pair-wise Separation for Departures

The static pair-wise separation scheme for departures (S-PWS-D) has been developed starting from the established distance-based S-PWS and using a methodology developed in RECAT-EU.

2.1 RECAT-EU 6 CAT time-based wake turbulence separation for Departures

In Europe, wake turbulence separation minima on departure are mostly applied by Tower Controllers based on time. As for distance-based separation, various time-based separation tables are defined with various levels of refinement.

The existing ICAO legacy provisions, provided in Table 1, are described in ICAO PAN-ATM doc 4444

[10] and complemented by a State letter for separation provisions behind A380-800 [11].

Leader / Follower	S	H	M	L
S		120s	180s	180s
H			120s	120s
M				120s
L				

Table 1: ICAO legacy time-based separation scheme for departure

RECAT-EU [2] revises those minima by increasing the number of wake turbulence categories and allowing some separation reductions behind smaller leaders and larger followers. The separation table is provided in Table 2.

Leader / Follower		Super Heavy	Upper Heavy	Lower Heavy	Upper Medium	Lower Medium	Light
		A	B	C	D	E	F
Super Heavy	A		100s	120s	140s	160s	180s
Upper Heavy	B				100s	120s	140s
Lower Heavy	C				80s	100s	120s
Upper Medium	D						120s
Lower Medium	E						100s
Light	F						80s

Table 2: RECAT-EU 6CAT time-based separation scheme for departure

In order to obtain the RECAT-EU reduced minima, EUROCONTROL developed a methodology to calculate the allowed separation reductions/increases compared to ICAO legacy provisions. It defines the time-based separation reductions/increases for departures compared to ICAO, based on the allowed distance-based separation reductions/increases allowed by RECAT-EU distance-based arrival scheme compared to the ICAO distance-based separation scheme for arrivals. More specifically, it consists in applying the same ratio of reduction (or increase) from reference ICAO reference scheme to the time-based separation minima on departure, while remaining conservative and rounding up the values.

This methodology is based on the underlying assumption that the derived time-based separations for departures do not lead to a wake turbulence encounter (WTE) severity increase greater than what has been justified for the wake turbulence minima design for arrivals. This is because in terms of wake encounter resistance, a departing aircraft responds to a wake encounter, should one occur, differently than the arriving aircraft. The departing aircraft is heavier, is at near full throttle, and configured and powered for climb, whereas an aircraft on approach is lighter, slower, and will need to be re-configured to perform a missed approach. Also, due to large variability of departing trajectories and climbing performance, an aircraft will be in the correct geometrical relationship to a departure only for a very short time for a WTE to occur, whereas an arriving aircraft flies “low and slow” and in trail of the preceding aircraft for longer.

In RECAT-EU, the rounding-up granularity was set to 20 s multiples due to ATCO constraints. The process is illustrated in Table 3 and Table 4, where the RECAT-EU relative time separation reductions compared to ICAO legacy are always seen to be lower or equal (hence conservative) than the relative distance-based separation reductions.

Leader / Follower		S	H		M		L
		A	B	C	D	E	F
S	A	+0.5	-2.0	-1.0	-2.0	-1.0	
H	B		-1.0		-1.0		+1.0
	C		-2.0 (-1.5)	-1.0	-2.0	-1.0	
M	D						
	E						-1.0
L	F						+0.5

Leader / Follower		S	H		M		L
		A	B	C	D	E	F
S	A	+20%	-33%	-17%	-29%	-14%	
H	B				-20%		+17%
	C				-40%	-20%	
M	D						
	E						-20%
L	F						+20%

Table 3: RECAT-EU distance-based separation reduction and increases compared to ICAO legacy: absolute value [NM] (top), relative evolution (bottom).

Leader / Follower		S	H		M		L
		A	B	C	D	E	F
S	A	+20s	-20s		-40s	-20s	
H	B				-20s		+20s
	C				-40s	-20s	
M	D						
	E						-20s
L	F						+20s

Leader / Follower		S	H		M		L
		A	B	C	D	E	F
S	A	+33%	-17%		-22%	-11%	
H	B				-17%		+17%
	C				-33%	-17%	
M	D						
	E						-17%
L	F						+33%

Table 4: RECAT-EU time-based separation reduction and increases compared to ICAO legacy: absolute value [s] (top), relative evolution (bottom).

2.2 Distance-based Static Pair-wise Wake Separation for Arrival and Departure

The distance-based S-PWS minima were initially determined for 96 aircraft types, frequent at European major airports and for which data are available to characterize the wake generation and wake encounter resistance. It was then extended to 103 aircraft types in the framework of SESAR Wave 2 in 2020.

Based on the observed obtained S-PWS minima, as well as the similarities in wingspan and maximum take-off mass (MTOM), 14 categories of aircraft types are defined as leader and follower, as a generalisation. The resulting 14-category scheme, based on a sub-division of the RECAT-EU 6 categories, covers most of the landplane aircraft types (about 90 %). Aircraft are assigned to one of the 14 categories, based on their MTOM, span and wing aspect ratio.

A third product has also been developed: a 20-category scheme that combines the 14-category scheme with the RECAT-EU 6 category scheme, in order to cover all landplane aircraft types. Both S-PWS and 20-CAT minima are inclusive of RECAT-EU 6 CAT.

Note that, according to ICAO PANS-ATM doc 4444[10], for some pairs in trail or evolving on Closely Spaced Parallel Runways (CSPR), no wake separation minima are prescribed. According to the same document, when no wake minima are prescribed, the separation cannot be below the surveillance minimum of 3 NM or 2.5NM under certain conditions. It is known that, even if no wake separation is prescribed, based on operational experience, these surveillance minima also act as wake mitigation. In RECAT-EU, RECAT-EU-PWS and RECAT 20CAT, the considered baseline wake separation minima were therefore the ICAO legacy minima combined with the minimum surveillance separation set to 2.5 NM. In RECAT-EU-PWS and RECAT 20CAT, some of those wake minima were reduced below 2.5 NM (but not below 2.0 NM) based on relative comparison with pivot pairs and using the reference wake separation minima described above (i.e. with no separation below 2.5 NM).

