Time-Based Separation (TBS) Principles as Alternative to Static Distance-Based Separation for Final Approach

Safety Case report

Edition: 1.1
Edition date: 30-09-2020
Classification: Amber (Restricted to EUROCONTROL Stakeholders)
Issue: Released version

SUPPORTING EUROPEAN AVIATION

FOUNDING MEMBER SESAR JOINT UNDERTAKING

NETWORK MANAGER

DOCUMENT CONTROL

Document Title	Time-Based Separation (TBS) Principles as Alternative to Static Distance-Based Separation for Final Approach
Document Subtitle	Safety Case report
Document Reference	Released version
Edition Number	1.1
Edition Validity Date	30-09-2020
Classification	Amber
Accessibility	NMD/OPS/APT Unit drive
Status	Release Issue
Author(s)	Ivan De Visscher, Frédéric Rooseleer
Contact Person(s)	Vincent Treve, Frédéric Rooseleer

APPROVAL TABLE

The following table identifies all management authorities who have approved the present issue of this document.

Authority	Date	Signature
Prepared by: Ivan De Visscher (NMD PRISME)	25/09/2020	
Reviewed and endorsed by: Frédéric Rooseleer (NMD/OPS/APT)	29/09/2020	
Approved by: Robert Graham (Head Of Unit, NMD/OPS/APT)	30/09/2020	

EDITION HISTORY

Edition No.	Validity Date	Author(s)	Reason
0.1	03/12/2015	Ivan De Visscher, Frédéric Rooseleer	Initial draft
0.2	03/02/2016	Ivan De Visscher, Frédéric Rooseleer	Update draft following internal review
1.0	07/07/2016	Ivan De Visscher, Frédéric Rooseleer	Released issue for review
1.1	30/09/2020	Ivan De Visscher, Frédéric Rooseleer	Introduction of 'TBS margins based on total wind' following SESAR PJ02 results, and operational application modes

TABLE OF CONTENT

DOCUMENT CONTROL ..... **I**
APPROVAL TABLE ..... **I**
EDITION HISTORY ..... **II**
EXECUTIVE SUMMARY **8**
1. DOCUMENT INFORMATION **9**
1.1 Purpose of the document **9**
1.2 Scope of the document **9**
1.3 Intended readership **9**
1.4 Document structure **9**
1.5 Definitions **10**
2. INTRODUCTION **11**
2.1 Background **11**
2.1.1 Reference safety studies 11
2.1.2 Reasonable worst-case conditions for WT risk 11
2.2 Time-Based Separation (TBS) for final approach **12**
2.3 Scope of this safety case **13**
3. TBS PRINCIPLE AND SAFETY CRITERION **14**
3.1 TBS minima determination principle **14**
3.2 Time-To-Fly / Air speed profiles **14**
3.3 Time separation margins below TBS minima based on total wind (TBS margins) **15**
3.4 Traffic safety risk on final approach influenced by TBS replacing DBS **16**
3.4.1 Impact on wake turbulence risk 16
3.4.2 Impact on mid-air collision risk 16
3.4.3 Impact on runway collision risk 17
4. TBS WAKE VORTEX ENCOUNTER RISK ASSESSMENT AND DATA **18**
4.1 Safety criterion and metric for TBS wake turbulence risk assessment **18**
4.2 TBS Wake vortex encounter risk assessment for In-Ground/Near-Ground effect (IGE/NGE) **18**
4.2.1 Wake decay characterisation for HEAVY generators 18
4.2.1.1 EGLL-1 wake database 18
4.2.1.2 Vortex total circulation vs. LiDAR-measured vortex circulation 19
4.2.1.3 Correction for generation altitude 20
4.2.1.4 Correction of the LiDAR measured vortex age depending on headwind 21
4.2.2 Wake decay characterisation for MEDIUM generators 21
4.2.2.1 LFPG wake database 21
4.2.2.2 Computation of “Living time” 21
4.2.3 Wake vortex encounter risk assessment of TBS principles 24
4.2.3.1 Methodology 24

4.2.3.2 Risk assessment results for HEAVY-generated vortices 24
4.2.3.3 Risk assessment results for MEDIUM-generated vortices 30
4.2.3.4 Risk assessment results for vortices generated by other aircraft types 31
4.3 Wake vortex encounter risk assessment of TBS margins 31
4.3.1 Methodology 31
4.3.2 Risk assessment results for **HEAVY**-generated vortices 32
4.3.3 Risk assessment results for MEDIUM-generated vortices 40
4.3.4 Risk assessment results for vortices generated by SUPER-HEAVY aircraft types 48
4.4 TBS Wake vortex encounter risk assessment for Out-of-Ground Effect (OGE) long lasting wakes 49
4.4.1 OGE LiDAR database 50
4.4.2 OGE wake turbulence risk assessment 51
4.4.2.1 OGE wake decay depending on the wind 51
4.4.2.2 OGE wake transport depending on the headwind 53
5. OPERATIONAL APPLICATIONS 56
5.1 TBS with support delivery tool: operational application and experience 56
5.1.1 Application 56
5.1.2 London Heathrow TBS operation experience 56
5.2 Procedural Wind-Based Conditional Reduction of Separation: concepts and applications 57
5.2.1 Introduction 57
5.2.2 Examples of derived concepts 57
5.2.2.1 WINDSEP with shifted Separation Delivery Point 57
5.2.2.2 Wind-Based reduced distance separation delivery 58
5.2.3 Methodology for definition of local concept applicability conditions in support of local safety case 58
6. ASSUMPTIONS AND OPERATIONAL LIMITATIONS 59
6.1 Operational limitations log 59
7. CONCLUSIONS 60
ANNEX A TBS MINIMA EXAMPLES 62
A.1 TBS minima calculation method 62
A.2 Low wind time-to-fly database 62
A.3 Example of median TBS Minima for 96 follower aircraft types 65
A.3.1 Median TBS minima for RECAT-EU scheme 65
A.3.2 Median TBS minima for ICAO legacy scheme 71
REFERENCES 75
ABBREVIATIONS 77

TABLE OF FIGURES

Figure 1: Example of time separation evolution corresponding to a given distance when operating DBS (left) or TBS (right) in low or strong headwind conditions. 14
Figure 2: LIDAR scanning scheme and coordinate system at EGLL 19
Figure 3: Minimum and maximum measured lateral position in each dataset as function of the total wind 22
Figure 4: Example of selected track for further analysis (Dataset 1000) 23
Figure 5: Example of non-selected track due to last measured lateral position (Dataset 1000) 23
Figure 6: Comparison of the p 50 circulation evolution of vortices generated by a B744 in various wind conditions. 25
Figure 7: Comparison of the p 50 circulation evolution of vortices generated by an A346 in various wind conditions. 25
Figure 8: Comparison of the p 75 circulation evolution of vortices generated by a B744 in various wind conditions. 26
Figure 9: Comparison of the p 90 circulation evolution of vortices generated by a B744 in various wind conditions. 26
Figure 10: Comparison of the p 50 circulation evolution of vortices generated by various large HEAVIES in various wind conditions. 28
Figure 11: Comparison of the p 50 circulation evolution of vortices generated by various small HEAVIES in various wind conditions. 29
Figure 12: Comparison of the mean (left) and mean+ 1 sigma (right) of the living time evolution of MEDIUM-generated vortices in various headwind conditions. 30
Figure 13: Comparison of the median (left) and 90th percentile (right) living time evolution of MEDIUM-generated vortices in various headwind conditions. 30
Figure 14: Comparison of the p50 (left) and p75 (right) circulation evolution of vortices generated by A388 in various headwind conditions. 31
Figure 15: Case B744-A310: RMC statistics (p50, p75, p90 and number of samples) when applying a 10, 20 and 30 s reduced time separation as a function of the anemometer total wind compared to ICAO separations in low wind. The vertical lines show the wind threshold above which the p50 RMC is lower than that of the baseline. 32
Figure 16: Case B744-CRJ1: RMC statistics (p50, p75, p90 and number of samples) when applying a 10, 20 and 30 s reduced time separation as a function of the anemometer total wind compared to ICAO separations in low wind. The vertical lines show the wind threshold above which the p50 RMC is lower than that of the baseline. 33
Figure 17: Case A30B-B764: RMC statistics (p50, p75, p90 and number of samples) when applying a 10, 20 and 30 s reduced time separation as a function of the anemometer total wind compared to ICAO separations in low wind. The vertical lines show the wind threshold above which the p50 RMC is lower than that of the baseline. 33
Figure 18: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total wind of 6 kts +/- 1 kt (red, top) and of 7 kts +/- 1 kt (red, bottom) compared to the baseline (blue)..... 41
Figure 19: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total wind of 8 kts +/- 1 kt (red, top) and of 9 kts +/- 1 kt (red, bottom) compared to the baseline (blue)..... 42
Figure 20: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total wind of 10 kts +/- 1 kt (red, top) and of 11 kts +/- 1 kt (red, bottom) compared to the baseline (blue)..... 43
Figure 21: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total

wind of 12 kts +/- 1 kt (red, top) and of 13 kts +/- 1 kt (red, bottom) compared to the baseline (blue) 44
Figure 22: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 6 kts +/- 1 kt (red, top) and of 7 kts +/- 1 kt (red, bottom) compared to the baseline (blue) 45
Figure 23: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 8 kts +/- 1 kt (red, top) and of 9 kts +/- 1 kt (red, bottom) compared to the baseline (blue) 46
Figure 24: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 10 kts +/- 1 kt (red, top) and of 11 kts +/- 1 kt (red, bottom) compared to the baseline (blue) 47
Figure 25: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 12 kts +/- 1 kt (red, top) and of 13 kts +/- 1 kt (red, bottom) compared to the baseline (blue) 48
Figure 26: Illustration of the required wind threshold for a 30 s reduction depending on the baseline time spacing 49
Figure 27: OGE LIDAR location 51
Figure 28: Wake circulation evolution depending on the headwind for large HEAVY (RECAT-EU Cat-B)- generated vortices 52
Figure 29: Wake circulation evolution depending on the headwind for HEAVY- generated vortices 53
Figure 30: Evolution of the percentage of remaining tracks in the LiDAR dataset of large HEAVY- (left) and HEAVY- (right) generated vortices depending on the headwind. 54
Figure 31: Example of LiDAR track stopped because of vortex transport outside of the scanning area 54
Figure 32: Evolution of the percentage of tracks not transported outside of the scanning area in the LiDAR dataset of large HEAVY- (top) and HEAVY- (bottom) generated vortices depending on the headwind. 55
Figure 33: REDSEP scheme: separation delivery at a displaced delivery point 57
Figure 34: Histograms of RADAR tracks collected per aircraft type and per airport ... 63
Figure 35: Example for some aircraft type of P50 of the Time-to-fly to 0.5 NM from runway threshold measured in low headwind conditions (<5 kts) in various airports and p50 of all data (blue) 64

TABLE OF TABLES

Table 1: Definitions 11
Table 2: Required surface total wind allowing time separation minima reduction depending on the leader aircraft type 15
Table 3: Number of tracks per aircraft type in the LFPG database 21
Table 4: Observed size of the scanning area 22
Table 5: Number of tracks for which living time is computed 23
Table 6: Colour code used in the maximum time reduction tables 33
Table 7: Summary of the anemometer total wind threshold required to allow a given vortex age reduction 34
Table 8: Allowed time reduction for each pair and for an anemometer total wind Tw =6 kts +/- 1 kt 35

Table 9: Allowed time reduction for each pair and for an anemometer total wind Tw =7 kts +/- 1 kt 35
Table 10: Allowed time reduction for each pair and for an anemometer total wind Tw =8 kts +/- 1 kt 36
Table 11: Allowed time reduction for each pair and for an anemometer total wind Tw =9 kts +/- 1 kt 36
Table 12: Allowed time reduction for each pair and for an anemometer total wind Tw =10 kts +/- 1 kt 37
Table 13: Allowed time reduction for each pair and for an anemometer total wind Tw =11 kts +/- 1 kt 37
Table 14: Allowed time reduction for each pair and for an anemometer total wind Tw =12 kts +/- 1 kt 38
Table 15: Allowed time reduction for each pair and for an anemometer total wind Tw =13 kts +/- 1 kt 38
Table 16: Allowed time reduction for each pair and for an anemometer total wind Tw =14 kts +/- 1 kt 39
Table 17: Total wind threshold required to allow a given time spacing reduction 40
Table 18: Operational Limitations log 59
Table 19: Number of flights per airport 62
Table 20: RECAT-EU WT distanced-based separation minima on approach and departure 65
Table 21: Example list of aircraft types assigned to RECAT-EU categories (Category names and letters are indicative) 66
Table 22: median time separations [s] for CAT-A to Cat-B followers 67
Table 23: median time separations [s] for CAT-C followers 67
Table 24: median time separations [s] for CAT-D followers 68
Table 25: median time separations [s] for CAT-E followers (1/2) 68
Table 26: median time separations [s] for CAT-E followers (2/2) 69
Table 27: median time separations [s] for CAT-F followers (1/2) 69
Table 28: median time separations [s] for CAT-F followers (2/2) 70
Table 29: ICAO PANS-ATM wake turbulence distance-based separation minima on approach and departure 71
Table 30: median time separations [s] for SUPER and HEAVY (1/2) followers 72
Table 31: median time separations [s] for HEAVY followers (2/2) 72
Table 32: median time separations [s] for MEDIUM followers (1/4) 72
Table 33: median time separations [s] for MEDIUM followers (2/4) 73
Table 34: median time separations [s] for MEDIUM followers (3/4) 73
Table 35: median time separations [s] for MEDIUM followers (4/4) 73
Table 36: median time separations [s] for LIGHT followers 74

Executive Summary

This document presents the safety case on Time-Based Separation principles on Final Approach ('TBS Principles) as alternative to Distance-Based Separation, focusing on wake turbulence risk.

Headwind conditions on final approach cause a reduction of the aircraft ground speed which results in increased time separation for each aircraft pair, hence reducing the landing rate.

By operating with TBS minima distribution, established from equivalent time to fly the distance minima in low wind conditions, the delivered time spacing distribution between aircraft on final approach will be maintained across headwind conditions.

This principle of replacing the distance-based minima by equivalent time-based minima in low wind conditions is here assessed from a wake turbulence risk perspective.

By introducing possible dynamic variation of DBS minima in function of head wind, with the application of fixed TBS minima between successive arrivals, some aircraft pairs will be exposed to different wake age compared to their current situation under distance-based separation scheme, and TBS may impact the wake strength that can be potentially encountered. Indeed, the headwind component transports the vortices toward the follower aircraft. When applying DBS, since the distance separation is maintained constant whatever the headwind condition, at first order the age of the vortex potentially encountered by the follower remains constant. On the contrary, when applying TBS in prevailing headwind conditions, because the time separation between the aircraft is maintained constant, the age of the vortex potentially encountered by the follower is reduced.

However, it is known from literature that, close to the ground, which constitutes the reference design case, the headwind enhances the wake vortex decay.

The wake turbulence encounter risk assessment presented in this safety case provides assurance that applying TBS minima converted from DBS minima are acceptably safe in principle due to the effect of wind on wake decay.

Furthermore, in case of strong wind conditions, the positive impact of the total wind on the wake decay allows for further reduction of the time separations even below the TBS minima. The allowed time separation reductions below TBS minima, called TBS margins, are also provided depending on the leader type and on the surface total wind condition.

The wake turbulence risk assessment is based on wake vortex data and operational traffic data, built on around 100.000 wake tracks collected by LiDAR technology at major European airports. The wake decay is characterised per generator aircraft type and compared between low wind and headwind conditions.

The statistics of (distribution of) TBS minima will need to be established on a local basis, based on local characterisation of the time-to-fly distribution for aircraft pairs on final approach. This will be supported by a EUROCONTROL Guidance material.

Example of TBS minima statistics obtained from speed profile measurements, and corresponding time-to-fly, are provided in Annex.

The operational application of TBS minima, with the display of equivalent distance to Air Traffic Controllers through a dedicated ATC separation delivery tool is not addressed in this safety case, and must be subject to a dedicated analysis, covering in particular the performance, accuracy and reliability of wind prediction, time-to-fly forecast and the ATC support tool. This will be supported by a EUROCONTROL Specification.

Procedural application of TBS as transitional step, without the use of a separation delivery tool, can also be developed and operated, on the basis of principles developed in this safety case.

1. Document information

1.1 Purpose of the document

This document presents the safety case on time-based separation minima for final approach to provide assurance that the principle of applying time intervals, established from equivalent time to fly the distance minima in low wind conditions, are acceptably safe from a wake turbulence risk perspective across headwind conditions.

Following the safety analysis of TBS concept developed as part of SESAR 06.08.01 project, including an assessment of wake turbulence encounter risk, and focusing on the TBS principle only, this safety case aims at confirming that the headwind effect on wake decay is sufficient to maintain acceptable risk of wake turbulence encounter across head wind conditions for arrival traffic on final approach spaced at time-based minima established from equivalent time to fly the distance minima in low wind conditions.

Example of TBS minima obtained from air speed profile measurements are provided in Annex.

This 'generic' safety case, is developed to support review and acceptance by appropriate Aviation Authorities, can be used by Air Navigation Service Providers as input to support local safety case covering TBS deployment which will address local TBS minima and the Air Traffic Services and system changes to enable TBS operations.

1.2 Scope of the document

The scope of this safety case addresses the wake turbulence risk assessment of TBS minima principle, established from equivalent time to fly the distance minima in low wind conditions, and applicable across head wind conditions.

The operational application of TBS minima with ATC support tool and local deployment with ATM system changes, are not addressed and remain to be subject to a complementary local safety assessment by the Air Navigation Service Provider.

1.3 Intended readership

This safety case report is intended to be used by the following organizations:

- EUROCONTROL Organization, Stakeholders and Partners
- EASA and Civil Aviation Authorities

1.4 Document structure

This report is structured as follows:

- Section 1 presents an introduction to the subject and document information
- Section 2 presents the TBS, background, concept and scope of this safety case
- Section 3 presents the TBS principles and safety criterion
- Section 4 presents the wake vortex encounter risk assessment and data for in-ground effect / near-ground effect and for out-of-ground effect (OGE) long lasting wakes
- Section 5 presents the possible operational applications with or without separation delivery tool
- Section 6 presents assumptions and operational limitations
- Section 7 presents the conclusions

The report is completed by a set of Appendices:

- Annex A presents examples of median TBS minima obtained from speed profile measurements

1.5 Definitions

Term	Definition
4 DME	This terminology is used to denominate a position on the final approach corresponding to 4 nautical miles from the runway threshold, where a DME is located.
Aircraft type	The aircraft types are identified as per list in ICAO Document 8643
Follower aircraft	An aircraft in a pair which can potentially encounter the wake turbulence of the lead aircraft
Γ_0	Initial (total) vortex circulation
Hazard	Any condition, event, or circumstance which could induce harmful effects (e.g. an accident).
In-Ground Effect (IGE)	IGE corresponds to the height above ground where wakes are influenced by the proximity of the ground, and the WV can rebound back to its generation altitude. The onset of ground effect occurs at a height of approximately half the generator aircraft wingspan.
Lead aircraft	An aircraft in a pair which generates wake vortex encounter hazard for the following aircraft
LiDAR	LiDAR (light detection and ranging) is a measurement technique that uses a laser to estimate the wake vortex position and strength in the scanning plane of the laser. Both WVs generated by an aircraft can be measured at the same time.
Near-Ground Effect (NGE)	NGE correspond to the height above ground where wakes start to be influenced by the proximity of the ground and this corresponds to the wake vortex generation altitude being of about one generator aircraft wingspan
Out-of-Ground Effect (OGE)	OGE corresponds to the height above ground where wakes are not influenced by the ground.
Wake turbulence (WT)	ICAO uses the term “wake turbulence” to describe the effect of rotating air masses generated behind the lifting surfaces of an aircraft. Wake turbulence mainly results from two counter-rotating wake vortices.
Wake vortex (WV)	The term used to describe the phenomenon of the rotating air masses which are generated when an aircraft wing is producing lift.
Wake vortex encounter (WVE)	A hazard occurring when an aircraft flies into the flow field of a wake vortex, or wake vortices, generated by a preceding aircraft, which can have various effects on the aircraft. These effects may range from a mild change in aircraft attitude through to impairment, or loss, of control of the encountering aircraft, and/or structural damage to the encountering aircraft. The consequences of WVE are a complex function of WV strength, WV structure, encounter geometry, altitude and the properties of the encountering aircraft. Can also be called wake turbulence encounter (WTE).