2.3 Time-based Pair-wise Wake Separation minima for Departure

In the RECAT-EU-PWS Safety case [4], EUROCONTROL also refined the RECAT-EU 6-CAT time-based separation for departure scheme by increasing the number of categories from 6 to 7, the F category being divided between ICAO Medium and ICAO Light aircraft types, see Table 5. This split removes some of the over-conservatism introduced in the separation increases in RECAT-EU 6CAT scheme.

			A380-800	ICAO HEAVY		ICAO MEDIUM			ICAO LIGHT
			RECAT-EU A	RECAT-EU B	RECAT-EU C	RECAT-EU D	RECAT-EU E	RECAT-EU F	
			A1, A	B1, B2, B	C1, C2, C3, C, C4	D1, D	E1, E2, E3, E	F1, F2	F, F3
A380-800	RECAT-EU A	A, A1	(*)	100	120	140	160	180	180
ICAO HEAVY	RECAT-EU B	B, B1, B2	(*)	(*)	(*)	100	120	140	140
ICAO HEAVY	RECAT-EU C	C, C1, C2, C3, C4	(*)	(*)	(*)	80	100	120	120
ICAO MEDIUM	RECAT-EU D	D, D1						100	120
ICAO MEDIUM	RECAT-EU E	E, E1, E2, E3							100
ICAO MEDIUM	RECAT-EU F	F, F1, F2							80
ICAO LIGHT	RECAT-EU F	F3							

Table 5: RECAT-EU 7CAT time-based separation scheme for departure. (*) means a lower bound of 60s has been used in the WT risk assessment, in absence of specific value of time separation minimum in ICAO provisions.

This lower bound value is extracted measurements of departure separation times at major European airport (collected over 2 years) where 60s is observed as effective minimum for HEAVY-HEAVY pairs on departure.

In order to determine departure pair-wise wake separation minima, a methodology similar to the one used for the determination of RECAT (distance-based) pair-wise wake minima on approach would require characterizing the "time-to-fly" on departure and necessary information of take-off speeds and departure speed profiles. Since these are currently not collected and available to support such an analysis, the proposed methodology relies on an extension of the RECAT-EU Time-Based Separation for departure determination methodology, recalled in Section 2.1, and further refined to be in line with RECAT-EU-PWS minima definition and related safety principles.

The S-PWS minima for departure are therefore obtained by applying the same ratio of reduction (or increase) from reference distance-based ICAO reference scheme allowed by distanced-based S-PWS to the time-based separation minima on departure, while remaining conservative in rounding up the values to the upper 10 s multiple. Note that the 10s granularity in the rounding (as opposed to 20 s in RECAT-EU) is consistent with RECAT-EU-PWS Safety Case where the separation minima are defined with a 0.5 NM granularity (as opposed to 1NM granularity in RECAT-EU).

For example, for an aircraft pair for which the legacy ICAO prescribes standard 5 NM distance-based WT separation for arrival and standard 2 minutes (or 120 seconds) time-based WT separation for departure if distance-based S-PWS allows for separation reduction from 5 NM to 3.5 NM (-30%), time-based S-PWS for departure will allow a reduction of separation from 120 seconds to 90 seconds (84 seconds rounded up to 90 seconds, hence a 25% separation reduction).

This methodology was applied in order to obtain both S-PWS for departures 103x103 matrix and a RECAT-20 CAT separation matrices starting from the corresponding distance-based separation matrices.
The methodology consists of 6 steps:

1. Starting from ICAO legacy time separations for departure, reductions/increases of the time separation minima are established as proportional to the fraction of distance separation reduction/increase allowed by RECAT-EU-PWS/RECAT-20 CAT compared to ICAO legacy distance-based separation. Recall that, as explained in Section 2.2, when no wake minima are prescribed by ICAO legacy, a separation minimum of 2.5 NM is considered for distance-based scheme (as per current ICAO doc 4444 provisions) for the reference separation scheme. For time-based separation for departure a 60 seconds minimum is used as per current ICAO doc 4444 provisions.
2. The obtained separations are then rounding up to the closest 10 seconds with a 2 seconds tolerance (except for ICAO Light followers due to greatest vulnerability). A time separation of 72 seconds will therefore be rounded down to 70 seconds whereas 73 seconds will be rounded up to 80 seconds. The 2 seconds tolerance is consistent with RECAT-EU-PWS Safety case where a tolerance of 0.1 NM was introduced in the rounding of the separations up to the closest 0.5 NM.
3. The obtained time separations are capped down to the RECAT-EU 7CAT time separation minima. This is consistent with RECAT-EU-PWS safety case methodology for S-PWS distance-based minima definition where no separation minima larger than RECAT-EU minima were allowed.
4. For A380 and MD11 leader aircraft pairs, the obtained separations are aligned to those of RECAT 7CAT. This is in line with RECAT-EU-PWS Safety Case methodology for S-PWS distance-based minima minima definition where the separations were increased up to RECAT-EU minima for A380 and MD11 leader aircraft pairs due to larger uncertainty on Out-of-Ground Effect wake behaviour for those generators.
5. Then, due to larger vulnerability of ICAO Light followers and lack of operational data allowing further justification of significant separation reductions for those aircraft on a pair-wise basis, the pair-wise separations for ICAO Light followers are aligned (i.e., increased up) to the RECAT 20-CAT time-based separation minima for departure.

6. Finally, for the pairs for which ICAO legacy does not prescribe any time separation minima and for which the minima are not increased in the new scheme (RECAT-20CAT or S-PWS), the minima are removed from the separation matrix (i.e., blank cases) to be in line with ICAO wake minima provision.

2.4 Safety case rationale and Flight Simulation campaign

The safety cases supporting the RECAT-EU 6-category scheme [2] and RECAT-EU-PWS [4] are based on a relative safety assessment of Wake Turbulence Encounter (WTE) risk. They compare differences in wake generation and wake resistance between aircraft types using ICAO legacy separation minima as an accepted baseline.

For the aircraft types impacted by a reduction of the wake separation minima, the WT risk will increase compared to the risk the same type is exposed to ICAO standard (based on 4 WT categories). Hence, the wake separation reduction must be such that each aircraft type will not be exposed to a greater maximum wake encounter severity than a reference level which can be considered as acceptable based on that currently experienced with the ICAO standard wake separation provisions. Some separation minimum reductions are related to a lower wake strength (i.e., lower circulation), while some are related to a higher wake encounter resistance of the follower, and some are related to both previously mentioned effects being combined. A WTE severity metric approved by the EASA [5][6], is used to characterise the wake impact. It is formulated as a Rolling Moment Coefficient (RMC), which accounts for the circulation of the generated wake, as well as characteristics of the encountering aircraft. For the approach and landing phases and initial departure phase, the WTE angles are indeed typically low. The predominant impact of wake vortex on the encountering aircraft is then a rolling motion. The formulation and calculation of RMC has been shown to properly yield good agreement with WTE flight test results conducted by AIRBUS [9].

For wake separation design, reference encounter conditions have been defined at the ICAO level, for the A380 and B747-8 Wake Vortex separation design. The generated wake shall evolve in reasonable worst-case condition (RWC) defined as leading to long-lasting vortices and with a specific encounter geometry. The RWC meteorological conditions were also defined at ICAO level in terms of turbulence, stratification and wind remaining below pre-agreed values.
For arrival operations, the RWC condition geometry corresponds to the encounter by the follower of long-lasting vortices generated at one generator wing span, coming into ground effect and rebounding toward the follower [7]. For departure operations, it corresponds to the encounter by the follower, being in ground proximity (i.e., similar altitude as for arrival definition), of long-lasting vortices generated above the follower (i.e., in Out-of-Ground Effect (OGE) region) and sinking toward it. Figure 1 compares the two encounter reference RWC configurations.

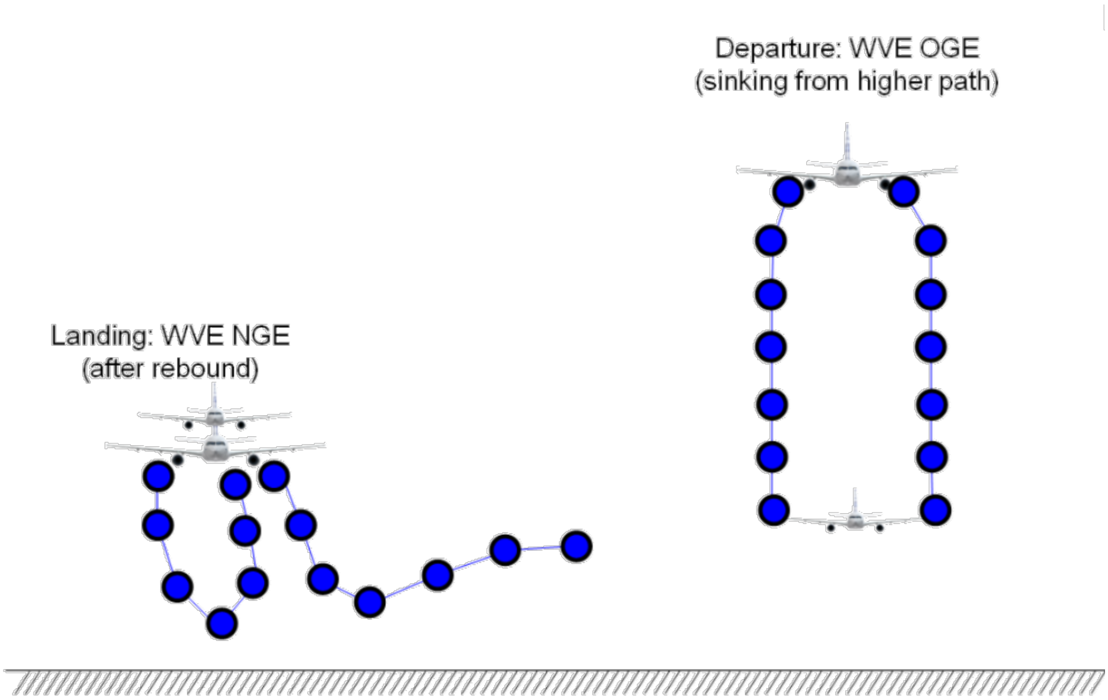

Figure 1: Illustration depicting the Reasonable Worst Case (RWC) definition for Arrival and Departure wake separation design. Blue dots show wake temporal evolution.

To complete the S-PWS safety case, evidence for acceptability of WT severity alignment between aircraft types of various sizes and under dynamic conditions have been obtained during a WTE flight simulation campaign, named Wake Impact Severity Assessment ('WISA') [8][12]. This campaign consisted in comparing the acceptability levels by a number of airline type-rated Pilots flying aircraft on final approach and exposed to various severity levels (expressed by RMC). The campaign made use of a research flight simulator. It considered six aircraft types with sizes ranging from Heavy to Light aircraft types, three phases of flights (3000ft level flight, final approach at 200ft and final approach at 100ft), and various RMC values. In total, 768 simulation runs were performed. The analysis showed that the RMC appears to be a good metric for WTE severity, as it strongly correlates with the pilot severity rating. These results also support the wake severity alignment for Medium and Light aircraft onto the references pivot pairs. The results furthermore show that this alignment can only be partially applied for Heavy aircraft.

Because, the granularity of the separations and hence the separation reductions are larger for S-PWS-D compared to RECAT-EU 6 CAT or 7 CAT time-based separation for departure, further complementary evidence, also with human in the loop, is founded needed for the risk transfer principle applied to obtain the S-PWS-D minima. These complementary evidences were collected through another flight simulation campaign described in the following section. In order to be in line with the RECAT-EU and RECAT-EU-PWS safety assessment methodology, the scenarios that were investigated during this new campaign correspond to the two RWC configurations described above.

3 WISA flight simulation campaign

3.1 Objectives

In a predecessor project, a-priori WT encounter severity metrics for aircraft on final approach have already been validated against observed severity, assessed by flight crews [8][12].