Term	Definition
WT scheme	A WT scheme should be understood here as a set of separations as a function of leader and follower aircraft categories and clear criteria of aircraft type allocation in to these categories

Table 1: Definitions

2. Introduction

2.1 Background

2.1.1 Reference safety studies

Safety cases on A380 WVE risk [4]and on B747-8 WV separation minima [5], submitted to and endorsed by ICAO, define reasonable worst-case conditions for wake turbulence risk assessment of separation minima, in particular a wake generation altitude of 1 generator wingspan.

In the framework of SESAR, TBS operational concept development and validation has been subjected to safety assessment studies, [13] and [15], which indicated that the wake turbulence risk remain acceptable with TBS principle.

2.1.2 Reasonable worst-case conditions for WT risk

The WT risk must be acceptable in all operating conditions, including the least favourable ones, which can reasonably be expected to occur.

As for previous changes to wake separation minima and accepted by regulation authorities on the basis of a safety case as referred in previous section, the wake turbulence separation minima are designed against the so-called reasonable worst-case (RWC) conditions, characterised by exposure to longest lasting wakes on final approach, as recognized design case for wake separation design.

For WT risk on approach, the reasonable worst-case situation for an arrival aircraft to encounter a WV can be defined by the following parameters for WV generation and evolution, and encountering aircraft recovery capabilities:

- weather conditions are such that the wake vortex is not transported by wind out of the flight corridor of the follower aircraft in case of in-trail arrivals to single runway;
- weather conditions affecting decay of wake vortex circulation, i.e., atmospheric turbulence and temperature stratification, are such that there is minimum decay of the wake vortex circulation (low wind, low turbulence, low stratification defined by criteria on agreed value1).
- the generator and follower aircraft are spaced at the separation minimum, since in this case the time for decay of wake vortex circulation is minimal;
- the follower aircraft encounters the wake vortex while flying close to the ground during its approach to landing. It is acknowledged that reportable wake turbulence encounters can also occur on the glide slope and especially at glide slope intercept during approach operations. Due to the missing interaction with the ground boundary layer the vortex strength is typically larger for identical separation distances under these circumstances. Nevertheless, these operational scenarios are regarded as less hazardous compared to encounters close to ground because more height above ground remains for counteracting the adverse effects of an encounter. The altitude of wake generation in RWC conditions is then defined as one wingspan of the generator aircraft.

[1] Turbulence Eddy Dissipation Rate (EDR) not above 2.10^{-3} m^2/s^3, Stratification Temperature Lapse Rate (N) not above $2.4.10^{-2}$ s^{-1} and total wind not above 5kt

- the encountering aircraft passes through or close to the centre of one vortex of the wake vortex flow field with a shallow horizontal encounter angle.
- especially in low wind conditions, the wake vortex potentially encountered close to the ground consists of a single vortex since the two rolled-up vortices of an aircraft wake are known to separate laterally when entering into interaction with the ground boundary layer.

These conditions have been already considered as representative of the reasonable worst case, in the previous developed safety cases on A380 WVE risk [4] and on B747-8 WV separation minima [5], submitted to and endorsed by ICAO.

The weather (atmospheric and wind) conditions corresponding to the reasonable worst-case were monitored by a large deployment of sensors controlling that the turbulence, stratification and wind remained into pre-agreed values as listed in the footnote.

2.2 Time-Based Separation (TBS) for final approach

Headwind conditions on final approach cause a reduction of the aircraft ground speed which results in increased time separation for each aircraft pair, a reduction of the landing rate, and a lack of stability of the runway throughput during arrival operations.

This has a negative impact not only the achieved capacity, but also the predictability of operations, time and fuel efficiency, and the environment (emissions). The impact on predictability for core hubs is particularly important at the network level. The service disruption caused by the reduction in achieved runway throughput compared to declared capacity in medium and strong headwinds has a significant impact on the overall network performance and is particularly exacerbated if this occurs on the first rotation of the day because of the impact on all the other rotations throughout the day.

The TBS concept is addressing this problem by enabling stable arrival runway throughput in all headwind conditions on final approach. This is achieved by stabilising the delivered time spacing between aircraft on final approach across headwind conditions. The objective of time-based separation is therefore to improve the landing rate resilience to headwind conditions on final approach through recovering the lost landing rate currently experienced when applying distance-based separations. The TBS concept involves changing the separation rules on final approach from distance-based separations to time-based separations.

The time intervals can be established from various distance-based separation schemes (e.g. ICAO provisions based on WT Categories, ICAO provisions based on WT Groups, RECAT-EU, RECAT-EU-PWS), using relevant air speed profiles measurements - function of the separation delivery point on final approach -, and must therefore be specified on a local basis.

Moreover, in case of strong wind conditions, the positive impact of the total wind on the wake decay allows for further reduction of the time separations even below the TBS minima. Those TBS margins depend on the total surface wind.

There will be a need to facilitate delivery to time based separation constraints by the final approach and tower controllers, with a support tool.

The European Regulation 716/2014 “PCP” requires deployment of Time-based Separation” at selected aerodromes, stating: “Time-Based Separation (TBS) consists in the separation of aircraft in sequence on the approach to a runway using time intervals instead of distances. It may be applied during final approach by allowing equivalent distance information to be displayed to the controller taking account of prevailing wind conditions. Radar separation minima and Wake Turbulence Separation parameters shall be integrated in a TBS support tool providing guidance to the air traffic controller to enable time-based spacing of aircraft during final approach that considers the effect of the headwind”

2.3 Scope of this safety case

The scope of this 'generic' safety assessment, applicable to any aerodrome, covers the wake turbulence risk assessment and acceptability of

- TBS minima principle, established from equivalent time-to-fly the distance minima in low wind conditions, and applicable across head wind conditions.
- Total wind effect on wake decay allowing separation below the TBS minima

Since these concepts can be, in a generic way, applicable on final approach down to runway threshold, the safety assessment will consider the wake turbulence risk on the whole final approach segment.

3. TBS principle and safety criterion

3.1 TBS minima determination principle

TBS consists in the separation of aircraft in sequence on the final approach to a runway using time intervals instead of distances.

The time-based separation minima are derived from the distance-based wake turbulence separation (DBS) minima in wind conditions when the achieved arrival capacity with the DBS rules are currently acceptable to busy capacity constrained arrival runway operations. From operational experience this is in low headwind conditions.

In given wind conditions, for a given aircraft type and for a given DBS minimum, due to the variability in aircraft flying speed, a time separation distribution is observed. When operating DBS, as headwind increases, this distribution is seen to be shifted towards larger values. This is illustrated in Figure 1.

The objective of TBS is to maintain equivalent time-separation distribution across headwind conditions, see Figure 1. This is achieved through a dynamic reduction of the applicable distance separation minima as the headwind increases.

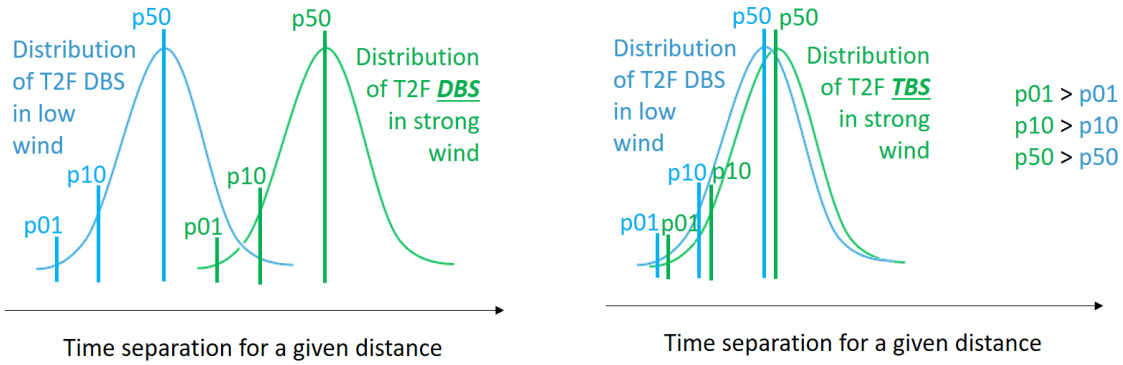

Figure 1: Example of time separation evolution corresponding to a given distance when operating DBS (left) or TBS (right) in low or strong headwind conditions.

The TBS minima rules are therefore established from the distribution of equivalent time-to-fly the distance minima in low wind conditions. When operating TBS, the obtained time-separation distribution must be aligned with the actual time-separation distribution observed in low wind conditions for the same aircraft type. This constraint can be verified through the comparison of quantiles, e.g. 1st, 10th and 50th (median) of the time separation distribution in low wind conditions.

The time interval statistics can be established from various distance-based separation schemes, using relevant speed profiles measurements - function of the separation delivery point on final approach -, and must therefore be specified on a local basis.

Example of TBS minima obtained from speed profile measurements are provided in ANNEX A .

3.2 Time-To-Fly / Air speed profiles

The standard reference wake turbulence separation minima for approach are historically expressed in distances, like to the reference ICAO or RECAT-EU provisions.

In a TBS scheme, the reference wake turbulence separation minima for approach are expressed in times corresponding to the times required for the aircraft to travel the reference distance separations in low wind conditions.

Moreover, for the WT risk assessment, the wake strength evolution (transport and decay) is always a function of time.

It is therefore necessary to properly convert the distance separation minima into the time for the following arrival aircraft to cover that distance.

For separation minima delivery on final approach applicable to runway threshold, this conversion should be done per aircraft type. Indeed, final approach speed profile varies between aircraft types and flight conditions. Different speed reduction on the glide and variation in stabilized final approach speed result in various time separations for a same distance separation.

Based on local time-to-fly (T2F) and approach speeds, TBS minima should therefore be locally established. In case of sufficient amount of data on an aircraft type to be able to determine its speed profile, TBS minima can be established and operated (with corresponding distance indication calculated with prevailing wind conditions and displayed to Approach and Arrival Runway Controllers), otherwise without these data, DBS should continue to be used.

For reference ICAO and RECAT-EU DBS schemes, examples of T2F for 96 frequent aircraft types, and resulting TBS minima for application on final approach down to runway threshold, are provided in ANNEX A .

These T2F are based on RADAR measurements and/or derived from EUROCONTROL Optimized Runway Delivery study (ORD) [14].

3.3 Time separation margins below TBS minima based on total wind (TBS margins)

In case of strong wind conditions, the positive impact of the total wind on the wake decay allows for further reduction of the time separations even below the TBS minima.

Extensive wake analysis, described in Section 4, led to define the allowed time separation reductions below TBS minima as a function of the pair type and the measured surface total wind. The obtained results are provided in Table 2. As an example, a total wind threshold of 8 to 9 kts is found to be required to ensure that a separation 15 s below TBS minima provides a wake encounter severity equal or below that found when applying DBS in low wind conditions.

Allowed time reduction	ICAO Medium Leader	ICAO Heavy and Super-Heavy Leader
5 s	6 kts	7 kts
10 s	8 kts	7 kts
15 s	9 kts	8 kts
20 s	11 kts	9 kts
25 s	N/A	10 kts
30 s	N/A	11 kts

Table 2: Required surface total wind allowing time separation minima reduction depending on the leader aircraft type

3.4 Traffic safety risk on final approach influenced by TBS replacing DBS

Since time-based separation minima are applicable on final approach and directly influence the traffic spacing on final approach, the following ATM traffic safety risk are relevant for assessment:

- Impact on wake turbulence risk;
- Impact on mid-air collision risk;
- Impact on runway collision risk.

3.4.1 Impact on wake turbulence risk

By introducing possible dynamic variation of DBS minima as a function of head wind, with the application of fixed TBS minima between successive arrivals, some aircraft pairs will be exposed to different wake age compared to their current situation under DBS wake turbulence category scheme application, and TBS may impact the wake strength that can be potentially encountered.

Indeed, the headwind component transports the vortices toward the follower aircraft. When applying DBS, since the distance separation is maintained constant whatever the headwind condition, at first order, the age of the vortex potentially encountered by the follower remains constant. On the contrary, when applying TBS in prevailing headwind conditions, because the time separation between the aircraft is maintained constant, the age of the vortex potentially encountered by the follower is reduced. However, it is known from literature that, close to the ground, which constitutes the design case, the headwind enhances the wake vortex decay.

The question to be addressed is hence: is this enhanced wake decay mitigating the effect of headwind transport blowing younger vortices toward the follower aircraft?

This would mean, in terms of wake turbulence risk, that the probability per approach of wake turbulence encounter of a given severity for a given traffic pair at TBS minima on final approach segment and for any headwind conditions must not increase compared to the same traffic pair spaced at DBS minima in reasonable worst conditions recognized for WT separation design.

In terms of impact on overall probability of wake vortex encounter, the impact can be expected to be limited and around 5 to 10% potential increase, since:

- In low wind, there will be no difference between TBS and DBS in terms of risk exposure (since in low wind the TBS spacing are by definition equal to the DBS),
- In moderate to strong headwind, there might be an increase due to the exposure to younger wakes, however in those conditions the wind impacts both the wake decay and transport, limiting the overall risk of wake vortex encounter

WVE reports statistics from a major European airport show that about 15% of WVEs are reported under moderate to strong headwind conditions. If the encounter probability increases by, e.g., 50% under these moderate to strong headwind conditions, this then represents an overall increase between 5 and 10%.

However, NATS UK has reported that the operational use of TBS at London Heathrow has delivered significant arrival throughput and performance benefits, and this has all been achieved without any increase in reported wake vortex encounters or go-arounds.”

3.4.2 Impact on mid-air collision risk

The ATC operational application (i.e. separation delivery) based on TBS minima might potentially lead traffic to be spaced closer than the local provisions set for airborne surveillance distance separation minima (e.g. during final approach interception phase), hence affecting mid-air collision

risk on approach. This potential impact on mid-air collision risk will need to be addressed as part of the (local) safety case about local ATC operations based on TBS minima.

3.4.3 Impact on runway collision risk

TBS minima, as well as the ATC application (i.e. separation delivery) based on TBS minima, will need to be established and operated such that these are compatible with local runway occupancy times (ROT).

The impact on runway collision risk will need to be addressed as part of the (local) safety case about local ATC operations based on local TBS minima where, in particular ensuring compatibility with runway occupancy times (ROT).

4. TBS Wake vortex encounter risk assessment and data

4.1 Safety criterion and metric for TBS wake turbulence risk assessment

Considering the previous elements, the following safety criterion is formulated:

the probability per approach of wake turbulence encounter of a given severity for a given traffic pair at TBS minima on final approach segment under any headwind conditions shall not increase compared to the same traffic pair spaced at DBS minima in reasonable worst conditions recognized for WT separation design.

The wake vortex encounter risk related to the application of TBS is therefore evaluated by the comparison of the potential encounter severity in strong headwind conditions to that in low headwind conditions and for the same separation time.

Since the TBS application should be valid for any aircraft pair, the severity is here only characterized by the strength of the leader-generated vortices at any possible time separation.

4.2 TBS Wake vortex encounter risk assessment for In-Ground/Near-Ground effect (IGE/NGE)

The objective of this section is to show the effect of the headwind on the vortex decay close to ground allowing the safe application of the TBS concept.

4.2.1 Wake decay characterisation for HEAVY generators

4.2.1.1 EGLL-1 wake database

The EGLL-1 LiDAR wake measurement database is used to characterise the wake decay on approach. The EGLL-1 measurement campaign started in October 2008 and ended in December 2010.

The LiDAR, a Lockheed-Martin “WindTracer” equipment owned by EUROCONTROL, was installed at London Heathrow, at about 1200 m from the 27L and 27R runway thresholds. The scanning plane was selected to capture NGE/IGE altitude for ICAO HEAVY category aircraft types.

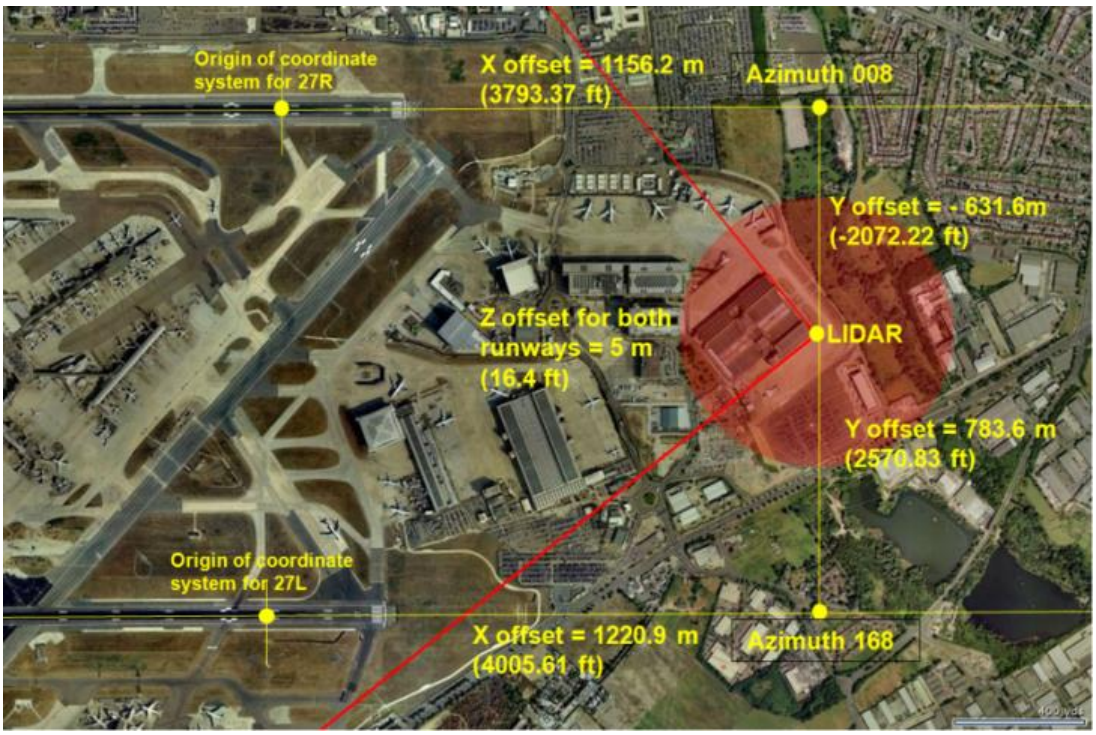

Figure 2: LIDAR scanning scheme and coordinate system at EGLL

In total, the database contains 121,636 tracks (among which 54,516 HEAVY and 66,237 MEDIUM in the sense of ICAO WT categories).

Some processing of the database was performed to obtain the wake vortex decay curves. This processing includes a fitting technique allowing a smoothing of the circulation decay curves.

The WV measurement fitting process for decay is described in [11] and [12].

All measurements were conducted in the same scanning plane and for the same generation altitude of around 80m.

4.2.1.2 Vortex total circulation vs. LiDAR-measured vortex circulation

The relevant WV circulation to be used as input for the computation of the severity metric is the total circulation (Γ_{tot}). Because of the LMCT LiDAR processing used to obtain the circulation (using a match filter algorithm with MF_ALPHA=2 see [6], [7] and [8]), a correction that depends on the generator span is applied to compute the total circulation Γ_{tot} from the partially averaged circulation as output by the LiDAR algorithm. The correction function corresponds to that used to obtain the total circulation from the $\Gamma_{5\text{-}15}$ and assuming a Proctor-Winckelmans distribution, scaling with the generator aircraft wing span (i.e., larger aircraft generate vortices with a more “spread” circulation distribution) (see [18]).

This correction function has been verified against the LiDAR experimental data using additional post-processed data from the same database using various MF_ALPHA values ranging from 2.5 to 5.0 and for various HEAVY aircraft types (applying an identical dimensional size for the modelled vortex in the LiDAR post-processing algorithm would lead to an error on the total circulation estimate that varies with the generating aircraft span) (see [19]).

For a relative safety assessment as that performed for TBS, the correction function to obtain the total circulation from the LiDAR processed circulation is verified to be consistent with that one obtains from additional data post-processing using other parameters in the vortex detection algorithm.

4.2.1.3 Correction for generation altitude

For separation design, it has been agreed that the wake vortex encounter risk is evaluated for wakes generated at one generator wingspan altitude. The wake measurements should hence be in a LiDAR scanning plane crossing the glide at one wingspan altitude (which is different from aircraft type to aircraft type) for capturing the reasonable worst-case conditions for in-trail wake vortex encounters.

However, for practical reason, all measurements were conducted in the same scanning plane and for the same generation altitude of 80m. In order to properly capture the reasonable worst case, the bias introduced by the scanning fixed altitude has to be corrected.

For aircraft with wing span smaller than 80m, the time needed for the wake to sink down to the generation altitude corresponding to the reasonable worst case (one wingspan) can be calculated.

During this time, the wake is considered as “out of ground effect” and the decay rate is significantly lower than in ground effect (below one wingspan altitude). The effect on the decay curve is an artificial extension of the low decay phase. This would tend to under estimate the decay rate in the reasonable worst case. This underestimation will be particularly significant for smaller Heavy aircraft for which 80 m may correspond to more than 1.5 wingspans. This difference of effect as a function of the aircraft span is particularly sensitive for the relative assessment if not properly corrected.

In order to compensate that bias in the analysis, the decay curves of all aircraft were shifted by a time corresponding to the time needed for reaching the one wing span altitude.

4.2.1.4 Correction of the LiDAR measured vortex age depending on headwind

For strong headwind conditions, an error is made on the vortex age measurement when measuring in a fixed 2-D scanning plane using a LiDAR. This error is here corrected to obtain a characterization of the vortex decay as a function of its age.

In case of headwind, younger vortices, generated by the aircraft after it crosses the measurement plane, are blown towards the measurement plane. The LiDAR provides measurement as a function of time w.r.t. the time at which the aircraft crosses the scanning plane. The vortex age t can be derived from the time measured by the LiDAR t_{LiDAR} by multiplied it by a correction function that depends on the headwind and on the generating aircraft speed:

$$t = t_{LiDAR}\left(1 - \frac{Hw}{V_{app}}\right)$$

One notes that the correction function is larger for stronger headwind values (as expected) and for slower flight speed. For the current project, the correction has been applied using the 10m anemometer *Hw* measurement, as an estimate of the headwind experienced by the vortices, and the final approach speed V_{app}, determined per aircraft type.

4.2.2 Wake decay characterisation for MEDIUM generators

4.2.2.1 LFPG wake database

The LFPG LiDAR wake measurement database is used to characterise the wake decay on approach for MEDIUM-generated vortices.

The analysis is based on LiDAR measurements of wake vortices generated by large MEDIUM aircraft types (i.e., A320 family and B737 NG family) measured at Paris-CDG (LFPG), between May and December 2007 (using the Lockheed-Martin “WindTracer” equipment owned by EUROCONTROL).

The database is composed of three datasets with varying scanning area. The datasets are numbered 1000, 1100 and 1300. The number of tracks for the aircraft of interest are reported in Table 3. One notices that the tracks from A320 family represent 77% of the total number of tracks, whereas the tracks from B737NG family represent 3% of the total number of tracks.

Ac type/ Dataset	“1000”	“1100”	“1300”	Combined	Percentage
A320	10653	11108	11217	32978	77%
B737NG	406	462	478	1346	3%
A320+B737NG	**11059**	**11570**	**11695**	**34324**	**80%**
All aircraft types	13659	14283	14805	42747	100%

Table 3: Number of tracks per aircraft type in the LFPG database

In what follows, only the B737-NG- and the A320-generated vortices are used for further analysis.

4.2.2.2 Computation of “Living time”

LiDAR circulation measurements of MEDIUM-generated vortices are less reliable due to the smaller size and lower induced velocity values compared to HEAVY-generated vortices. As pointed out in the literature (see e.g., [20][21]) the circulation measurement of MEDIUM-generated vortices are subjected to bias.

Consequently, the analysis that follows is based on the “living time” of the vortex and not on its LiDAR measured circulation.

The size of the scanning area is first evaluated based on the range of lateral positions measured in each dataset. The results are provided in Figure 3. Based on these results, the scanning area extents (absolute value rounded up to the closest 10 m) are evaluated and reported in Table 4.

Dataset	1000	1100	1300
Min [m]	-1530	-1220	-650
Max [m]	710	980	1590

Table 4: Observed size of the scanning area

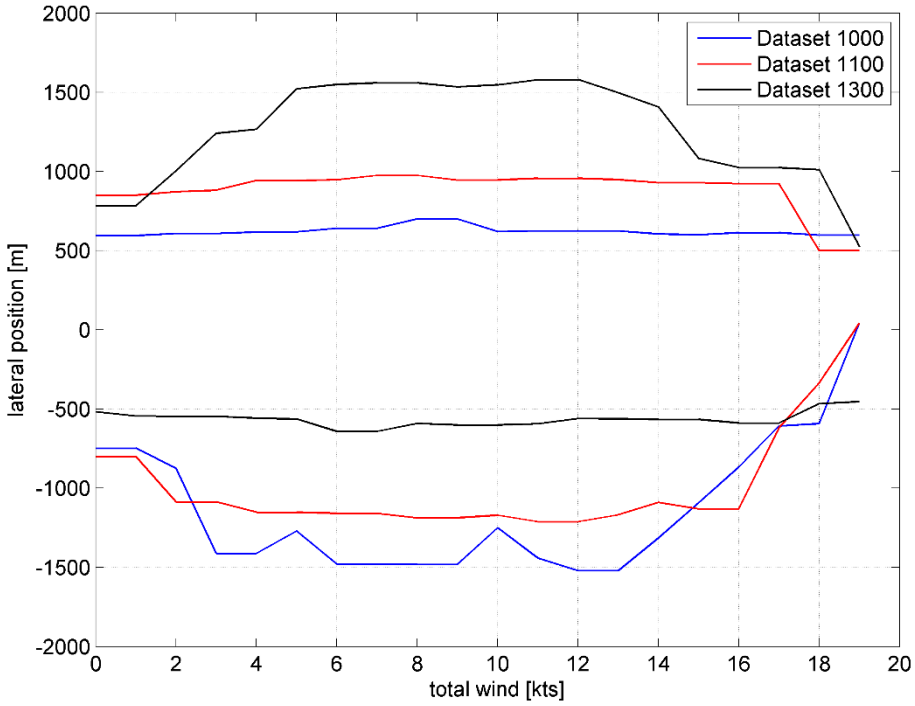

Figure 3: Minimum and maximum measured lateral position in each dataset as function of the total wind

The living time (expressed as a percentage) is then computed for each LiDAR track by defining t_{living}=100% at the first measurement point and t_{living}=0% at the first time at which the vortex is no longer measured because of its decay. A linear evolution of the living time is then assumed between those two times. To find the time corresponding to t_{living}=0%, we consider that the vortex is sufficiently decayed when:

- it should still be in the scanning area (i.e. the extrapolated lateral position after the last measured points is still within the scanning area +/- 100 m);
- its last measured circulation is sufficiently low (i.e. the last measured circulation is below or equal to 130 m²/s).

Examples of selected and non-selected tracks are provided in Figure 4 and Figure 5.

The number of remaining useable tracks in each dataset is provided in Table 5.

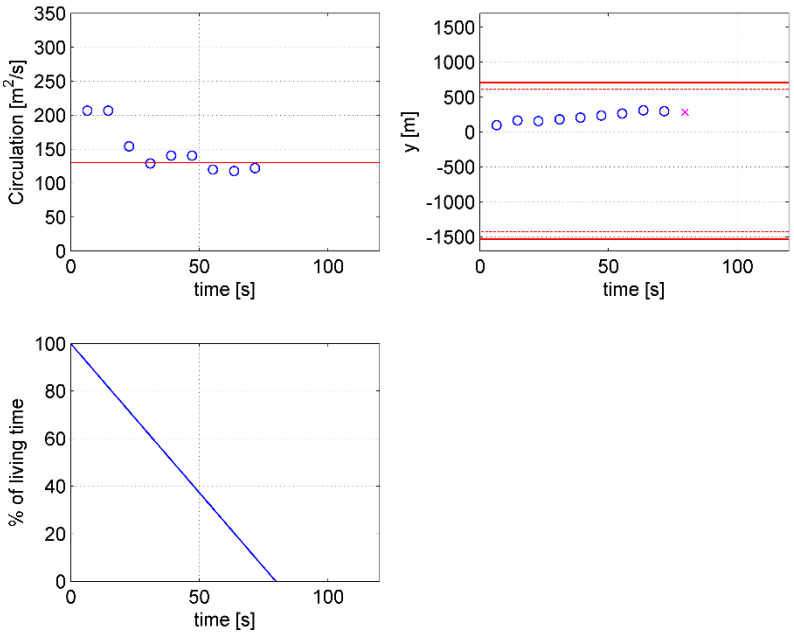

Figure 4: Example of selected track for further analysis (Dataset 1000)

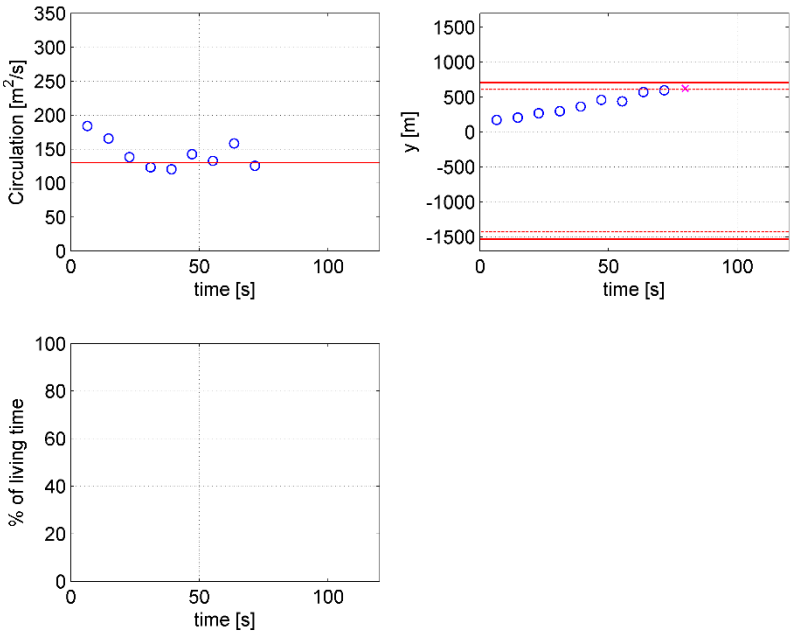

Figure 5: Example of non-selected track due to last measured lateral position (Dataset 1000)

Dataset	1000	1100	1300	Combined
Number of selected tracks	4983	5051	4528	14562

Table 5: Number of tracks for which living time is computed

4.2.3 Wake vortex encounter risk assessment of TBS principles

4.2.3.1 Methodology

The headwind component transports the vortices toward the follower aircraft. When applying DBS, since the distance separation is maintained constant whatever the headwind condition, at first order the age of the vortex potentially encountered by the follower remains constant. On the contrary, when applying TBS in prevailing headwind conditions, because the time separation between the aircraft is maintained constant, the age of the vortex potentially encountered by the follower is reduced. However, it is known from literature that, close to the ground, which constitutes the design case, the headwind enhances the wake vortex decay. The question addressed in this section is hence: Is this enhanced wake decay mitigating the effect of headwind transport blowing younger vortices toward the follower aircraft?

The wake vortex encounter risk related to the application of TBS is evaluated by the comparison of the potential encounter severity in strong headwind conditions to that in low headwind conditions and for the same separation time.

Since the TBS application should be valid for any aircraft pair, the severity is here only characterized by the strength of the leader-generated vortices at any possible time separation. The follower characteristics (i.e., span, flight speed, aspect ratio, size of the vortex compared to the wing span) that have to be taken into account in a wake encounter severity metrics are indeed unchanged in TBS compared to DBS and can hence be neglected. The strength of the vortices are characterized by the circulation for HEAVY-generated vortices and by the vortex living time for MEDIUM-generated vortices, for the reasons detailed above.

When using LiDAR measurements, the time is measured w.r.t. the time at which the aircraft has crossed the scanning plane. Hence, the measured LiDAR wakes directly correspond to those a follower could encounter for a given time separation between two aircraft, and equal to the LiDAR-measured “vortex age”.

4.2.3.2 Risk assessment results for HEAVY-generated vortices

For each leader HEAVY aircraft for which sufficient LiDAR measurements are found in the EGLL database, and for various headwind (HW) values ranging from 5 kts to 20 kts, by step of 5 kts the statistics (50^{th}, 75^{th} and 90^{th} percentiles) of the circulation are computed.

In order to obtain more statistically converged results, for each headwind value HW, all tracks for which the headwind was measured within a range HW +/- 1kt are used.

The baseline corresponds to the tracks for which the measured headwind was below 5 kts.

The vortex circulation statistics are then compared for time separations ranging from 46 to 173 s (i.e., time covering all time separations corresponding to longitudinal distance separation minima on approach behind HEAVY aircraft).

Figure 6 and Figure 7 provide comparisons of the p50 (i.e. 50^{th} percentile=median) circulation evolution for the B744 and A346.

One observes the expected effect of the headwind on the vortex decay allowing the safe application of TBS concept.

For each case presented (each leader type and each wind condition), the number of tracks available in the database is also provided in the legend (N value).

One notes that as the wind increases, since the tracking rate is reduced, the number of tracks drastically decreases, making complicated fine statistical analysis (such as the p90 computation).

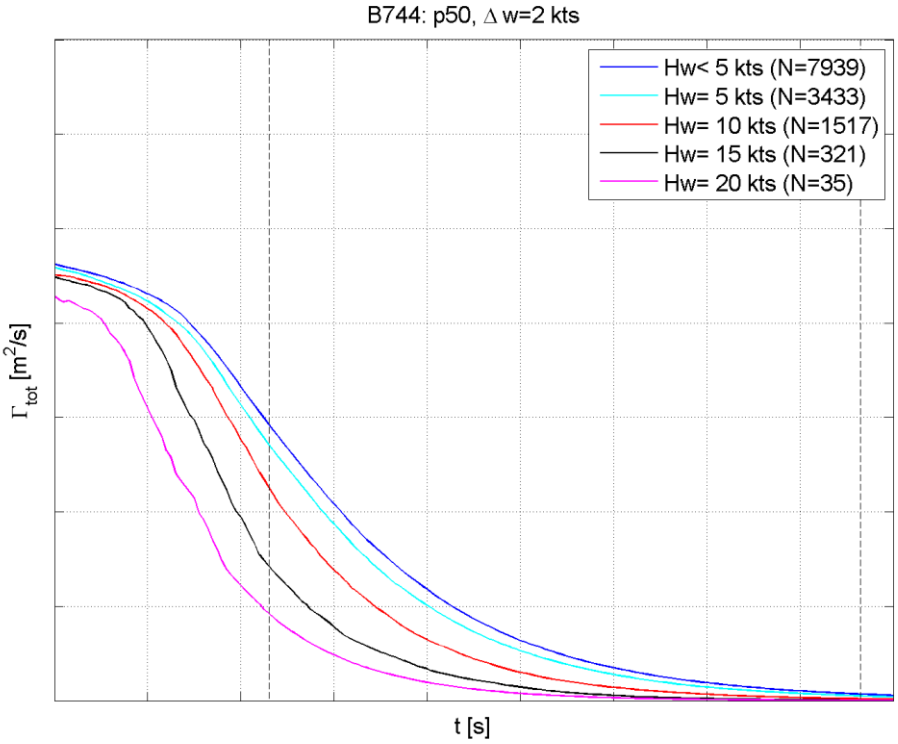

Figure 6: Comparison of the p 50 circulation evolution of vortices generated by a B744 in various wind conditions.

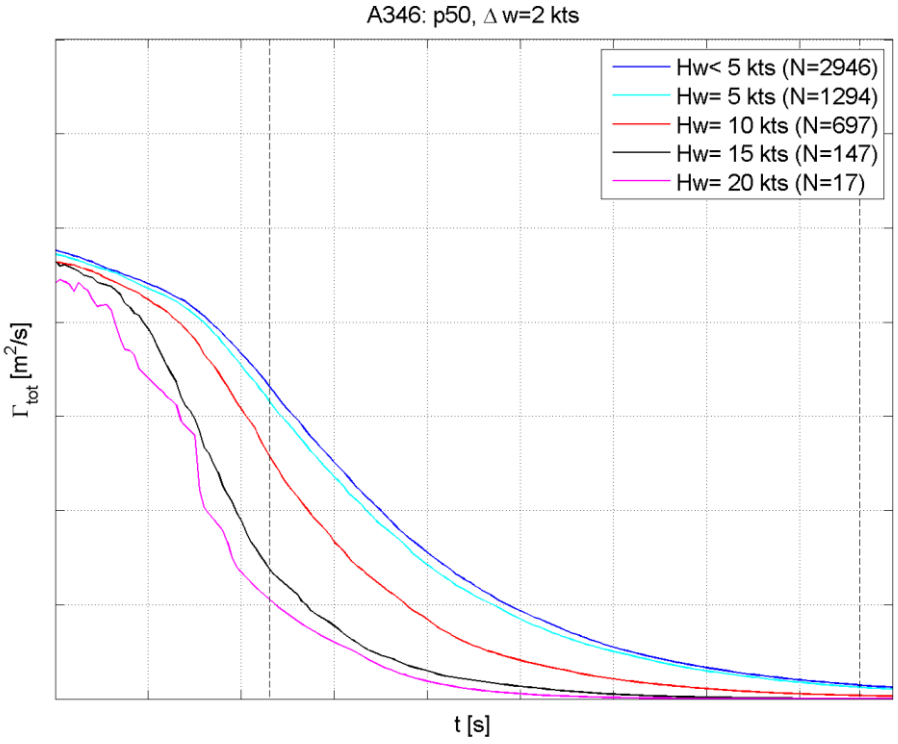

Figure 7: Comparison of the p 50 circulation evolution of vortices generated by an A346 in various wind conditions.

Figure 8 and Figure 9 show that this behaviour is also observed when comparing the p75 or p90 circulation evolutions.