The flight simulation for S-PWS-D minima was conducted to assess the pilots' perception of wake impact severity (Wake Impact Severity Assessment - WISA) associated with the separation reduction during the initial departure path compared to the separation reduction on final approach path (S-PWS-A). The safety objectives of the flight simulation, as well as the set-up of the exercise, were driven by the requirement to validate the methodology, which was used to develop the TB S-PWS-D minima.

The aim was to provide evidence that the underlying principle of the safety case that justifies the reduction in departure separations under S-PWS compared to ICAO standard (based on 4 WT categories) through "equivalence" to arrival separation minima is valid. The exercise was expected to assess whether the relative increase in the "objective" wake impact severity for S-PWS-D compared to ICAO standard was perceived similarly or lower than the relative increase in wake impact severity for S-PWS-A compared to ICAO standard (based on 4 WT categories). In addition, the exercise assessed whether any increase in perceived wake severity was acceptable to pilots .

This was achieved by assessing pilots' perception of various strength wake encounters on departure and arrival, in the two reference RWC configurations described in Section 2.4, when applying the ICAO standard (based on 4 WT categories) category scheme and S-PWS WT minima. The difference between the WT schemes were emulated by using differences in modelled encounter severity; this severity measurement was based on LiDAR data analysis and wake modelling.

3.2 Wake vortex input function

The wake vortex encounter disturbance was added in the flight simulation through the addition of forces and moments. In the previous WISA arrival campaign, only the roll moment component, which is the primary wake encounter effect, was added, whereas in the actual simulation campaign three moment components (i.e., roll, pitch and yaw) and 2 force components (i.e., lateral and vertical) were added.

The theoretical RMC level corresponding to the S-PWS and ICAO standard separation schemes were calculated based on a combination of LiDAR data analysis and wake modelling, following RECAT-EU and S-PWS safety assessment. For arrival, in RECAT-EU, the RWC wake decay characterisation was established for several large aircraft types based on the analysis of a large LiDAR wake measurement database collected at London airport and called EGLL-1 [7]. For departure, in RECAT-EU, the RWC wake decay characterisation was established for some large aircraft types based on the analysis of a large LiDAR wake measurement database (yet smaller compared to arrival database) collected at Frankfurt airport and called EDDF-1. Both datasets are described in detail in the RECAT-EU-PWS Safety Case [4]. Through these campaigns, a range of possible wake circulation values in RWC conditions was obtained for given separation times, depending on the leader, and "worst case" leader types were identified.

In the RECAT-EU and RECAT-PWS safety cases, the estimated wake encounter RMC severity was computed for each pair at reference (ICAO) and reduced (RECAT-EU or S-PWS) minima. The RMC was computed using as input the wake decay characterization in RWC and the follower speed established from operational data collected in several airports and follower aircraft dimensions. It considers a "centred" encounter (i.e., aircraft centre hitting the vortex core) which is worst-case.

The list of RMC values and scenarios that were investigated in WISA flight simulation were then chosen based on the RMC values obtained in RECAT-EU-PWS safety case (considering median circulation evolution and median time-to-fly profiles in low wind to convert distance separation into time separation value). The comparison of the median RMC levels only has been showed to be relevant and conservative in RECAT-EU Safety Case. Note that the baseline RMC values obtained for the departure cases are larger compared to those obtained for arrivals. This is as expected considering the definition of RWC wake vortex encounter for departure (with wake generation OGE) compared to arrival (with wake generation IGE).

To reproduce realistic encounter conditions, the wake vortex input functions for the flight simulations were extracted from WTE simulation results obtained by AIRBUS. Those results consisted of time histories of wake-induced forces and moments produced by the AIRBUS WTE model used in the OSMA flight dynamics simulation environment, using an AIRBUS A320 aircraft model.

The inputs to the WTE model for each scenario were the vortex core size (taken as 3.5% of the leader wingspan corresponding to what is used in the RECAT-EU and S-PWS severity metric [9]) and a circulation value adjusted in order to reach (according to A320 speed and dimensions) the theoretical RMC corresponding to ICAO or S-PWS arrival or departure minima in RWC. The WTE simulations were performed forcing an encounter as close as possible from the wake vortex core. The induced moments and forces were then measured and recorded.

In order to add some variability in the encounter scenarios, each scenario is repeated with the encounter of positive or negative circulation vortex. In addition, for the departure cases, the encounter of a single vortex but also the encounter of a pair of vortices with either first the positive or the negative sign vortex was emulated. This leads to 4 cases for each departure scenario and 2 cases for each arrival scenario.

As examples, Figure 4 and Figure 5 show the recorded wake-induced forces and moments for the two extreme RMC values of the arrival runs, the departure with single vortex runs, and the departure with two vortices runs. The plots also show the function for positive and negative circulation vortex. Note, that the X-force is not computed by the chosen model. Noticeably, the RMC measured in the simulation results are very close from those obtained using the simple "theoretical" RMC severity metric.

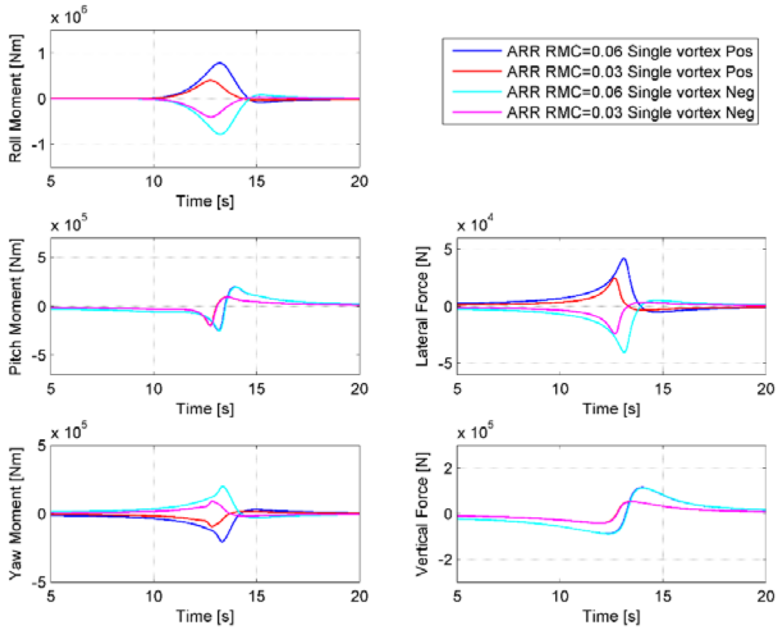

Figure 2: Comparison of the Wake vortex encounter input forces and moments for the arrival scenarios with RMC= 0.03 and 0.06 and with positive or negative vortex circulation

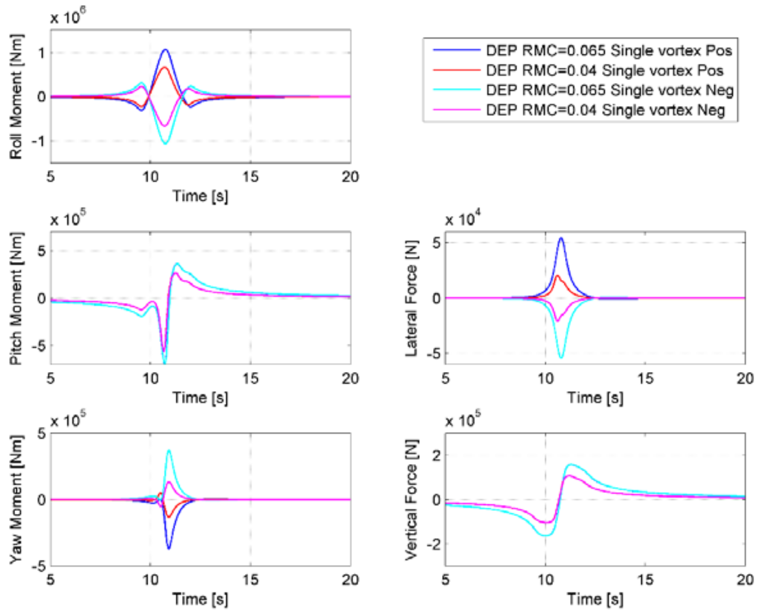

Figure 3: Comparison of the Wake vortex encounter input forces and moments for the departure scenarios with single vortex with RMC= 0.04 and 0.065 and with positive or negative vortex circulation

For the flight simulations, the recorded input data provided by AIRBUS were then rescaled in order to correspond to the requested dimensionless severity levels of each of the scenario. This rescaling is performed in two steps. First, all force and moment functions were rescaled according to the ratio between the maximum measured RMC in the AIRBUS data and the theoretical RMC of the scenario. As explained above, this scaling factor is very close to one since RMC levels very close to the targets were achieved in the AIRBUS simulations. Yet, in order to avoid any bias in the relative assessment, this rescaling was found appropriate. Then, since in the flight simulations, the encountering aircraft dimensions and/or speed differed from what was tested in AIRBUS simulation, the results were rescaled based on the Calibrated airspeed, wingspan and wing area leading to equivalent dimensionless forces and moments. The moments and forces were stored in time series asci files used as input by the flight simulators.

3.3 Simulator Validation

Before the trials were performed a thorough validation of the implemented upset functions took place. This validation was divided into two separate parts: first an objective validation with a comparison of simulator output data against the reference data set, and a second step, which was a subjective validation with experienced pilots who assessed the realism of the WTE behaviour of the simulator.

The verification of the WTE input function and WTE reaction model within the two different flight simulation platforms was performed in two steps: an initial test session led by simulator operators followed by test sessions led by pilots.

During the first step, after programming of the wake encounter reactions of the two aircraft, based on the provided wake vortex input functions, several initial test runs were performed by the simulator operator and pilots of the project team prior to the arrival of the test pilots. The initial test runs were verified as follows:

- An initial (subjective) verification was conducted by the simulator operator to assess whether the simulator behaviour is plausible / realistic. The verification runs were performed without (i.e. stick free) and with pilot interactions.
- The recorded data obtained from the test runs were evaluated by the simulator operators and the project team. The reactions of the simulator to the simulated wake encounters were compared to the expected behaviour also based on AIRBUS reference simulation results.

The analysed data as well as the feedback of the simulator operators were provided to EUROCONTROL for further analysis and discussions.

After this first step, test pilot(s) were invited to verify the subjective feeling and impression of the aircraft behaviour during the wake encounter.

During the simulator testing and validation, it turned out that the motion cue (i.e., the system which transforms the simulation computer output into movement of the motion platform) was not capable to accurately simulate the quick and changing roll accelerations during the wake vortex encounter, even with the top-end state-of-the-art electrical motion system used in the simulators. Indeed, it is important to mention that 6-Degrees-Of-Freedom-(DOF)-simulators cannot simulate a sole roll motion, it will always be a mix between movements in all three axes, hence not fully realistic. Based on the high-quality visual system and the overall behaviour of all other systems, the non-motion simulations were judged as sufficient by experienced test pilots to achieve the relative assessment envisaged in this campaign. Only the non-motion results are therefore presented in this paper.

3.4 Experimental Setup

3.4.1 Flight Simulator and Pilots

Two full flight simulators (Level-D) representing aircraft types of the upper medium (Airbus A320) and lower medium (ATR72-600) RECAT-EU wake category were used in the flight simulation campaign.

The trials were carried out with 27 type-rated pilots. 20 pilots were invited to participate in the Airbus A320 simulation campaign (Figure 2) and 7 pilots participated in the ATR72-600 simulator campaign (Figure 3).

In total, each pilot participated in 36 runs (either arrival or departure): 18 as pilot flying and 18 as pilot monitoring. A within subject experimental design was applied so all pilots experienced all arrival and departures scenarios under ICAO and S-PWS wake separation schemes. The pilots were not aware about the separation (ICAO or PWS) and rated the encounter after each run with a pre-defined rating scale. Additionally, some of the scenarios were performed with and others without motion. Both cases were assessed separately. The difference between the S-PWS and ICAO WT schemes was emulated by using differences in modelled encounter severity, see Section 3.2.3.