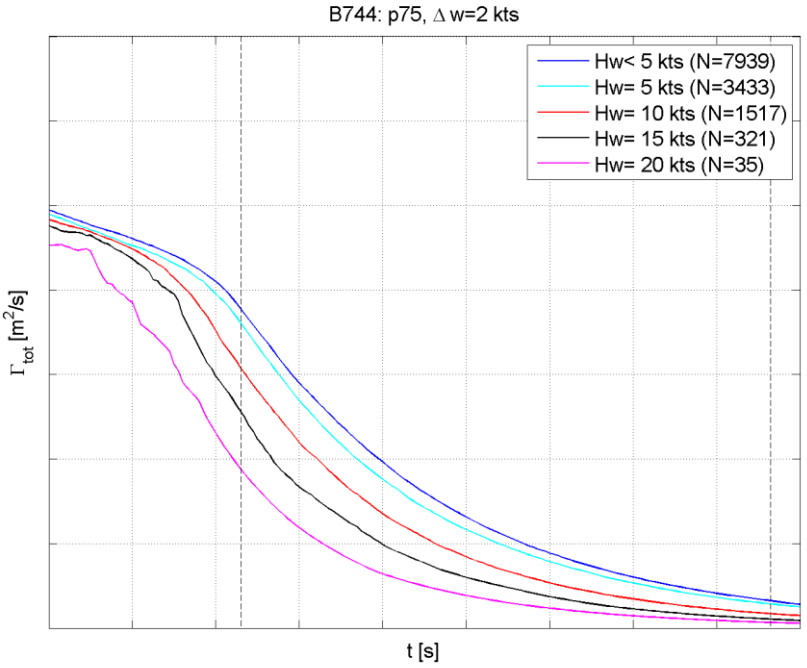

Figure 8: Comparison of the p 75 circulation evolution of vortices generated by a B744 in various wind conditions.

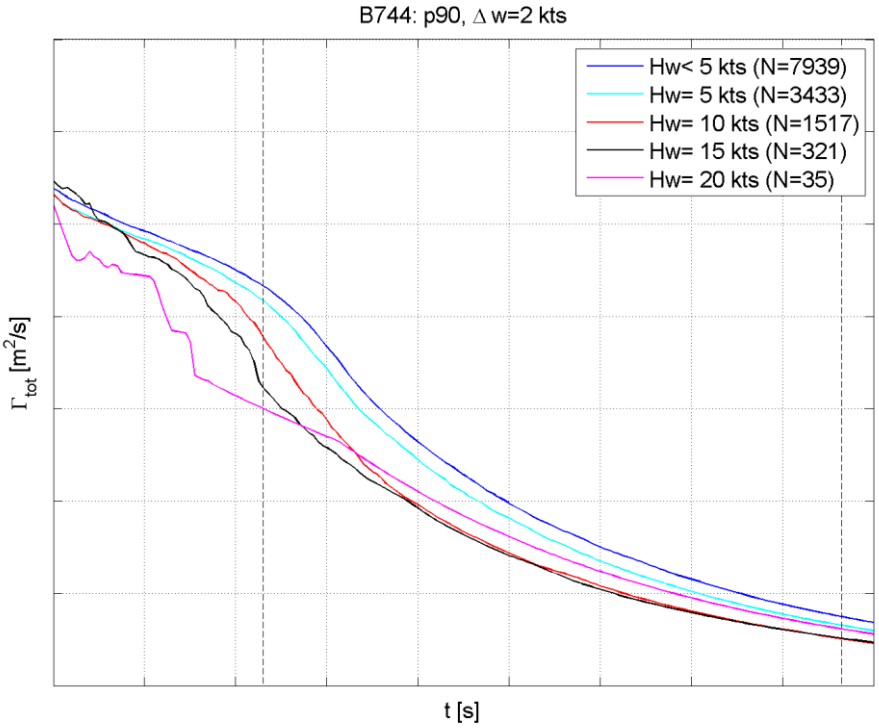

Figure 9: Comparison of the p 90 circulation evolution of vortices generated by a B744 in various wind conditions.

Finally, and for completeness, the comparison of the p50 circulation evolutions are provided in Figure 10 and Figure 11 for all generating HEAVY aircraft for which sufficient data are available in the EGLL database.

It is to be noted that due to the too low number of data for some of these aircraft, the comparison of the p90 circulation evolution cannot be performed and is hence not presented here.

Based on this analysis, it is shown that close to the ground (i.e., at one generator wing span altitude), which constitutes the design case, the headwind enhances the wake vortex decay mitigating the effect of headwind transport blowing younger vortices toward the follower aircraft.

This behaviour is observed, without distinction, for all HEAVY (i.e. RECAT-EU Cat-B and Cat-C) aircraft for which sufficient number of data are available. It is hence expected that the headwind will have the same effect on decay for SUPER- (i.e. RECAT-EU Cat-A) and for MEDIUM-generated vortices.

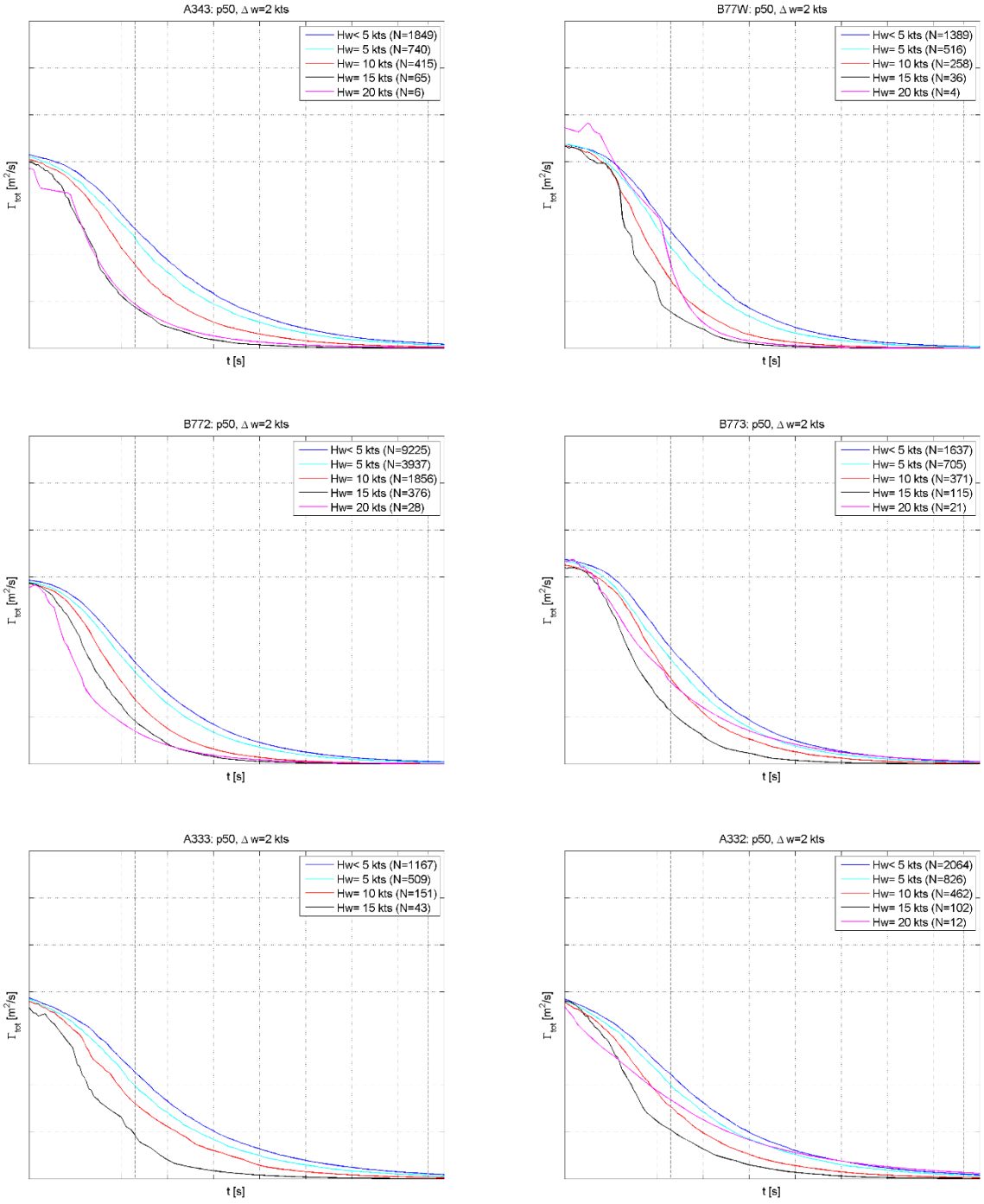

Figure 10: Comparison of the p 50 circulation evolution of vortices generated by various large HEAVIES in various wind conditions.

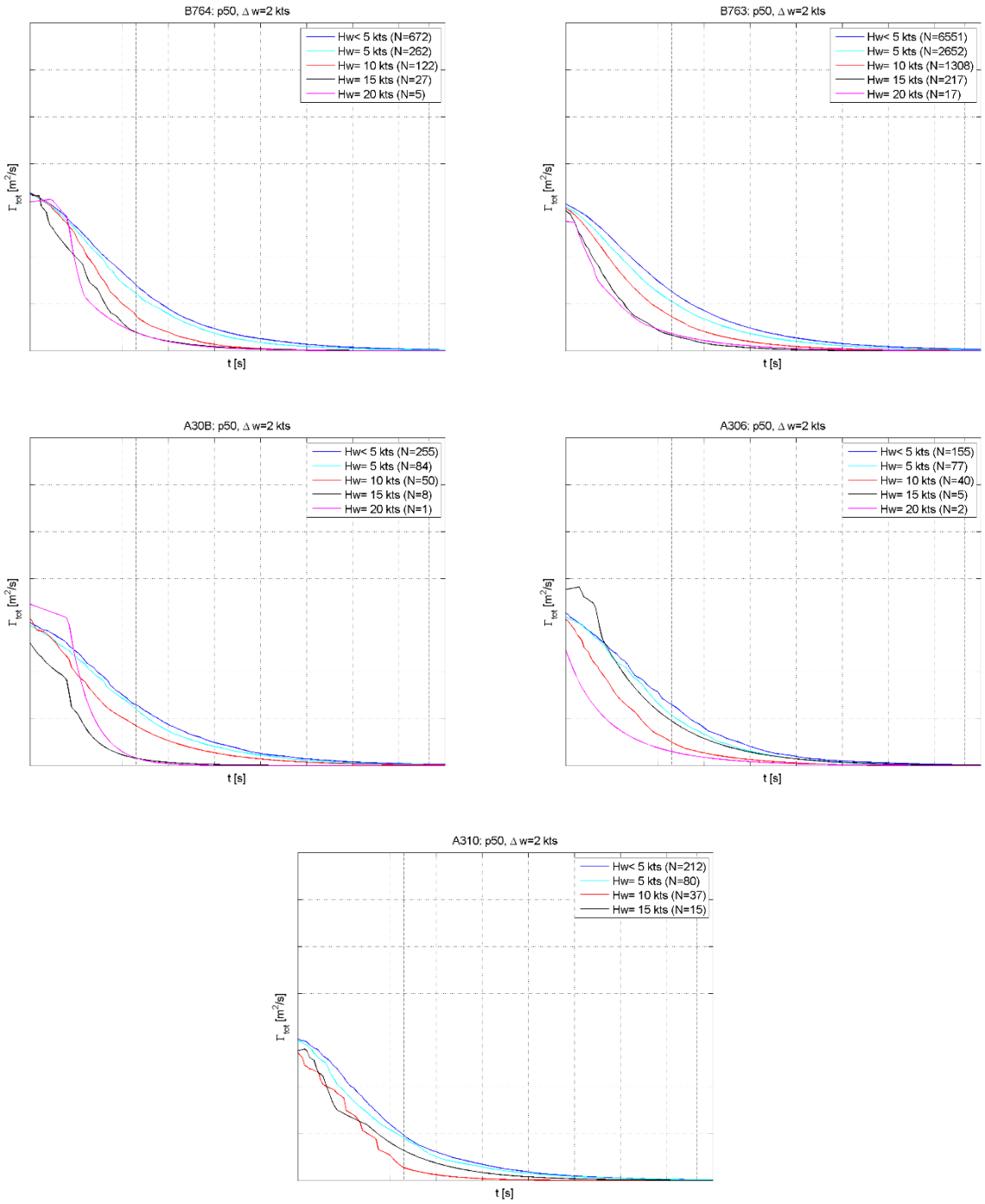

Figure 11: Comparison of the p 50 circulation evolution of vortices generated by various small HEAVIES in various wind conditions.

4.2.3.3 Risk assessment results for MEDIUM-generated vortices

The same type of analysis as that performed in Section 4.2.3.2 is here performed for MEDIUM leaders. The main differences are:

- the living time is used as wake encounter severity since the wake circulation cannot be reliably obtained from LiDAR measurements of MEDIUM-generated vortices;
- the time separations to be considered behind MEDIUM leaders are smaller.

Using all tracks of large-MEDIUM-generated vortices, and for various headwind values HW ranging from 5 kts to 20 kts by step of 5 kts, the statistics (mean, standard deviation, 50th and 90th percentiles) of the living time are computed. In order to obtain more statistically converged results, for each headwind value HW, all tracks for which the headwind was measured within a range HW +/- 1kt are used. The baseline corresponds to the tracks for which the measured headwind was below 5 kts.

Figure 12 provides the temporal evolution of the mean and mean plus one standard deviation (sigma) depending on the headwind, for time separations up to 120 s. Figure 13 provides the same results in terms of 50th (p50) and 90th (p90) percentiles. As for Heavy-generated vortices, the headwind effect on wake decay is seen to mitigate the transport of younger vortices toward the scanning plane. For all separation times, the living time curves for headwind values above 6 kts are indeed seen to be below the baseline curve, in terms of mean, mean + one standard deviation, median and 90th percentile.

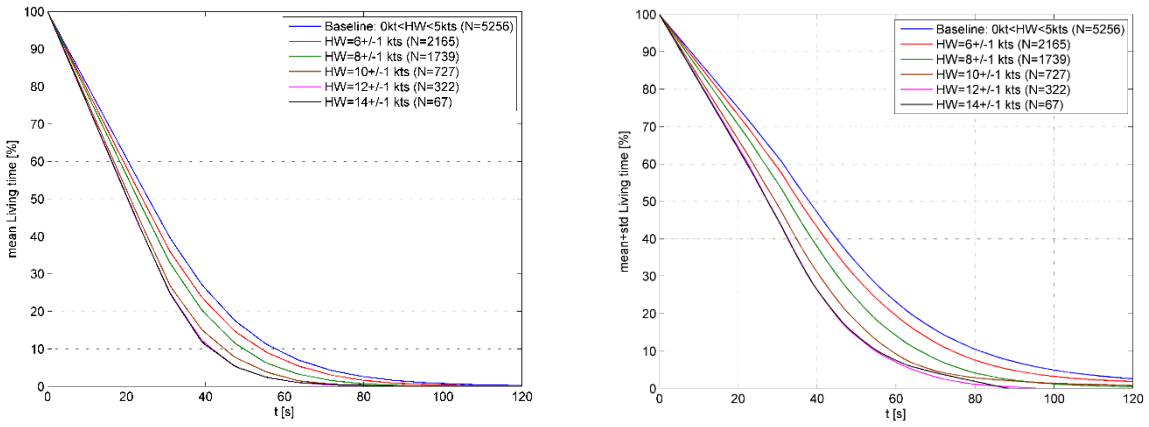

Figure 12: Comparison of the mean (left) and mean+ 1 sigma (right) of the living time evolution of MEDIUM-generated vortices in various headwind conditions.

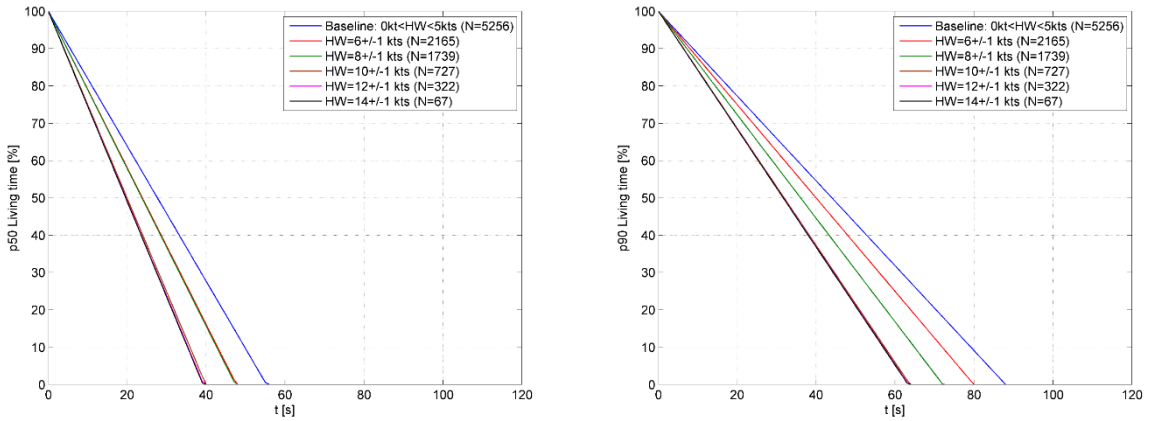

Figure 13: Comparison of the median (left) and 90th percentile (right) living time evolution of MEDIUM-generated vortices in various headwind conditions.

4.2.3.4 Risk assessment results for vortices generated by other aircraft types

It was shown in the previous sections that, close to the ground (i.e., at one wing span altitude), which constitutes the design case, the headwind enhances the wake vortex decay mitigating the effect of headwind transport blowing younger vortices toward the follower aircraft.

This was observed, without distinction, for all HEAVY- (Cat-B and Cat-C) and MEDIUM- generated vortices for which sufficient number of data are available.

It is concluded that the headwind will have the same effect on decay for vortices generated by any aircraft type, including SUPER HEAVY and LIGHT aircraft types.

This last part is further verified using a dataset of LiDAR measurements collected at another airport outside ECAC between September and November 2014 for vortices generated by A388 and evolving in ground proximity. The same post-processing methodology, described in Section 4.2.1, is here applied to the DXB dataset. The circulation median and 75th percentile are provided in Figure 14. The observed results confirm the positive effect of the headwind of vortex decay allowing safe application of TBS for another aircraft type.

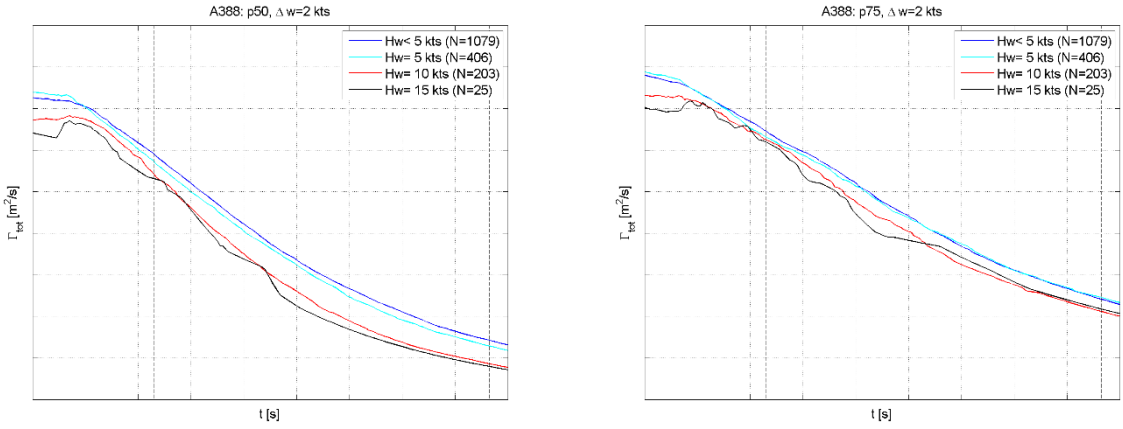

Figure 14: Comparison of the p50 (left) and p75 (right) circulation evolution of vortices generated by A388 in various headwind conditions.

4.3 Wake vortex encounter risk assessment of TBS margins

4.3.1 Methodology

The wind thresholds above which a time separation reduction of X s below TBS is allowed is estimated, for each aircraft pair, by comparing the wake severity to that of the baseline. The baseline corresponds to DBS operations in low wind conditions (total surface wind lower than 5 kts) and applying ICAO legacy distance-based separations.

It is to be noted that all along this section, the total wind Tw is computed using the 10 m anemometer wind.

For each aircraft pair a sample of severity values is computed using

- All measured circulation tracks for that generator aircraft type evaluated at the time corresponding to the baseline separation and in low wind conditions (Tw_{anem} <5 kts)
- All measured circulation tracks for that generator aircraft type for various wind values (Tw_{anem}= 5kts +/- Δwind, Tw_{anem} = 6kts +/- Δwind, …, Tw_{anem}=20 kts +/- Δwind)

The ∆wind is here taken equal to 1kt. The statistics of the samples are then compared. The allowed TBS margin is then evaluated as that leading to the same severity value as that of the baseline.

4.3.2 Risk assessment results for HEAVY-generated vortices

For various anemometer total surface wind values, the maximum time separation reduction is computed for a sample of aircraft pairs, using the set of leader HEAVY aircraft for which LiDAR data are available in EGLL database and a set of typical follower aircraft. This time reduction is computed such that the 50th quantile (i.e. median) p50 circulation (or equivalently the median RMC) potentially encountered in DBS low wind is equivalent to that potentially encountered in the considered total wind condition when reducing the vortex age.

In this study, the objective is to investigate the risk related to the encounter of vortices X s younger for various values of total wind independently on the wind direction. The LiDAR measurements are thus corrected following the methodology described in Section 4.2.1.4. This correction enables to obtain a characterization of the vortex decay as a function of its age and as a function of the total wind no matter the wind direction.

Examples of results are provided in Figure 15 to Figure 17.

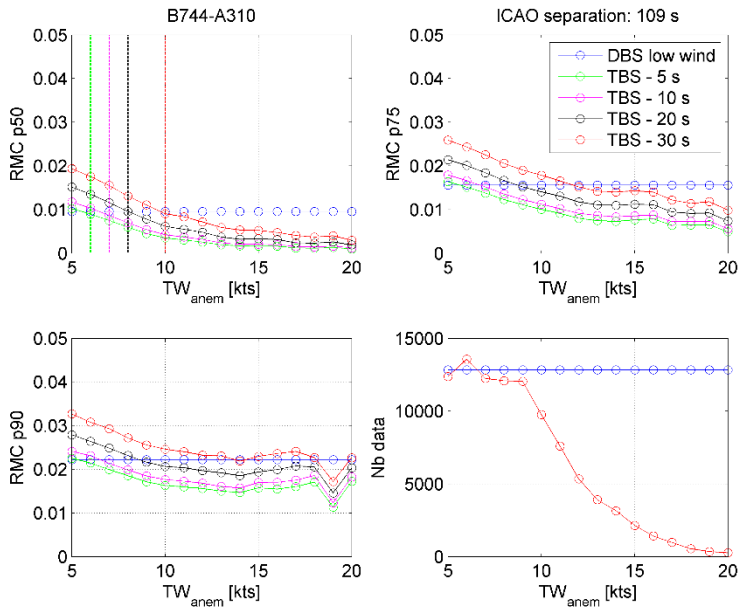

Figure 15: Case B744-A310: RMC statistics (p50, p75, p90 and number of samples) when applying a 10, 20 and 30 s reduced time separation as a function of the anemometer total wind compared to ICAO separations in low wind. The vertical lines show the wind threshold above which the p50 RMC is lower than that of the baseline.

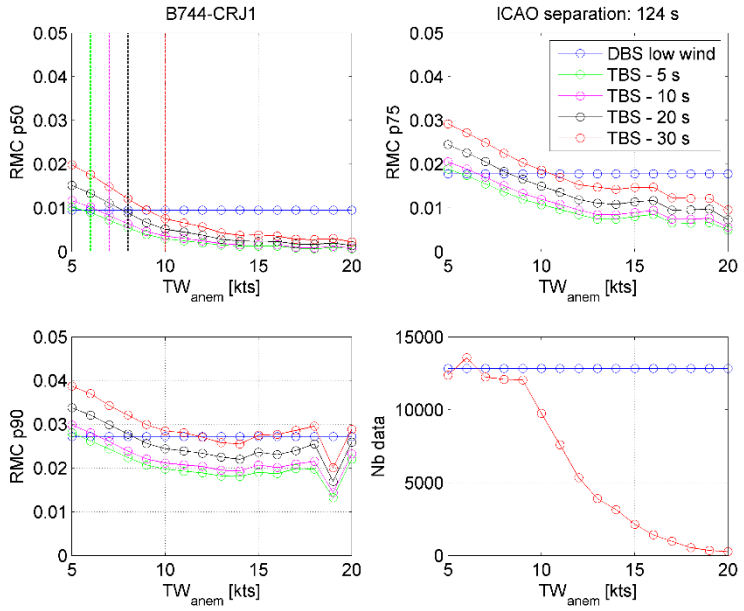

Figure 16: Case B744-CRJ1: RMC statistics (p50, p75, p90 and number of samples) when applying a 10, 20 and 30 s reduced time separation as a function of the anemometer total wind compared to ICAO separations in low wind. The vertical lines show the wind threshold above which the p50 RMC is lower than that of the baseline.

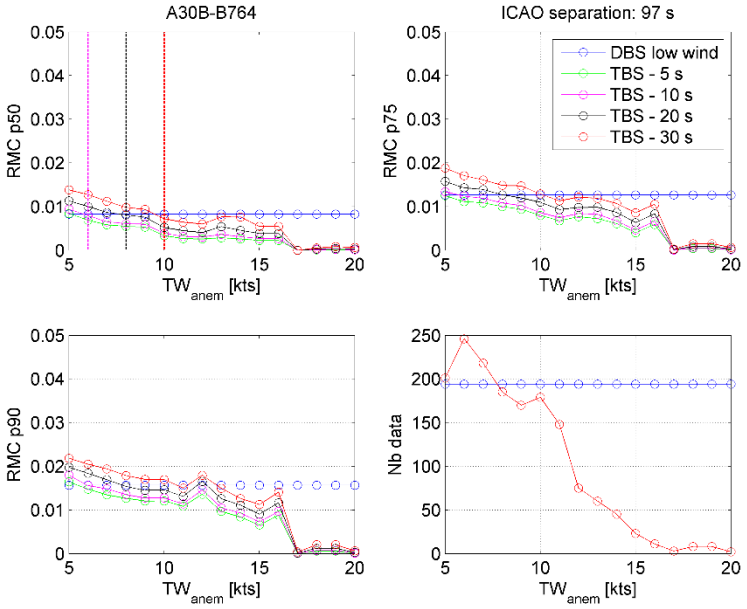

Figure 17: Case A30B-B764: RMC statistics (p50, p75, p90 and number of samples) when applying a 10, 20 and 30 s reduced time separation as a function of the anemometer total wind compared to ICAO separations in low wind. The vertical lines show the wind threshold above which the p50 RMC is lower than that of the baseline.

The detailed results are reported in Table 8 to Table 16. The colour code used in those tables is provided in Table 6.

Min	0.0	5.0	10.0	15.0	20.0	25.0	30.0
Max	4.9	9.9	14.9	19.9	24.9	29.9	40.0

Table 6: Colour code used in the maximum time reduction tables

Table 7 summarizes the obtained anemometer total wind thresholds required to allow an error on the vortex age potentially encountered ranging from 5 to 30 s and obtained considering the maximum wind threshold when considering all ICAO HEAVY aircraft types. These values are also reported in Table 2.

Vortex age reduction	Pair by pair HEAVY leaders
5 s	7 kts
10 s	7 kts
15 s	8 kts
20 s	9 kts
25 s	10 kts
30 s	11 kts

Table 7: Summary of the anemometer total wind threshold required to allow a given vortex age reduction

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	7.0	6.8	7.3	7.3	7.3	7.3	6.8	6.8	7.5	7.4	7.2	7.5	7.2	7.4	7.1	7.1	7.2	7.5	7.3	7.3	7.3	7.0	7.2	7.1	7.1	7.3	7.4	7.0	7.0	7.3	7.4	7.6	7.7	7.1	7.3	7.7	7.3	7.3	7.2	7.1	7.5	7.0	7.0	7.1
A346	8.9	8.7	9.7	9.7	9.8	9.8	8.7	8.6	9.7	9.8	9.4	9.4	9.4	10.3	9.5	10.1	9.5	10.3	10.4	10.2	10.3	10.1	9.5	9.9	9.7	9.6	9.5	10.1	10.1	10.3	10.3	10.7	10.6	9.5	10.2	10.7	10.2	10.3	9.5	9.6	10.6	10.1	10.1	10.1
B772	10.3	10.2	11.0	11.0	10.7	10.6	10.1	10.2	11.5	10.6	11.3	11.4	11.3	13.0	12.2	12.7	12.2	13.1	12.9	12.9	12.9	12.3	12.1	12.3	12.3	12.2	12.0	12.6	12.4	12.9	13.0	13.5	14.0	12.2	12.9	14.2	12.8	12.9	12.1	12.2	13.3	12.5	12.6	12.7
B773	9.2	8.9	9.4	9.5	9.5	9.5	8.9	9.0	10.7	9.6	10.1	10.3	10.1	11.1	10.6	10.9	10.4	11.1	10.8	11.0	10.8	10.6	10.4	10.6	10.6	10.4	10.4	10.8	10.6	10.9	11.1	11.4	11.9	10.6	11.0	11.9	10.9	10.9	10.5	10.5	11.4	10.7	10.8	10.9
B77W	7.1	7.8	6.7	6.7	6.5	6.5	7.8	7.7	7.4	6.6	6.8	7.3	6.9	10.4	9.3	10.1	9.1	10.3	10.6	10.5	10.8	9.8	9.1	9.6	9.5	9.1	8.8	10.0	9.9	10.7	10.4	10.8	11.3	9.4	10.6	11.2	10.4	10.7	9.2	9.2	10.5	10.0	10.0	10.1
A332	10.9	10.7	11.4	11.5	11.5	11.5	10.7	10.8	12.3	11.5	12.1	12.3	12.1	12.8	12.1	12.9	12.0	12.8	12.9	12.7	12.9	12.8	12.0	12.5	12.4	11.9	11.9	12.9	12.8	12.9	12.8	12.3	12.8	12.2	12.7	12.9	12.9	12.9	12.0	12.1	12.6	12.9	12.9	12.9
A333	13.3	12.8	13.5	13.7	13.1	13.1	12.7	12.9	14.6	13.2	14.1	14.2	14.1	16.8	16.3	16.6	16.2	16.7	16.8	16.9	16.9	16.6	16.3	16.4	16.3	16.2	16.0	16.6	16.7	17.0	16.8	17.1	18.1	16.3	17.0	18.1	16.7	17.0	16.2	16.3	16.8	16.7	16.6	16.6
A343	13.3	12.7	14.5	14.7	13.8	13.8	12.7	12.8	15.4	13.7	15.2	15.6	15.2	18.3	17.6	17.7	17.5	18.5	18.0	18.2	18.1	17.7	17.5	17.6	17.6	17.4	16.9	17.6	17.8	18.2	18.3	18.9	19.3	17.7	18.2	19.5	17.9	18.3	17.5	17.6	19.0	17.7	17.7	17.7
B764	5.4	6.0	6.7	6.6	6.3	6.3	6.0	6.1	6.2	6.3	6.4	6.5	6.4	6.1	7.0	6.4	7.0	6.0	6.3	6.2	6.3	6.8	7.0	6.9	6.9	7.0	6.8	6.4	6.7	6.2	6.1	6.1	6.1	7.0	6.2	6.2	6.3	6.2	7.0	7.0	5.9	6.5	6.4	6.4
B763	11.9	11.5	12.9	13.0	12.7	12.6	11.5	11.6	13.4	12.6	13.1	13.3	13.1	16.3	15.0	15.6	14.8	16.3	15.9	16.3	16.0	15.3	14.9	15.2	15.1	14.7	14.5	15.5	15.4	16.1	16.3	16.6	16.9	15.0	16.3	16.9	15.8	16.1	14.9	14.9	16.4	15.5	15.5	15.6
A306	6.6	6.7	3.7	3.8	3.6	3.6	6.7	6.5	4.4	3.6	4.1	4.3	4.1	2.9	4.5	3.6	4.7	2.9	3.3	3.0	3.2	4.0	4.6	4.2	4.3	4.8	5.3	3.7	3.9	3.2	3.0	2.7	3.7	4.4	3.0	3.9	3.4	3.2	4.6	4.6	2.7	3.7	3.6	3.6
A30B	11.8	12.0	13.1	12.9	13.0	12.9	12.0	11.9	11.8	12.8	12.0	11.8	11.9	16.1	14.7	14.8	14.1	16.2	15.4	15.9	15.5	15.1	14.3	15.1	15.0	13.8	12.6	14.8	15.0	15.6	16.0	16.9	17.7	14.7	15.9	17.8	15.1	15.7	14.4	14.5	16.5	14.8	14.8	14.8
A310	21.6	20.8	24.9	25.1	23.9	23.8	20.8	21.0	28.2	23.7	26.8	27.7	26.9	34.4	31.8	33.5	31.5	34.4	34.2	34.4	34.4	32.5	31.6	32.3	32.1	31.3	30.5	33.4	32.8	34.4	34.4	35.4	37.6	31.9	34.4	38.1	33.9	34.4	31.6	31.7	34.9	33.3	33.4	33.6

Table 8: Allowed time reduction for each pair and for an anemometer total wind Tw =6 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	12.6	12.1	13.3	13.4	13.1	13.1	12.1	12.2	13.7	13.1	13.4	13.7	13.5	15.7	14.8	15.3	14.8	15.8	15.5	15.6	15.5	15.0	14.8	14.9	14.8	14.8	14.5	15.3	15.1	15.5	15.7	16.0	16.1	14.8	15.5	16.2	15.4	15.5	14.8	14.8	15.8	15.2	15.3	15.3
A346	14.9	14.5	15.8	15.8	15.6	15.6	14.6	14.6	17.0	15.6	16.2	16.7	16.2	19.8	18.4	19.3	18.4	19.8	19.6	19.7	19.7	19.0	18.4	18.8	18.7	18.4	18.1	19.2	19.0	19.7	19.8	20.1	20.3	18.5	19.7	20.3	19.4	19.7	18.4	18.5	20.0	19.2	19.3	19.3
B772	16.1	15.7	16.9	16.9	16.5	16.5	15.7	15.8	17.8	16.4	17.4	17.7	17.5	20.9	19.5	20.3	19.4	21.0	20.5	20.7	20.5	19.8	19.4	19.7	19.6	19.4	19.1	20.2	19.9	20.6	20.8	21.4	22.3	19.5	20.7	22.5	20.5	20.6	19.4	19.5	21.2	20.1	20.2	20.3
B773	14.7	14.2	15.8	15.9	15.6	15.6	14.1	14.3	17.3	15.6	16.4	16.7	16.4	18.8	17.9	18.3	18.0	18.9	18.4	18.8	18.5	17.9	18.0	18.0	18.0	18.0	18.2	18.2	18.0	18.6	18.8	19.0	19.4	18.0	18.8	19.4	18.3	18.6	18.0	17.9	18.8	18.2	18.2	18.3
B77W	14.6	14.4	14.7	14.7	14.5	14.5	14.4	14.5	15.0	14.5	14.1	14.7	14.2	19.6	17.1	18.7	16.8	19.5	19.4	19.7	19.6	18.0	16.8	17.7	17.5	16.8	16.6	18.6	18.2	19.7	19.6	20.0	20.9	17.2	19.7	20.9	19.0	19.7	16.9	17.0	19.7	18.6	18.6	18.7
A332	18.8	18.4	19.2	19.2	19.2	19.2	18.4	18.5	20.3	19.2	19.9	20.0	19.9	24.0	21.9	23.1	21.8	24.0	23.5	23.9	23.7	22.4	21.9	22.1	22.1	21.7	21.0	23.0	22.6	23.8	24.0	24.0	24.5	21.9	24.0	24.8	23.2	23.9	21.9	21.9	24.3	23.0	23.1	23.1
A333	19.7	19.7	20.9	21.0	20.4	20.4	19.7	19.8	21.7	20.4	21.6	21.4	21.5	23.2	22.0	22.5	22.1	23.1	23.0	23.3	23.2	22.2	22.1	22.0	21.9	22.1	22.0	22.4	22.5	23.3	23.2	24.2	25.4	22.0	23.3	25.3	22.7	23.3	22.1	22.0	23.5	22.4	22.4	22.5
A343	19.3	18.8	21.4	21.5	20.7	20.6	18.8	18.9	22.8	20.5	22.3	22.8	22.4	26.4	24.7	25.4	24.5	26.5	25.7	26.3	25.8	25.1	24.6	25.0	24.9	24.5	23.9	25.3	25.2	25.9	26.4	26.9	27.4	24.8	26.2	27.5	25.6	26.0	24.6	24.6	26.9	25.2	25.3	25.4
B764	14.1	14.4	14.6	14.5	14.5	14.5	14.4	14.3	15.7	14.5	15.1	15.5	15.1	19.0	19.1	19.7	18.8	18.8	19.5	19.2	19.4	19.6	18.9	19.4	19.3	18.6	17.7	19.7	19.8	19.4	19.0	18.8	19.0	19.1	19.2	19.3	19.6	19.3	18.9	19.0	18.7	19.8	19.7	19.7
B763	18.2	17.8	19.2	19.3	18.9	18.9	17.8	17.8	20.7	18.8	19.9	20.3	19.9	24.5	23.0	23.7	22.8	24.5	24.0	24.4	24.1	23.3	22.9	23.2	23.1	22.7	22.4	23.5	23.4	24.2	24.5	25.1	25.9	23.0	24.4	26.1	23.9	24.3	22.9	22.9	24.8	23.5	23.5	23.7
A306	13.1	14.3	13.8	13.9	13.0	13.0	14.3	14.0	14.3	12.9	14.3	14.4	14.3	18.4	16.0	17.4	15.6	18.5	17.8	18.3	18.0	16.7	15.7	16.5	16.3	15.4	14.5	17.3	16.9	18.0	18.4	19.0	19.3	16.1	18.2	19.3	17.6	18.1	15.8	15.9	18.7	17.2	17.3	17.4
A30B	18.7	18.4	19.9	19.9	20.0	20.0	18.4	18.5	19.5	19.9	19.8	19.4	19.8	24.0	22.7	23.2	22.5	24.1	23.3	23.8	23.4	23.1	22.6	22.9	22.8	22.4	21.9	23.2	23.2	23.5	23.9	24.9	25.5	22.7	23.8	25.8	23.2	23.6	22.6	22.6	24.5	23.2	23.2	23.2
A310	23.4	22.3	25.6	25.7	24.9	24.9	22.3	22.6	29.2	24.8	27.3	28.3	27.4	36.7	33.5	35.5	33.1	36.8	36.3	36.7	36.5	34.4	33.2	34.1	33.9	32.9	31.9	35.3	34.7	36.6	36.7	37.9	40.4	33.6	36.7	41.0	36.0	36.6	33.3	33.4	37.3	35.2	35.4	35.6