Figure 24: AMST A320 simulator cockpit (inside view with operator and observer seat on left side and outside view on right side)

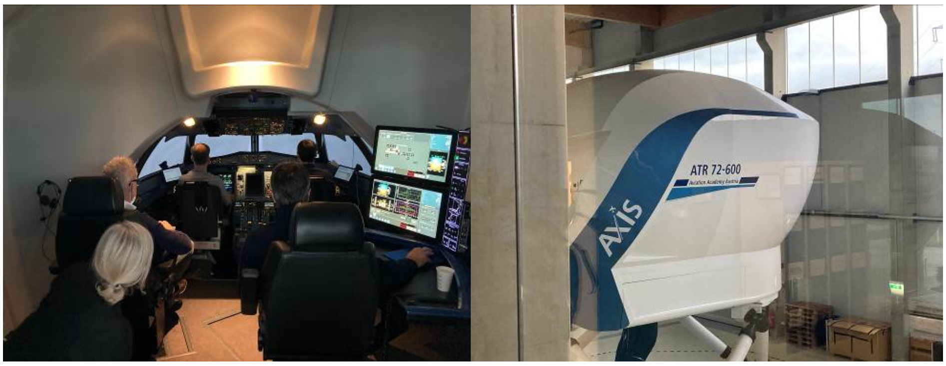

Figure 3: ATR72-600 simulator at Aviation Academy Austria

The pilots were able to rate each encounter and give short feedback notes after each run. At the end of each simulator session, a de-briefing took place where the pilots gave additional feedback.

3.4.2 Reference and Solution Scenarios

The scenarios simulated in terms of lead and follower aircraft (i.e., wake generator aircraft and wake encounter aircraft) were based on examples of where the greatest reduction of separation is proposed under S-PWS compared to the ICAO standard (based on 4 WT categories) category scheme, which was considered to be the ‘’worst case scenario”. Therefore, it was assumed that if a certain RMC increase due to separation reduction was considered acceptable for the aircraft types used in the simulation departure scenarios (i.e., amongst the pairs with larger separation reductions) it will also be acceptable to a different aircraft type where the reductions in separation under S-PWS compared to ICAO are smaller.

For the A320 simulations, it was chosen to simulate two types of aircraft pair:

- A320 with RECAT-20CAT CAT-B2 leader type (e.g., A330, B777) for which the separations are reduced from 5 NM to 3.5 NM in S-PWS-A and from 120 s to 90s in S-PWS-D;
- A320 with RECAT-20CAT CAT-C2 leader type (e.g., B767) for which the separations are reduced from 5 NM to 2.5 NM in S-PWS-A and from 120 s to 60s in S-PWS-D.

For the AT72-600 (AT76) simulations, a pair with RECAT-20CAT CAT-C2 leader type (e.g., B767) is selected for which the separations are reduced from 5 NM to 3 NM in S-PWS-A and from 120 s to 70s in S-PWS-D.

3.4.2.1 Reference scenarios

To address the above-mentioned objectives and to justify the reduction of departure separations through "equivalence" to arrival separation minima, the reference scenarios consisted of two approach scenarios based on different separation schemes (S-PWS and ICAO standard with 4 WT categories).

The most critical phase for a wake vortex encounter on final approach is close to the ground. Therefore, based on scenarios simulated in the WISA arrival campaign, the encounter was around 200ft AGL. Two wake encounter scenarios of different severity (levels of RMC) were assessed for arrivals. In both reference arrival scenarios, instrument approaches and landings were simulated at London Gatwick Airport (for Airbus A320 trials) and London Heathrow (for ATR72 trials). Furthermore, International Standard Atmosphere (ISA), Visual Meteorological Conditions (VMC) and no wind were simulated.

The simulation started while the aircraft was positioned on the ILS at 1000 ft AGL established in landing configuration with final approach target speed on localizer and glideslope. Landing checklist/clearance was assumed to be completed/obtained. From this position the pilot had to manually fly the approach to landing. The pilot was furthermore asked to try to land the aircraft, even if in an operational setting he would have initiated a go-around. As such, he was able to evaluate the severity by correcting for the disturbance. If the pilot was not able to perform the landing at all, he had to initiate a go around or call "STOP" and the simulator had been put in flight freeze.

After each run each pilot had to indicate whether he would have initiated a go-around in an operational setting and which factors played a role in this decision. The pilots have also been asked to rate the perceived severity of the encounter using the pre-defined rating scale, see Section 3.2.4, to enable comparisons between scenarios.

3.4.2.2 Solution Scenarios

The solution scenarios consisted of two departure scenarios based on different separation schemes, so that the increase in perceived wake encounter severity between ICAO standard for departure and S-PWS-D could be compared to the increase in perceived severity between ICAO standard for arrival and S-PWS-A:

In both, the S-PWS-D and ICAO solution scenarios, the wake encounter took place around 200 ft AGL. The simulation started while the aircraft was positioned on the runway. From this position the pilot had to manually fly the initial departure path. As with the arrival scenarios, the pilots were asked to rate the perceived severity of the encounter after each run using a pre-defined rating scale, to enable comparisons between scenarios.

In order to provide evidence that the reduced separations under S-PWS are acceptable to the flight crew based on pilot's perception of the impact severity of wake encounters experienced under S-PWS-D, feedback was obtained from the pilots regarding the acceptability of the WT impact experienced under S-PWS using post exercise questionnaires and debriefing forms.

3.4.3 WTE Severity Rating Scale

The WTE Severity Rating Scale below was presented and explained to the pilots during the pre flight simulation briefings. The pilots were asked to rate the severity of the wake vortex just encountered according to the definition prescribed therein.

Wake Encounter Severity Rating Scale		Pilot Rating	
Noticeable disturbance			
	Negligible pilot compensation required to maintain desired flight path.		①
Small disturbance			
	Light pilot compensation required to maintain desired flight path.	Minor	②
		Major	③
Large disturbance			
	Moderate pilot compensation required to maintain desired flight path or	Minor	④
ARR:	avoid ground contact (safe go-around possible)	Major	⑤
DEP:	avoid sink rate (safe climb out possible).		
Severe disturbance			
	Significant/maximum pilot compensation required to maintain desired flight path or	Minor	⑥
ARR:	avoid ground contact (safe go-around possible)	Major	⑦
DEP:	avoid sink rate (safe climb out still possible but TOGA Power required, comparable to wind shear recovery).		
Extreme disturbance			
	Maximum pilot control authority exceeded, inability to maintain desired flight path or		⑧
ARR:	avoid ground contact		
DEP:	avoid sink rate/ground contact.		