Table 9: Allowed time reduction for each pair and for an anemometer total wind Tw =7 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	18.5	18.1	19.6	19.7	19.2	19.2	18.1	18.1	20.5	19.2	20.0	20.4	20.1	24.1	22.1	23.1	22.1	24.2	23.6	23.9	23.6	22.5	22.1	22.4	22.3	22.1	21.9	23.0	22.7	23.7	24.0	24.7	25.4	22.1	23.9	25.6	23.4	23.8	22.1	22.1	24.4	22.9	23.0	23.1
A346	21.2	20.6	22.8	22.8	22.7	22.6	20.6	20.7	24.0	22.6	23.6	23.8	23.6	28.2	26.1	27.4	26.1	28.3	27.9	28.1	28.0	26.7	26.1	26.5	26.4	26.0	25.6	27.3	26.8	28.1	28.2	28.7	29.8	26.2	28.1	30.1	27.7	28.1	26.1	26.1	28.7	27.2	27.3	27.4
B772	22.2	21.6	24.0	24.1	23.3	23.3	21.6	21.7	25.5	23.2	24.7	25.2	24.8	30.3	28.4	29.3	28.4	30.4	29.8	30.1	29.9	28.7	28.4	28.6	28.6	28.3	27.9	29.2	28.9	29.9	30.3	31.0	32.2	28.4	30.1	32.5	29.6	30.0	28.4	28.4	30.6	29.1	29.2	29.4
B773	17.3	16.8	18.1	18.2	17.7	17.7	16.8	17.0	19.5	17.7	18.9	19.1	18.8	21.9	20.6	21.3	20.3	22.0	21.5	21.9	21.6	20.6	20.4	20.5	20.6	20.3	20.3	21.2	20.8	21.7	21.9	21.9	22.5	20.7	21.9	22.6	21.3	21.8	20.5	20.6	21.9	21.1	21.2	21.3
B77W	20.6	20.2	21.6	21.7	20.9	20.9	20.2	20.4	23.2	20.9	22.3	22.9	22.4	29.8	26.9	28.8	26.6	29.8	29.6	29.8	29.8	27.7	26.7	27.4	27.3	26.5	25.9	28.6	28.0	29.9	29.8	30.6	31.2	27.0	29.9	31.4	29.3	29.9	26.7	26.8	30.2	28.5	28.6	28.8
A332	25.2	24.4	26.7	26.7	25.9	25.9	24.4	24.6	28.5	25.9	27.8	28.2	27.9	33.6	31.5	32.6	31.2	33.7	33.3	33.5	33.5	32.0	31.3	31.8	31.8	31.1	30.3	32.5	32.1	33.6	33.6	34.1	34.8	31.6	33.5	35.1	33.0	33.6	31.4	31.4	33.9	32.4	32.5	32.7
A333	25.7	25.1	26.8	26.9	26.1	26.1	25.1	25.3	27.9	26.1	27.0	27.3	27.0	31.8	30.7	31.8	30.5	31.7	32.2	31.9	32.2	30.9	30.6	30.8	30.8	30.3	30.5	31.6	31.2	32.2	31.8	32.6	34.5	30.7	32.0	35.0	32.1	32.1	30.6	30.7	31.9	31.5	31.6	31.8
A343	26.6	25.5	28.2	28.3	27.6	27.6	25.5	25.8	30.4	27.4	29.4	30.2	29.5	34.8	33.4	33.8	33.1	34.9	34.1	34.6	34.2	33.8	33.2	33.6	33.6	32.9	32.3	33.7	33.7	34.3	34.8	35.5	36.8	33.5	34.6	37.0	33.9	34.4	33.2	33.3	35.3	33.7	33.7	33.8
B764	19.2	18.8	21.0	21.1	20.7	20.7	18.8	18.9	23.0	20.7	21.9	22.5	22.0	27.2	26.9	27.4	26.8	27.1	27.4	27.3	27.4	27.2	26.8	27.1	27.0	26.6	26.0	27.3	27.3	27.4	27.2	27.3	28.1	27.0	27.4	28.3	27.4	27.4	26.8	26.9	27.1	27.3	27.3	27.4
B763	24.4	23.9	26.0	26.2	25.5	25.5	23.9	24.1	27.9	25.4	27.0	27.5	27.1	34.0	31.5	32.6	31.3	34.1	33.3	33.9	33.4	31.9	31.3	31.8	31.7	31.1	30.7	32.4	32.1	33.5	34.0	34.8	35.9	31.5	33.9	36.1	32.9	33.6	31.4	31.4	34.4	32.3	32.4	32.6
A306	17.6	19.6	16.9	17.1	16.4	16.4	19.7	19.2	19.0	16.4	18.1	18.6	18.2	21.8	21.8	21.6	21.5	21.8	21.2	21.6	21.3	22.0	21.6	21.9	21.9	21.4	20.6	21.7	21.9	21.3	21.7	21.8	22.8	21.8	21.6	23.1	21.3	21.4	21.6	21.7	21.7	21.7	21.7	21.6
A30B	21.1	20.9	22.7	22.7	22.7	22.6	20.9	20.8	22.2	22.6	22.5	22.3	22.5	24.8	23.9	25.1	24.0	24.9	25.1	24.8	25.0	24.2	24.1	23.9	23.9	23.9	23.4	24.9	24.4	24.9	24.8	25.4	26.3	23.9	24.8	26.6	25.2	24.9	24.1	24.0	25.2	24.8	24.9	25.1
A310	24.0	23.0	27.1	27.3	26.1	26.0	22.9	23.2	30.6	25.9	29.2	30.1	29.3	38.1	35.2	36.4	35.0	38.3	37.4	38.0	37.6	35.5	35.1	35.4	35.3	34.8	33.6	36.2	35.6	37.7	38.1	39.6	42.1	35.2	38.0	42.7	36.9	37.8	35.1	35.1	38.9	36.0	36.2	36.4

Table 10: Allowed time reduction for each pair and for an anemometer total wind Tw =8 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	23.6	22.8	25.0	25.1	24.6	24.6	22.8	23.0	26.3	24.5	25.6	26.0	25.7	32.4	30.0	31.2	29.8	32.6	31.8	32.3	31.9	30.4	29.9	30.2	30.2	29.7	29.1	31.1	30.6	32.0	32.4	33.4	34.4	30.1	32.2	34.7	31.5	32.0	29.9	30.0	32.9	31.0	31.1	31.3
A346	26.0	25.5	27.4	27.4	27.3	27.3	25.5	25.5	29.1	27.3	28.2	28.7	28.3	34.7	32.5	33.8	32.3	34.8	34.4	34.6	34.5	33.3	32.3	33.0	32.8	32.2	31.5	33.7	33.4	34.5	34.7	35.4	36.4	32.5	34.6	36.8	34.1	34.5	32.4	32.4	35.2	33.6	33.7	33.8
B772	28.0	27.4	30.0	30.2	29.3	29.2	27.3	27.5	32.3	29.1	31.3	31.9	31.4	39.2	36.3	37.8	36.1	39.3	38.5	39.1	38.6	36.9	36.2	36.7	36.6	36.1	35.4	37.6	37.1	38.7	39.2	40.0	41.5	36.4	39.0	42.0	38.2	38.8	36.2	36.2	39.6	37.5	37.6	37.8
B773	21.6	21.0	23.3	23.5	22.5	22.5	21.0	21.2	25.1	22.4	24.4	24.6	24.3	28.7	27.3	27.7	27.1	28.8	28.0	28.6	28.1	27.3	27.1	27.3	27.4	27.2	27.2	27.5	27.3	28.2	28.7	29.2	29.5	27.4	28.5	29.4	27.8	28.3	27.1	27.2	29.0	27.5	27.6	27.7
B77W	27.0	26.6	28.5	28.6	27.9	27.9	26.6	26.8	30.6	27.9	29.4	30.1	29.5	38.9	36.0	37.7	35.5	38.9	38.5	38.8	38.6	36.9	35.6	36.6	36.4	35.4	34.4	37.6	37.2	38.7	38.9	39.8	41.2	36.1	38.8	41.5	38.1	38.7	35.7	35.8	39.2	37.5	37.6	37.8
A332	29.8	28.8	32.3	32.4	31.5	31.4	28.8	29.0	34.4	31.3	33.5	34.1	33.5	41.0	37.9	40.1	37.6	41.1	40.7	40.9	40.9	38.8	37.7	38.5	38.3	37.4	36.9	40.0	39.2	41.0	41.0	41.5	43.1	38.0	40.9	43.7	40.4	41.0	37.7	37.8	41.3	39.8	40.0	40.1
A333	28.2	27.8	30.2	30.4	29.3	29.3	27.8	28.0	32.9	29.3	31.3	32.1	31.4	38.6	37.0	37.6	36.9	38.7	38.1	38.6	38.3	37.4	36.9	37.2	37.1	36.7	36.0	37.6	37.6	38.4	38.6	39.7	41.5	37.0	38.6	41.7	37.8	38.4	36.9	37.0	39.1	37.6	37.6	37.6
A343	31.4	30.4	34.3	34.4	33.3	33.3	30.4	30.6	36.3	33.2	35.5	36.2	35.6	43.9	41.2	42.4	40.8	44.1	43.2	43.8	43.4	42.0	40.9	41.6	41.5	40.7	39.7	42.1	42.1	43.5	43.9	45.3	46.5	41.3	43.7	46.9	42.8	43.5	41.0	41.1	44.7	42.1	42.1	42.4
B764	28.3	27.2	29.9	30.0	29.6	29.6	27.2	27.5	31.8	29.5	31.1	31.6	31.2	38.9	36.3	37.7	35.9	38.9	38.2	38.8	38.4	36.9	36.0	36.7	36.6	35.7	34.7	37.6	37.2	38.5	38.9	39.6	41.1	36.3	38.8	41.5	38.0	38.6	36.1	36.2	39.2	37.5	37.6	37.8
B763	30.0	29.3	32.0	32.2	31.3	31.3	29.3	29.4	34.1	31.2	33.1	33.6	33.1	41.8	38.8	40.2	38.5	41.9	40.9	41.6	41.1	39.3	38.6	39.1	39.0	38.4	37.7	40.0	39.6	41.2	41.8	42.6	44.1	38.8	41.6	44.5	40.6	41.3	38.6	38.7	42.2	39.9	40.0	40.2
A306	21.4	21.4	20.6	20.6	20.5	20.6	21.4	21.4	21.2	20.6	20.9	21.1	20.9	22.0	22.3	22.7	22.2	22.1	22.3	21.9	22.1	22.9	22.2	22.7	22.5	22.2	22.0	22.8	23.0	22.1	22.0	22.1	23.2	22.3	21.9	23.5	22.5	22.0	22.3	22.3	22.1	22.8	22.8	22.7
A30B	24.1	24.2	23.8	23.5	24.7	24.6	24.2	24.1	23.8	24.6	23.3	23.5	23.3	27.0	25.2	26.2	25.0	27.1	26.6	26.9	26.7	25.7	25.1	25.5	25.4	25.0	24.6	26.1	25.8	26.7	27.0	27.7	28.7	25.3	26.9	29.1	26.4	26.7	25.1	25.2	27.3	26.1	26.1	26.2
A310	31.2	30.4	33.2	33.3	32.5	32.5	30.4	30.6	36.5	32.4	34.8	35.7	34.9	46.0	43.1	44.9	42.6	46.1	45.7	46.0	45.8	43.8	42.8	43.6	43.5	42.4	41.3	44.7	44.1	45.9	46.0	47.2	49.6	43.2	46.0	50.3	45.3	45.9	42.8	43.0	46.6	44.6	44.7	44.9

Table 11: Allowed time reduction for each pair and for an anemometer total wind Tw =9 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	28.3	27.5	30.2	30.4	29.5	29.5	27.5	27.7	32.4	29.4	31.3	32.0	31.3	39.1	36.3	37.7	36.2	39.3	38.4	38.9	38.5	36.8	36.2	36.6	36.5	36.1	35.4	37.6	37.0	38.6	39.1	40.0	41.2	36.3	38.9	41.6	38.0	38.7	36.2	36.3	39.6	37.5	37.6	37.7
A346	29.4	28.7	31.1	31.2	30.6	30.5	28.7	28.8	33.4	30.5	32.1	32.9	32.2	41.5	38.1	40.5	37.8	41.5	41.2	41.4	41.3	39.2	37.9	38.8	38.6	37.6	36.7	40.3	39.6	41.3	41.5	42.2	44.1	38.2	41.4	44.3	40.9	41.3	37.9	38.0	41.9	40.1	40.3	40.5
B772	33.0	32.0	35.5	35.6	34.6	34.5	32.0	32.3	38.0	34.4	37.0	37.6	37.0	46.8	43.5	45.5	43.1	46.9	46.1	46.6	46.2	44.4	43.2	44.1	43.9	42.8	42.0	45.3	44.6	46.3	46.8	47.9	49.7	43.6	46.6	50.2	45.8	46.3	43.2	43.4	47.4	45.2	45.3	45.6
B773	28.3	27.4	30.7	30.9	29.8	29.8	27.4	27.6	33.4	29.7	32.4	32.9	32.4	38.6	36.3	37.4	36.1	38.8	37.7	38.4	37.9	36.6	36.1	36.4	36.4	36.0	35.7	37.3	36.8	38.0	38.5	39.7	41.1	36.3	38.4	41.1	37.6	38.0	36.1	36.2	39.3	37.2	37.3	37.4
B77W	31.1	30.8	32.5	32.7	31.7	31.7	30.8	30.9	35.1	31.7	33.7	34.5	33.8	43.8	40.0	42.3	39.6	43.9	43.4	43.7	43.5	41.0	39.6	40.6	40.4	39.4	38.7	42.0	41.3	43.6	43.8	45.0	46.4	40.1	43.7	46.7	42.8	43.6	39.7	39.8	44.4	41.9	42.1	42.3
A332	34.4	33.4	36.9	37.0	36.1	36.1	33.4	33.6	39.5	36.0	38.3	39.0	38.4	48.9	45.2	47.3	44.6	49.0	48.3	48.7	48.5	46.3	44.8	46.1	45.8	44.3	43.2	47.0	46.5	48.6	48.9	49.9	51.5	45.4	48.7	52.1	47.8	48.6	44.8	45.0	49.5	46.9	47.0	47.3
A333	32.5	31.4	34.7	34.8	33.7	33.7	31.4	31.7	37.0	33.6	35.9	36.4	35.9	44.1	40.7	43.2	40.6	44.1	43.7	44.0	43.8	41.6	40.7	41.2	41.0	40.5	40.0	43.0	42.1	43.9	44.1	45.3	46.7	40.8	44.0	47.0	43.4	43.9	40.7	40.7	44.6	42.9	43.1	43.2
A343	37.6	36.3	40.1	40.2	39.4	39.3	36.3	36.6	42.9	39.2	41.5	42.4	41.6	51.6	48.4	49.8	48.1	51.8	50.7	51.4	50.9	49.0	48.2	48.7	48.6	47.9	46.8	49.6	49.3	51.1	51.6	52.8	54.6	48.5	51.4	54.9	50.2	51.1	48.2	48.3	52.3	49.6	49.7	49.8
B764	30.0	29.3	32.3	32.3	31.4	31.4	29.3	29.4	33.6	31.3	33.3	33.6	33.4	40.5	37.9	39.6	37.6	40.5	40.1	40.4	40.1	38.7	37.7	38.4	38.2	37.4	36.2	39.5	38.9	40.2	40.5	41.2	42.5	38.0	40.4	43.1	39.9	40.2	37.7	37.8	40.8	39.4	39.5	39.7
B763	34.9	34.1	37.3	37.4	36.5	36.4	34.1	34.2	40.0	36.3	38.7	39.4	38.8	48.9	45.4	47.2	44.9	49.0	47.9	48.7	48.1	46.3	45.1	46.0	45.8	44.7	43.8	47.0	46.6	48.3	48.9	49.8	51.8	45.5	48.7	52.3	47.6	48.4	45.1	45.2	49.3	47.0	47.1	47.3
A306	28.5	29.6	28.6	28.7	27.6	27.6	29.6	29.4	29.6	27.5	29.2	29.3	29.2	33.8	33.0	33.4	32.8	33.9	33.4	33.7	33.5	33.3	32.8	33.2	33.1	32.7	32.1	33.4	33.3	33.6	33.8	34.1	35.6	33.0	33.7	36.0	33.4	33.6	32.8	32.9	33.9	33.4	33.4	33.4
A30B	34.4	33.1	36.5	36.5	36.4	36.3	33.1	33.4	37.5	36.2	36.8	37.1	36.8	44.2	42.1	43.2	41.8	44.3	43.7	44.1	43.8	42.6	41.9	42.4	42.3	41.7	41.0	43.1	42.7	43.9	44.2	44.9	45.7	42.1	44.1	46.1	43.5	44.0	42.0	42.0	44.6	43.0	43.1	43.2
A310	38.4	37.2	41.5	41.7	40.6	40.5	37.2	37.5	45.6	40.4	43.8	44.8	43.9	56.4	52.3	54.9	51.7	56.5	55.9	56.4	56.1	53.4	51.9	53.0	52.7	51.4	50.1	54.6	53.8	56.2	56.4	57.6	60.7	52.4	56.3	61.6	55.4	56.3	51.9	52.1	57.0	54.4	54.7	54.9

Table 12: Allowed time reduction for each pair and for an anemometer total wind Tw =10 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	30.5	29.7	32.6	32.8	31.8	31.8	29.7	29.8	34.6	31.7	33.7	34.2	33.8	42.5	39.0	40.8	38.8	42.6	41.6	42.3	41.8	39.7	38.8	39.4	39.3	38.6	37.7	40.6	40.0	41.9	42.5	43.4	44.8	39.1	42.2	45.0	41.2	41.9	38.9	39.0	42.9	40.5	40.6	40.9
A346	31.7	31.0	34.0	34.1	33.4	33.3	31.0	31.1	36.0	33.3	34.9	35.5	34.9	42.9	39.7	41.4	39.4	43.1	42.1	42.7	42.2	40.8	39.4	40.4	40.2	39.3	39.1	41.2	41.0	42.3	42.9	44.0	45.3	39.8	42.6	45.4	41.7	42.4	39.5	39.5	43.6	41.2	41.3	41.4
B772	35.5	34.4	38.1	38.3	37.2	37.1	34.3	34.6	40.7	37.1	39.6	40.3	39.7	49.7	46.2	48.2	45.9	49.9	48.9	49.5	49.0	47.0	46.0	46.7	46.5	45.7	44.8	47.9	47.3	49.2	49.7	50.8	52.6	46.2	49.5	53.2	48.6	49.2	46.0	46.1	50.2	47.8	48.0	48.2
B773	31.0	30.0	33.3	33.4	32.6	32.6	30.0	30.2	35.7	32.5	34.3	35.0	34.3	42.2	39.6	41.1	39.1	42.4	41.5	42.0	41.6	40.2	39.2	40.0	39.9	38.9	38.4	40.9	40.5	41.7	42.2	43.2	44.7	39.7	42.0	44.9	41.3	41.8	39.3	39.4	42.7	40.9	41.0	41.1
B77W	30.6	30.1	32.0	32.0	31.2	31.2	30.0	30.3	33.8	31.1	32.6	33.1	32.6	42.6	38.8	41.1	38.4	42.6	42.0	42.5	42.2	40.0	38.5	39.6	39.3	38.3	37.7	40.9	40.3	42.3	42.6	43.6	44.9	39.0	42.5	45.1	41.6	42.3	38.6	38.7	43.1	40.8	41.0	41.2
A332	37.8	36.4	40.8	41.0	39.7	39.6	36.4	36.7	43.6	39.6	42.6	43.0	42.7	52.7	49.6	51.3	49.1	52.9	51.8	52.4	52.0	50.4	49.3	50.0	49.9	48.9	47.8	51.2	50.6	52.1	52.6	53.7	55.2	49.7	52.4	55.8	51.5	52.1	49.3	49.5	53.3	51.1	51.2	51.3
A333	39.8	39.2	41.8	42.0	40.7	40.7	39.2	39.4	44.3	40.7	43.6	44.1	43.7	50.7	48.3	49.2	48.1	50.7	50.0	50.6	50.2	48.8	48.2	48.5	48.5	48.0	47.5	49.1	48.9	50.3	50.6	51.8	53.6	48.3	50.6	53.9	49.6	50.4	48.2	48.3	51.1	49.1	49.1	49.3
A343	41.6	40.6	44.7	44.9	43.5	43.4	40.5	40.8	47.8	43.3	46.7	47.5	46.8	58.3	55.0	56.5	54.4	58.6	57.3	58.1	57.5	55.7	54.5	55.4	55.3	54.2	52.7	56.3	56.0	57.6	58.3	59.8	61.7	55.1	58.1	62.3	56.9	57.7	54.6	54.8	59.2	56.3	56.3	56.5
B764	36.7	36.1	38.4	38.4	37.9	37.8	36.1	36.2	40.8	37.7	39.9	40.5	40.0	49.9	46.2	48.6	45.6	49.9	49.4	49.9	49.5	47.2	45.8	46.9	46.6	45.3	43.9	48.4	47.6	49.6	49.9	50.4	51.6	46.3	49.9	51.9	49.1	49.7	45.8	46.0	50.1	48.2	48.4	48.7
B763	37.4	36.5	39.9	40.0	39.1	39.0	36.5	36.7	42.3	38.9	41.1	41.7	41.1	51.4	47.8	49.7	47.5	51.6	50.5	51.3	50.7	48.5	47.6	48.3	48.1	47.3	46.5	49.5	48.9	50.9	51.4	52.6	54.4	47.9	51.2	54.9	50.1	50.9	47.6	47.7	52.1	49.4	49.5	49.7
A306	40.0	40.4	38.6	38.6	38.4	38.4	40.4	40.4	41.2	38.4	39.7	40.5	39.8	51.5	48.6	50.6	48.1	51.6	51.2	51.5	51.3	49.5	48.2	49.2	49.0	47.8	46.7	50.4	49.8	51.3	51.5	52.1	53.9	48.7	51.5	54.4	50.9	51.4	48.3	48.4	51.7	50.3	50.4	50.6
A30B	36.0	35.0	39.1	39.3	38.1	38.0	35.0	35.3	41.8	37.9	40.7	41.3	40.8	50.0	47.4	48.9	47.2	50.1	49.5	49.9	49.6	47.9	47.3	47.8	47.6	47.0	46.2	48.7	48.2	49.7	50.0	50.8	53.0	47.5	49.9	53.6	49.2	49.7	47.3	47.4	50.4	48.6	48.7	48.9
A310	39.3	38.5	43.6	43.8	42.0	41.9	38.5	38.7	47.2	41.8	46.4	46.8	46.5	60.6	55.4	58.4	54.7	60.8	59.5	60.4	59.8	56.6	54.9	56.2	55.9	54.4	52.9	58.1	57.1	60.0	60.6	62.3	65.0	55.5	60.3	65.6	59.0	60.1	55.0	55.2	61.5	57.9	58.1	58.4

Table 13: Allowed time reduction for each pair and for an anemometer total wind Tw =11 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	33.3	32.4	35.5	35.7	34.9	34.9	32.4	32.6	38.0	34.9	36.9	37.6	36.9	45.6	42.5	44.1	42.3	45.8	44.8	45.4	45.0	43.1	42.4	42.9	42.8	42.2	41.5	43.9	43.4	45.2	45.6	46.7	48.4	42.6	45.4	48.8	44.4	45.2	42.4	42.5	46.2	43.8	43.9	44.1
A346	35.2	34.6	36.0	36.0	35.8	35.8	34.6	34.7	38.8	35.9	37.8	38.2	37.8	45.7	43.0	44.5	42.8	45.8	45.0	45.6	45.2	43.9	42.9	43.6	43.4	42.7	42.0	44.4	44.0	45.3	45.7	46.6	48.4	43.1	45.5	48.8	44.7	45.3	42.9	43.0	46.3	44.3	44.4	44.5
B772	37.1	36.0	39.8	40.0	38.9	38.8	36.0	36.2	42.7	38.7	41.4	42.2	41.5	51.5	48.2	50.0	47.9	51.7	50.6	51.3	50.7	48.9	48.0	48.7	48.5	47.7	46.7	49.8	49.2	50.8	51.5	52.7	54.6	48.2	51.2	55.2	50.4	50.9	48.0	48.1	52.1	49.7	49.8	50.1
B773	34.6	33.7	37.3	37.5	36.1	36.0	33.6	33.9	40.1	35.9	39.0	39.3	38.9	49.2	45.3	47.0	44.8	49.5	47.9	49.0	48.1	45.9	44.9	45.7	45.6	44.6	43.9	46.7	46.2	48.4	49.2	50.7	52.2	45.4	48.9	52.6	47.4	48.4	45.0	45.2	50.1	46.6	46.8	47.0
B77W	34.4	33.7	36.5	36.7	35.6	35.6	33.7	33.9	39.1	35.5	37.9	38.6	38.0	49.0	45.1	47.9	44.4	49.0	48.6	49.0	48.8	46.5	44.6	46.0	45.7	44.1	43.0	47.7	46.9	48.8	49.0	49.8	50.9	45.3	49.0	51.1	48.2	48.9	44.7	44.9	49.4	47.6	47.7	47.9
A332	42.7	41.3	45.4	45.6	44.5	44.4	41.3	41.6	48.6	44.3	47.1	47.8	47.2	59.5	55.1	57.5	54.4	59.6	58.3	59.2	58.6	56.2	54.6	55.8	55.6	54.2	52.9	57.3	56.6	58.8	59.5	60.3	62.6	55.2	59.2	63.2	58.0	58.9	54.7	54.9	59.9	57.1	57.3	57.6
A333	43.4	42.9	46.6	46.8	45.2	45.1	42.9	43.2	49.6	45.0	48.2	49.0	48.3	58.2	55.0	56.5	54.6	58.2	57.5	58.2	57.8	55.8	54.7	55.5	55.3	54.4	53.6	56.3	56.1	57.9	58.2	59.1	61.9	55.1	58.1	62.4	57.0	57.9	54.8	54.9	58.5	56.3	56.4	56.5
A343	41.5	40.9	44.4	44.6	43.3	43.2	40.9	41.0	47.7	43.1	46.5	47.4	46.6	56.8	53.7	55.5	53.2	57.0	56.0	56.6	56.1	54.5	53.3	54.2	54.0	53.0	52.0	55.3	54.8	56.2	56.8	58.0	60.2	53.8	56.5	60.8	55.8	56.2	53.4	53.5	57.6	55.2	55.3	55.6
B764	43.6	42.4	46.8	47.0	46.1	46.0	42.3	42.6	50.0	45.9	48.8	49.5	48.9	57.9	54.8	56.6	54.4	57.9	57.2	57.8	57.4	55.6	54.5	55.3	55.1	54.1	53.1	56.4	55.9	57.5	57.9	58.6	61.1	54.9	57.8	61.9	57.0	57.5	54.6	54.7	58.2	56.3	56.4	56.6
B763	39.7	38.8	42.4	42.6	41.4	41.4	38.8	39.0	45.4	41.3	44.1	44.9	44.2	54.6	51.3	53.1	50.9	54.8	53.9	54.5	54.1	52.1	51.0	51.8	51.6	50.7	49.7	52.9	52.4	54.2	54.6	55.9	57.9	51.3	54.5	58.2	53.5	54.3	51.1	51.2	55.3	52.8	52.9	53.2
A306	36.8	37.0	37.3	37.5	36.4	36.4	36.9	37.0	40.4	36.4	39.6	40.2	39.7	44.0	43.5	43.9	43.3	44.1	44.0	44.0	44.0	43.9	43.4	43.8	43.7	43.2	42.6	43.9	43.9	44.0	44.0	44.3	45.8	43.6	44.0	46.2	44.0	44.0	43.4	43.5	44.1	43.9	43.9	43.9
A30B	40.0	39.2	42.1	42.0	41.9	41.8	39.2	39.4	43.5	41.8	42.6	43.1	42.7	52.6	50.8	51.8	50.2	52.7	52.2	52.5	52.3	51.4	50.4	51.2	51.1	50.0	48.5	51.7	51.5	52.4	52.6	53.0	53.7	50.9	52.5	54.1	52.0	52.4	50.5	50.6	52.8	51.7	51.8	51.8
A310	31.3	29.8	35.7	36.0	34.3	34.2	29.8	30.2	40.0	34.1	38.5	39.4	38.6	48.6	44.6	47.0	44.1	48.7	47.9	48.5	48.1	45.5	44.2	45.2	45.0	43.8	42.8	46.7	45.9	48.3	48.6	50.0	52.8	44.7	48.5	53.5	47.5	48.3	44.3	44.4	49.4	46.6	46.8	47.0

Table 14: Allowed time reduction for each pair and for an anemometer total wind Tw =12 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	37.1	36.2	39.6	39.8	38.7	38.7	36.2	36.4	42.1	38.6	41.0	41.8	41.1	51.4	47.0	49.3	46.4	51.6	50.2	51.1	50.4	48.1	46.6	47.7	47.5	46.2	45.5	49.1	48.4	50.6	51.3	52.3	54.3	47.1	51.1	54.8	49.7	50.7	46.7	46.8	51.9	49.0	49.1	49.3
A346	38.4	37.4	41.5	41.6	40.7	40.6	37.4	37.6	43.3	40.5	42.6	42.8	42.6	51.8	49.2	50.8	49.0	51.9	51.3	51.8	51.4	50.1	49.1	49.8	49.6	49.0	48.1	50.6	50.3	51.5	51.8	52.8	54.3	49.3	51.7	54.8	51.1	51.6	49.1	49.2	52.4	50.5	50.7	50.9
B772	40.1	39.2	42.8	43.0	41.8	41.7	39.2	39.4	46.0	41.6	44.7	45.4	44.8	55.9	51.9	53.9	51.4	56.2	54.8	55.7	55.0	52.7	51.6	52.5	52.3	51.2	50.2	53.6	53.0	55.1	55.9	57.4	59.5	52.0	55.6	60.1	54.4	55.2	51.6	51.7	56.8	53.5	53.6	53.9
B773	39.7	38.7	43.9	44.2	42.5	42.4	38.7	39.0	47.5	42.2	45.9	46.6	46.0	56.5	51.6	54.2	51.1	56.7	55.1	56.2	55.4	52.6	51.2	52.2	52.0	51.0	50.8	54.0	53.0	55.6	56.5	58.0	61.0	51.7	56.2	61.6	54.7	55.7	51.2	51.4	57.2	53.8	54.0	54.3
B77W	38.7	38.5	43.3	43.5	41.8	41.7	38.5	38.6	46.4	41.5	45.1	45.7	45.2	58.9	54.4	56.9	53.9	59.1	58.0	58.8	58.2	55.4	54.0	55.0	54.8	53.6	52.3	56.6	55.8	58.4	58.9	60.3	62.6	54.4	58.8	63.1	57.5	58.5	54.1	54.2	59.6	56.5	56.7	56.9
A332	45.9	44.6	48.9	49.1	48.0	47.9	44.6	44.9	52.8	47.8	51.0	52.0	51.2	64.1	59.7	62.0	59.1	64.3	62.9	63.8	63.2	60.8	59.3	60.4	60.2	58.9	57.8	61.8	61.1	63.4	64.1	65.4	68.1	59.8	63.8	68.9	62.5	63.5	59.4	59.5	64.9	61.7	61.8	62.1
A333	45.0	44.0	47.6	47.8	46.3	46.2	44.0	44.3	51.9	46.1	49.9	51.1	50.1	62.2	58.7	60.4	58.2	62.3	61.3	62.1	61.5	59.7	58.3	59.3	59.1	57.9	56.9	60.2	59.9	61.7	62.2	63.4	65.7	58.8	62.0	66.1	60.8	61.7	58.4	58.6	62.7	60.2	60.2	60.4
A343	41.7	40.5	44.5	44.6	43.5	43.4	40.5	40.7	47.2	43.3	46.0	47.0	46.2	55.2	51.9	53.2	51.5	55.4	54.2	55.0	54.4	52.1	51.6	52.0	52.0	51.3	50.3	53.0	52.3	54.5	55.2	56.7	58.8	52.0	54.9	59.0	53.8	54.6	51.6	51.8	56.0	52.8	53.0	53.3
B764	45.8	44.7	47.9	48.0	47.6	47.6	44.7	44.9	51.4	47.5	50.2	50.9	50.3	61.2	58.0	59.9	57.6	61.3	60.6	61.1	60.7	58.9	57.7	58.6	58.4	57.3	56.1	59.7	59.2	60.8	61.2	62.1	64.7	58.1	61.1	65.3	60.3	60.9	57.8	57.9	61.6	59.6	59.8	59.9
B763	44.4	43.2	47.4	47.6	46.5	46.4	43.2	43.5	50.5	46.3	49.0	49.8	49.1	60.9	56.8	58.7	56.5	61.1	59.7	60.7	59.9	57.6	56.6	57.3	57.1	56.3	54.8	58.5	57.9	60.1	60.9	62.2	64.4	56.9	60.6	64.9	59.2	60.2	56.6	56.7	61.6	58.4	58.5	58.7
A306	36.8	37.0	38.3	38.4	37.4	37.3	36.9	37.0	40.6	37.2	39.9	40.3	40.0	45.7	43.9	45.0	43.5	45.8	45.3	45.6	45.4	44.4	43.6	44.3	44.1	43.4	42.8	44.9	44.6	45.4	45.7	46.4	48.4	43.9	45.6	49.0	45.1	45.5	43.7	43.8	46.0	44.8	44.9	45.0
A30B	32.6	31.8	34.5	34.6	34.7	34.6	31.8	31.9	36.4	34.6	35.3	35.9	35.4	46.5	42.3	44.4	41.9	46.8	45.4	46.3	45.6	43.0	42.1	42.8	42.6	41.7	40.7	44.2	43.4	45.8	46.5	47.9	50.2	42.4	46.2	50.9	44.9	45.9	42.1	42.2	47.3	44.0	44.2	44.4
A310	43.3	41.8	47.8	48.1	46.3	46.2	41.8	42.1	53.4	46.1	50.9	52.3	51.1	70.6	64.3	68.0	63.5	70.8	69.3	70.3	69.6	65.9	63.8	65.4	65.0	63.1	61.3	67.6	66.5	69.8	70.6	72.5	76.1	64.5	70.3	77.0	68.7	69.9	63.8	64.1	71.6	67.4	67.7	68.0

Table 15: Allowed time reduction for each pair and for an anemometer total wind Tw =13 kts +/- 1 kt

	B744	A346	B772	A332	A333	A343	MD11	B764	B762	B763	A306	A30B	A310	B752	B753	B737	B738	B736	B739	A318	A319	A320	A321	MD82	MD83	MD88	MD90	B733	B734	B735	E190	DH8D	AT72	CRJ9	E170	AT43	CRJ7	SF34	CRJ1	CRJ2	D328	E135	E145	E120
B744	38.5	37.6	41.3	41.5	40.6	40.6	37.5	37.8	43.8	40.5	42.9	43.4	42.9	53.3	49.3	51.3	49.0	53.6	52.4	53.0	52.6	50.1	49.1	49.7	49.6	48.8	47.8	51.1	50.4	52.7	53.3	54.8	56.6	49.4	52.9	57.1	51.9	52.7	49.2	49.2	54.2	50.9	51.1	51.4
A346	42.4	42.1	45.3	45.5	44.2	44.1	42.1	42.1	49.1	44.0	47.6	48.4	47.7	60.3	56.1	58.3	55.7	60.5	59.4	60.1	59.6	57.3	55.8	56.9	56.6	55.5	54.4	58.0	57.6	59.7	60.3	61.6	63.1	56.2	60.1	63.6	58.9	59.8	55.8	56.0	61.0	57.9	58.0	58.3
B772	41.5	40.4	44.6	44.8	43.6	43.5	40.4	40.7	48.1	43.4	46.5	47.4	46.6	59.0	54.5	57.1	54.1	59.2	57.9	58.8	58.2	55.6	54.2	55.3	55.0	53.8	52.8	56.8	56.0	58.3	59.0	60.2	62.6	54.6	58.7	63.3	57.5	58.4	54.2	54.4	59.6	56.7	56.9	57.1
B773	40.6	39.5	43.7	44.0	42.5	42.4	39.5	39.8	47.6	42.3	46.0	46.7	46.0	57.1	54.0	55.6	53.5	57.2	56.2	56.9	56.4	54.7	53.6	54.4	54.3	53.3	52.3	55.4	54.9	56.5	57.1	58.1	60.5	54.1	56.9	60.8	55.9	56.6	53.7	53.8	57.6	55.3	55.5	55.6
B77W	42.5	41.7	44.6	44.8	43.6	43.5	41.7	41.9	47.5	43.5	46.0	46.8	46.1	62.1	55.4	59.1	54.7	62.3	60.6	61.8	60.9	57.0	54.9	56.4	56.1	54.3	52.8	58.8	57.6	61.2	62.0	63.9	66.3	55.6	61.7	66.9	59.9	61.3	55.0	55.2	63.1	58.5	58.8	59.2
A332	51.1	49.7	54.4	54.5	53.6	53.5	49.7	50.0	57.7	53.4	56.3	57.1	56.4	69.4	64.4	67.6	63.7	69.7	68.4	69.1	68.6	65.8	63.9	65.3	65.0	63.4	62.1	67.3	66.3	68.8	69.4	71.2	74.3	64.6	69.1	75.1	68.0	68.8	64.0	64.2	70.5	67.1	67.3	67.6
A333	45.3	44.5	48.6	48.7	47.8	47.8	44.4	44.7	52.2	47.6	50.6	51.5	50.7	63.8	58.6	61.3	57.9	64.1	62.4	63.5	62.7	59.9	58.1	59.4	59.1	57.6	56.3	61.1	60.4	62.9	63.8	65.7	68.9	58.7	63.5	69.5	61.9	63.0	58.2	58.4	64.8	60.9	61.1	61.4
A343	45.9	44.5	49.5	49.7	48.3	48.2	44.5	44.8	52.9	48.1	51.3	52.3	51.4	62.7	58.7	60.8	58.4	63.0	61.7	62.5	61.9	59.6	58.4	59.3	59.1	58.2	57.2	60.6	60.0	62.1	62.7	64.3	66.2	58.8	62.5	66.8	61.3	62.2	58.5	58.6	63.6	60.5	60.6	60.8
B764	48.0	46.6	50.2	50.3	49.8	49.7	46.6	47.0	53.2	49.7	51.6	52.5	51.8	63.3	60.8	62.5	60.2	63.3	62.9	63.3	63.0	61.8	60.4	61.4	61.2	59.9	58.5	62.4	62.0	63.1	63.3	63.8	65.0	60.9	63.3	65.7	62.8	63.1	60.5	60.7	63.5	62.3	62.4	62.5
B763	45.6	44.3	48.3	48.5	47.3	47.3	44.3	44.6	51.7	47.2	50.1	50.9	50.2	62.0	58.2	60.2	57.9	62.1	61.0	61.8	61.2	59.1	58.0	58.8	58.6	57.6	56.6	59.9	59.4	61.3	62.0	63.3	65.7	58.3	61.7	66.4	60.6	61.4	58.0	58.1	62.7	59.8	59.9	60.2
A306	49.6	48.2	50.4	50.6	49.7	49.7	48.1	48.5	54.5	49.6	52.4	53.5	52.6	64.8	61.8	63.5	61.3	65.0	64.1	64.7	64.3	62.6	61.4	62.3	62.1	61.1	60.0	63.3	62.8	64.4	64.8	65.8	68.4	61.9	64.6	69.0	63.8	64.4	61.5	61.6	65.3	63.2	63.4	63.5
A30B	32.4	31.2	36.2	36.4	35.2	35.2	31.2	31.4	40.1	35.0	38.3	39.3	38.4	50.5	47.1	48.9	46.6	50.7	49.7	50.3	49.8	47.8	46.8	47.5	47.4	46.4	45.3	48.7	48.1	50.0	50.5	51.5	53.2	47.1	50.3	53.7	49.3	50.0	46.8	46.9	51.1	48.6	48.7	48.9
A310	47.6	46.1	52.1	52.4	50.7	50.6	46.0	46.4	57.3	50.4	55.0	56.3	55.2	73.1	67.1	70.6	66.3	73.4	71.9	72.9	72.2	68.5	66.6	68.0	67.7	66.0	64.3	70.2	69.1	72.4	73.1	75.0	78.8	67.2	72.9	79.8	71.3	72.5	66.6	66.9	74.1	70.0	70.3	70.6

Table 16: Allowed time reduction for each pair and for an anemometer total wind Tw =14 kts +/- 1 kt

4.3.3 Risk assessment results for MEDIUM-generated vortices

In order to find the total wind thresholds allowing a time reduction of X seconds, one compares the mean and median evolutions of the living time for a given total wind values to those of the baseline (i.e., total wind lower than 5 kts). This exercise is performed using the LFPG wake database described in Section 4.2.2.