Figure 4: WTE Severity Rating Scale

3.5 Simulation Results

During the evaluation process, the recorded parameters and the severity ratings obtained from the pilots following each run related to ICAO and S-PWS scenarios have been analysed. Furthermore, the pilots were able to give short feedback after each run. The corresponding input was assessed accordingly. During the mission debriefings, the pilots were able to note additional statements with help of questionnaires, which has also been recorded and used for evaluation.

Because some of the scenarios were performed with and others without motion and since the motion has been seen to significantly affect the pilot's ratings, both cases were assessed separately.

The findings and conclusions identified during the evaluation process have been supported by extensive feedback and statement of expert pilots obtained during the preparation of the experiments, their execution and, of course, through targeted gathering of verbal feedback. In addition, through collection of expert feedback susbsequent to the simulation missions, important findings were obtained.

3.5.1 Flight data recordings

The flight data recordings were first analysed. As an example, the roll angles for the departure scenarios are depicted herein after.

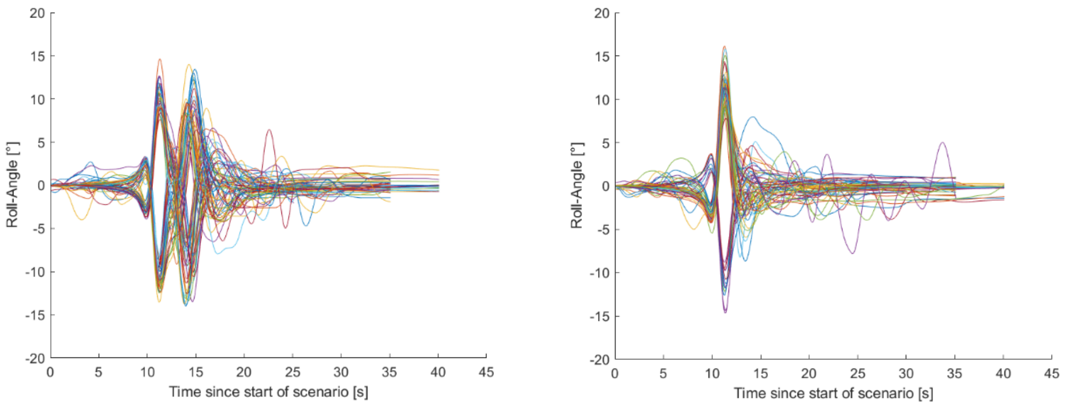

Figure 5: roll-angles over time for A320 PWS departure scenarios

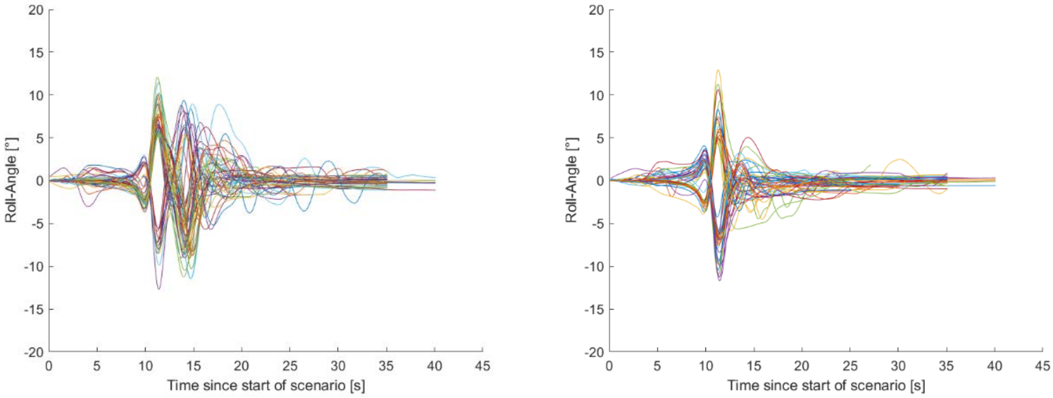

Figure 6: roll-angles over time for A320 ICAO departure scenarios

Figure 7 shows the roll-angles of the S-PWS-D scenarios over time, while Figure 8 shows the ICAO departure scenarios. The scenarios started at t=0 sec and the encounter took place 10 seconds after. The left figures show the encounter scenarios with two vortices whereas the right figures provide the encounter scenarios with a single vortex. After a bit more than 5 seconds the majority of roll-rates are back to a level as before the encounter. Even with an increase of the maximum roll-angles for the S-PWS scenarios the overall behaviour and the damping effects are very similar for S-PWS-D as well as ICAO scenarios.

Table 6 provides the average of maximum absolute value of roll angle for each scenario. As expected, all S-PWS arrival and departure scenarios lead to an increase of maximum roll angle compared to ICAO scenarios. Arrival and departure A320 scenarios lead to similar maximum roll whereas, for AT76 scenarios, larger roll angles are observed for departure compared to arrival cases.

	ICAO ARR	S-PWS-A	Δ ARR	ICAO DEP 1V	S-PWS-D 1V	Δ DEP 1V	ICAO DEP 2V	S-PWS-D 2V	Δ DEP 2V
CAT-B2-A320	9.3	11.9	2.6	9.7	11.5	1.9	10.2	11.7	1.5
CAT-C2-A320	7.2	11.4	4.2	6.6	11.6	4.9	8.0	11.3	3.3
CAT-C2-AT72	8.1	12.8	4.8	8.8	14.4	5.6	9.9	14.6	4.6

Table 6: Average maximum Roll angle for the various scenarios

3.5.2 WTE severity ratings

Table 7 provides the average of WTE ratings for each scenario. Globally, larger WTE ratings are observed for S-PWS scenarios, as expected. One also notes that the departure scenarios lead to lower WTE ratings, both for references and solutions. Finally, the departure scenarios with two vortices lead to larger ratings compared to those with single vortex encounter. It therefore appears that the worst case, and hence the design case for departure separation is the encounter with a vortex pair and not a single vortex.

	ICAO ARR	S-PWS-A	Δ ARR	ICAO DEP 1V	S-PWS-D 1V	Δ DEP 1V	ICAO DEP 2V	S-PWS-D 2V	Δ DEP 2V
CAT-B2-A320	3.7	4.6	**0.9**	2.4	2.9	**0.5**	3.2	3.4	**0.2**
CAT-C2-A320	3.1	4.4	**1.3**	1.6	2.7	**1.0**	2.5	3.3	**0.9**
CAT-C2-AT72	2.9	3.8	**0.9**	1.9	3.4	**1.4**	2.9	3.8	**0.9**

Table 7: Average WTE rating for the various scenarios

The results of the A320 simulation exercises (without motion) show that, when considering the mean WTE severity rating values, the increase in severity between the ICAO standard and S-PWS for all departure scenarios are overall lower than that the corresponding increase for arrival scenarios. Furthermore, in all cases, the departures WTE severity ratings at S-PWS-D minima are significantly lower compared to those at S-PWS-A minima and ranging from 2.7 up to 3.4, which corresponds to major small disturbance up to minor large disturbance. Note finally, that those lower ratings observed for departure cases compared to arrivals are obtained even if the input RMC are larger for departures.

The AT72-600 simulation exercise results vary more than the results from the A320 simulator trials. The S-PWS-D scenario with encounter of a vortex pair leads to an average increase of the severity rating equivalent to the increase when reducing from ICAO to S-PWS-A for the arrival cases and to a same level of severity. For the S-PWS-D scenario with single vortex encounter, the increase in WTE severity rating is larger compared to the arrival case. Yet, the absolute WTE severity value is below what is obtained for the arrival cases both for reference and solution scenario and below 'large disturbance' level. It should also be noted that only 7 pilots participated in the AT72-600 flight simulations as opposed to the 20 pilots for the A320 simulations. Therefore, those results are less converged from a statistical point of view.

3.5.3 Pilot Feedback

Based on the experts' extensive experience in piloting especially Light and Medium category aircraft, it was overall found that all WTEs experienced during the experiments were controllable without problems or did not raise any concerns about the safety of flight operation. In total, the WTEs appeared NOT to be more critical than regular turbulence encounters like atmospheric conditions (CAT, inversion, tropopause), special weather phenomena (top of clouds, thermals, thunderstorms in the vicinity, convective air layers, jet streams) or topographic conditions (mountain waves).

The subjective feedback gathered in the post simulation questionnaires and debriefs supported the wake severity rating findings. The pilot feedback from the debriefs following the A320 & AT76 exercise runs showed that overall, the simulated WTEs for both arrival and departure scenarios were easy to handle and would have caused no safety issue in real life. In addition, the pilots stated that overall, the severity of wake encounters during departures was less severe than the wake encounters on arrival. According to the pilots, this judgement could be based on the more critical situation during approach (closer to ground, reduced weight and speed, less engine power).

Overall, the pilots had no concerns regarding reduced separations during departures as proposed with S-PWS. Therefore, the reduced separations under S-PWS-D were considered acceptable to the pilots.

4 Conclusions

This paper describes the time-based static pairwise separation scheme for departures that has been developed by EUROCONTROL. The determination of those separation minima relies on the same methodology used to develop the time-based RECAT-EU departure scheme which has been approved by EASA [2]. This methodology defines the allowed time-based separation reductions/increases for departures compared to ICAO standard, based on the allowed distance-based separation reductions/increases allowed by distance-based static pairwise scheme compared to the ICAO distance-based separation scheme for arrivals. This methodology is based on the underlying assumption that the derived time-based S-PWS for departures do not lead to a wake turbulence encounter (WTE) severity increase greater than what has been justified for the S-PWS minima design for arrivals. This paper also describes a flight simulation campaign, named WISA (Wake Impact Severity Assessment), which was performed in order to further verify and validate this assumption.

Two full flight simulators (Level-D), representative of aircraft types of the upper medium (Airbus A320) and lower medium (ATR72-600) RECAT-EU wake category were used in the flight simulation campaign. The scenarios simulated in terms of lead and follower aircraft (i.e. wake generator aircraft and wake encounter aircraft) were based on examples of where the greatest reduction of separation is proposed under S-PWS compared to the ICAO standard, which was considered to be the ''worst case scenario". Realistic wake upset input functions were calculated and validated representative of reasonable worst-case conditions, relevant for wake separation design. After the successful validation of the simulator and wake input function, the trials were carried out with 27 type-rated pilots (20 pilots for the A320 simulations and 7 pilots for the ATR72-600 simulations). Each pilot performed 36 runs with different scenarios. The pilots were not aware about the separation (ICAO or PWS) applied in each scenario and rated the encounter after each run with a pre-defined rating scale. During the evaluation of the recorded parameters, the increase in severity rating between ICAO and S-PWS has been analysed.

From the analysis of pilot's perceived wake encounter severity of the various tested scenarios, several conclusions could be drawn.

i) Departure wake encounters (both at ICAO standard or at S-PWS minima) are on average rated as less severe for departure compared to arrival even if the rolling moment coefficient (and hence also the obtained maximum roll angles) are larger for departure.

ii) The S-PWS departure scenarios are on average rated below the scale of 4 defining the threshold of large disturbance, whereas some S-PWS arrival were rated on average above 4 (yet below 5).

iii) For departure scenarios, encounter of a vortex pair rather that a single vortex is always perceived as more severe and should thus be considered as worst case for wake separation design (also since this encounter geometry is realistic for wake encounter for departure).

iv) The increase in perceived severity when reducing separation from ICAO standard to S-PWS minima are larger or equal for arrivals compared to departures with a vortex pair, validating the assumption underlying S-PWS-D separation determination methodology.

The safety assessment and efficient deployment of S-PWS for departures will benefit from the further assurances from Pilots' perspective collected from this WISA flight simulation in terms of both the characterisation of the wake impact severity on departure and the acceptability from pilots' perspective in an operational context, of the risk transfer principles for WTE severity (associated with separation reduction) on departure against final approach phases of flight.

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6 Copyright Statement

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proceedings.

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