For each total wind value, a window of size 2 kts is taken around the mean total wind value. The comparison of the statistics for total wind values ranging from 6 to 13 kts are provided in Figure 18 to Figure 21 for the mean evolutions and in Figure 22 to Figure 25 for the median evolution. For completeness, the mean +/- one standard deviation, the 10th quantile (p10) and the 90th quantile (p90) evolutions are also provided in the plots. Note that those curves are not used to determine the required wind thresholds.

Based on those results, a wind threshold of 8 to 9 kts is found to be required to ensure that an error on the FTD leading to a 15 s under-spacing compared to TBS is mitigated by the total wind effect on the vortex decay. A summary of the required wind thresholds is provided in Table 17. In order to be conservative, the maximum values obtained by either approach are to be used and are reported in Table 2.

Allowed time reduction	Based on mean	Based on median	Conservative wind threshold
5 s	6 kts	6 kts	6 kts
10 s	7 kts	8 kts	8 kts
15 s	9 kts	8 kts	8 kts
20 s	11 kts	11 kts	11 kts

Table 17: Total wind threshold required to allow a given time spacing reduction

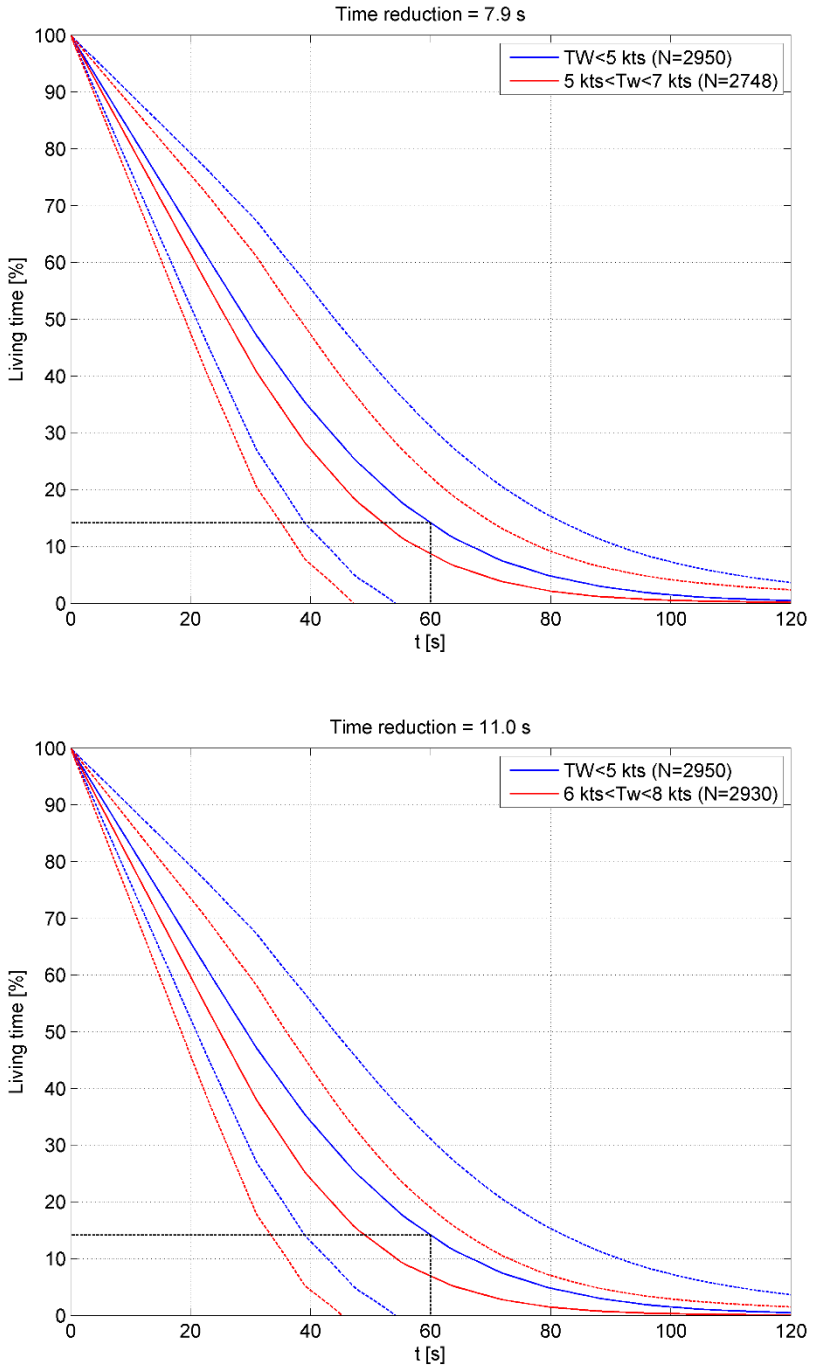

Figure 18: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total wind of 6 kts +/- 1 kt (red, top) and of 7 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

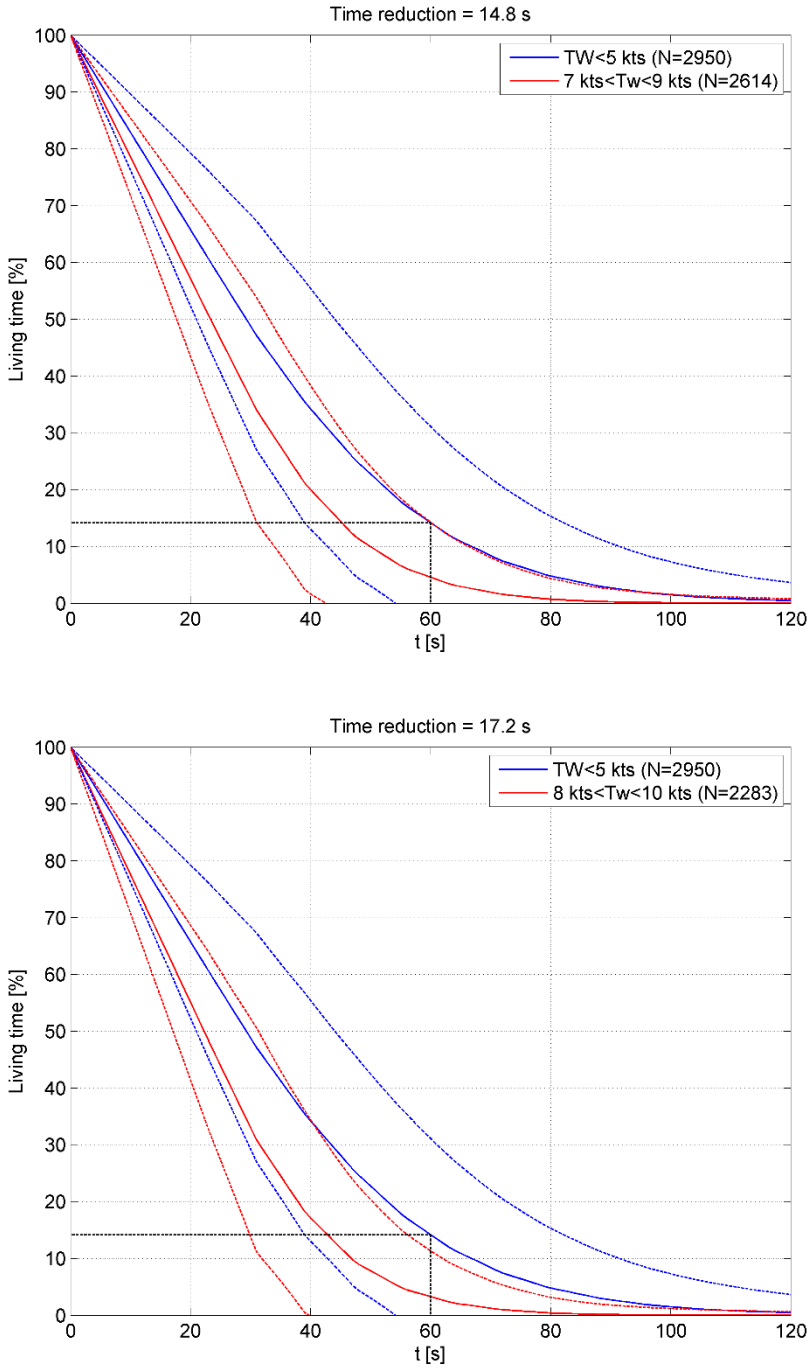

Figure 19: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total wind of 8 kts +/- 1 kt (red, top) and of 9 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

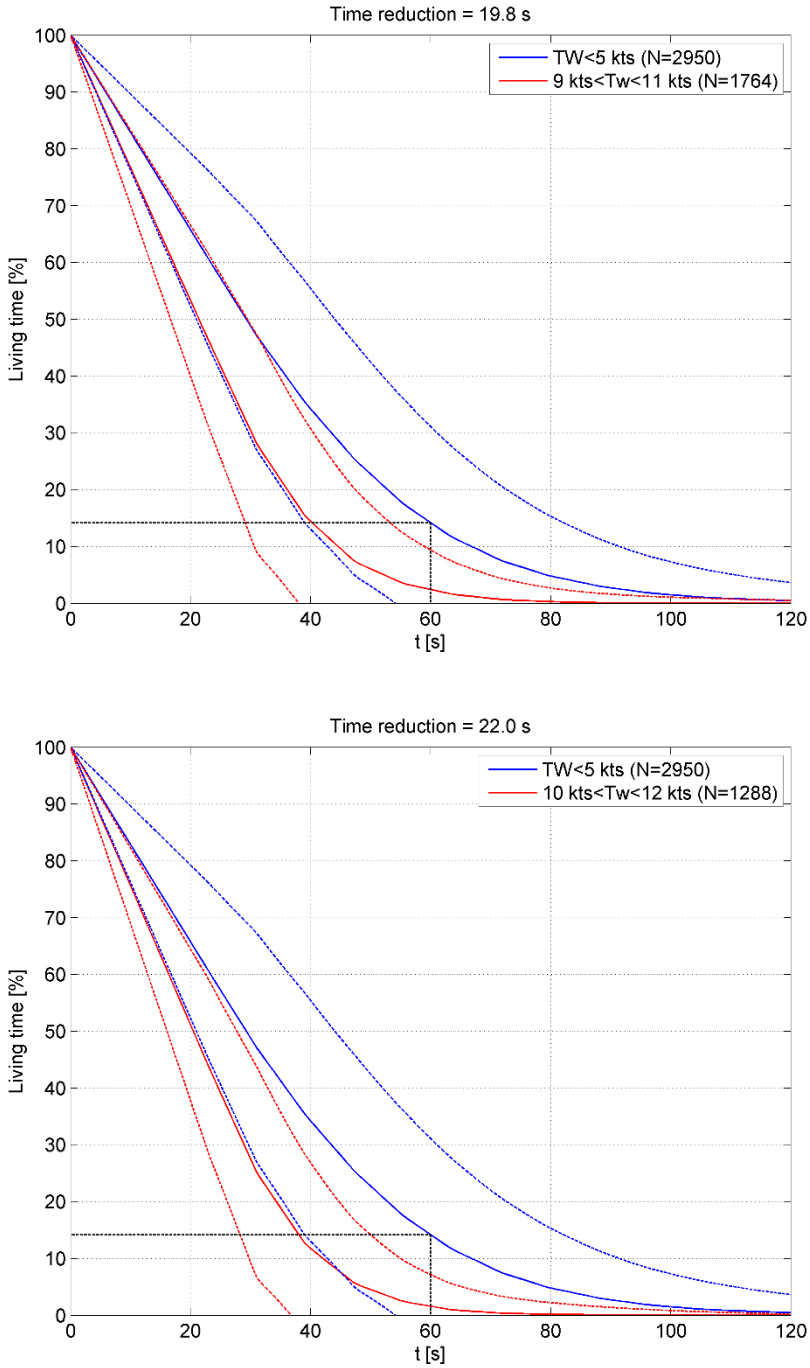

Figure 20: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total wind of 10 kts +/- 1 kt (red, top) and of 11 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

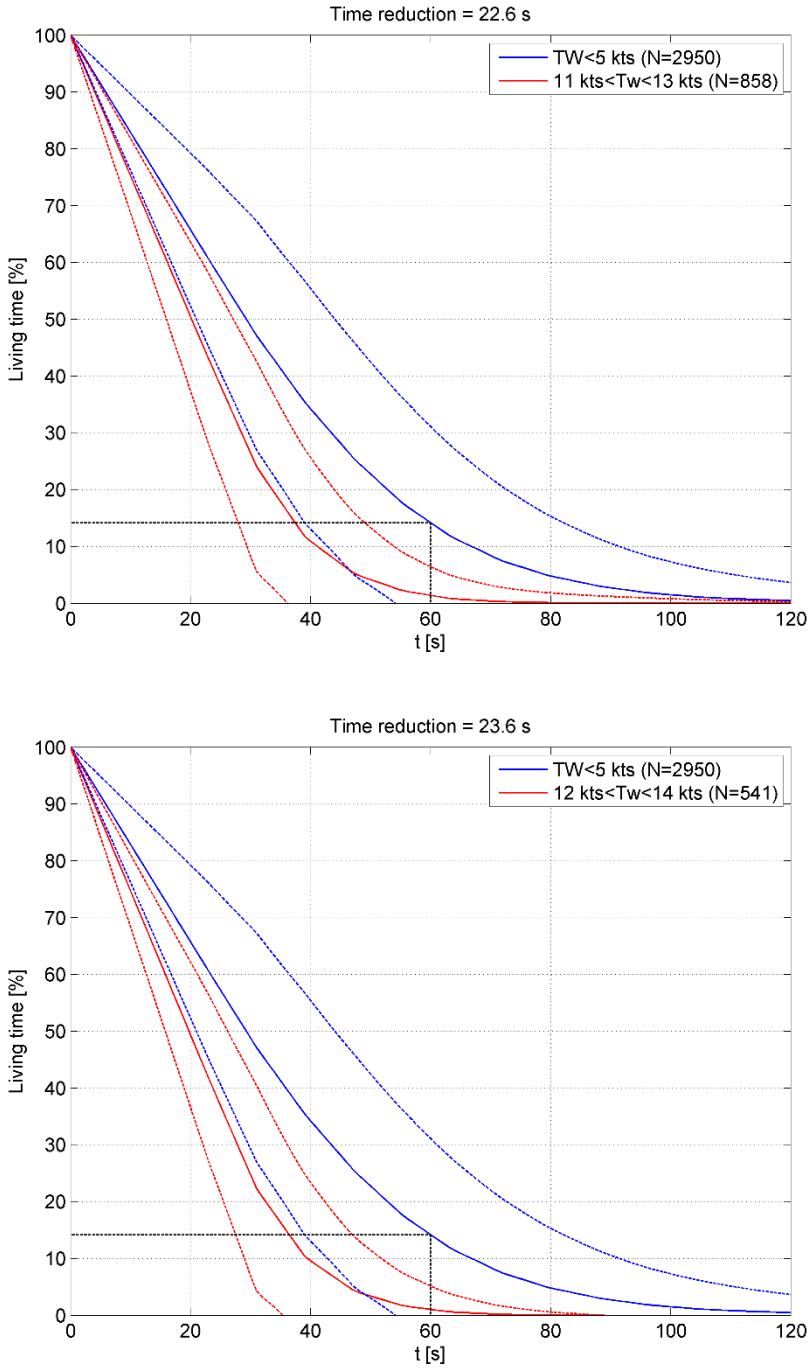

Figure 21: Statistics (mean (solid), mean +/- 1 std (dash)) of the living time for a total wind of 12 kts +/- 1 kt (red, top) and of 13 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

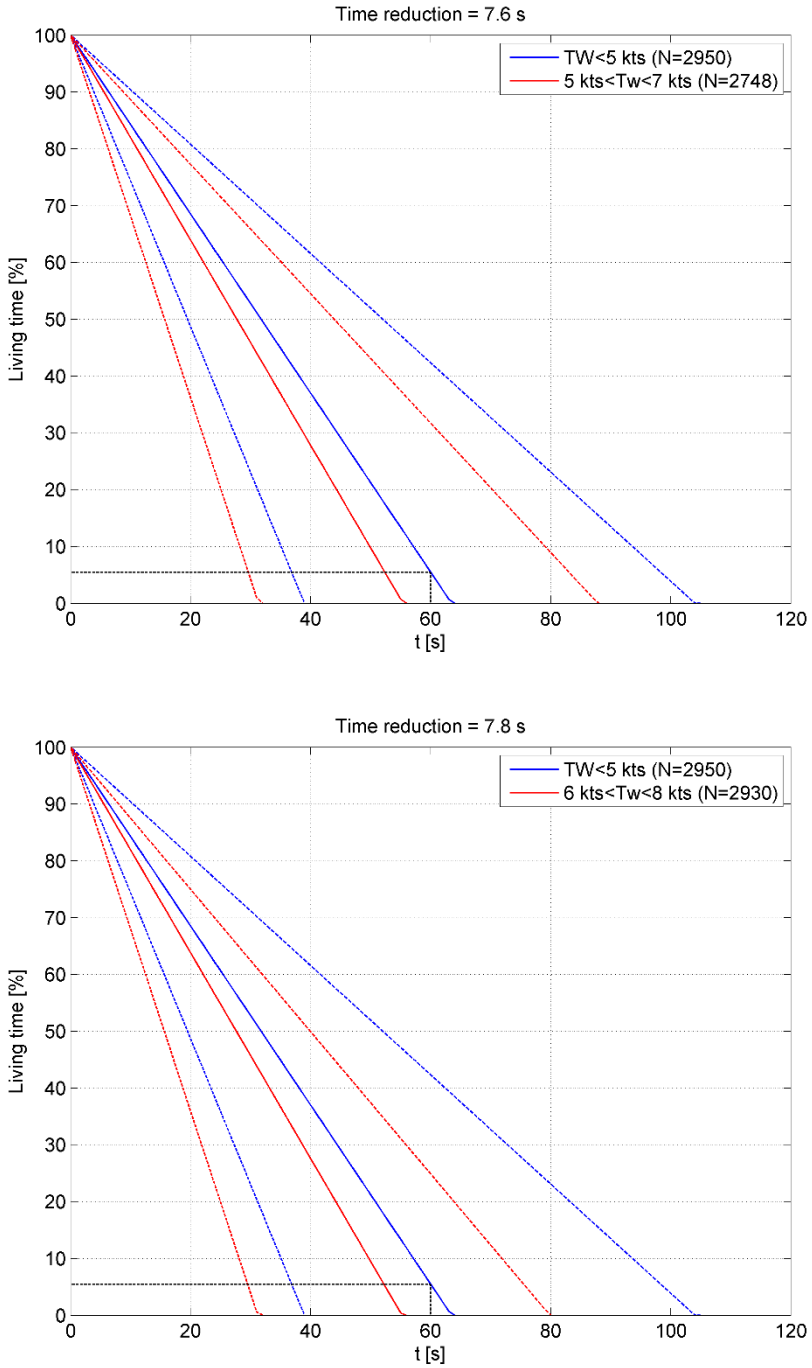

Figure 22: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 6 kts +/- 1 kt (red, top) and of 7 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

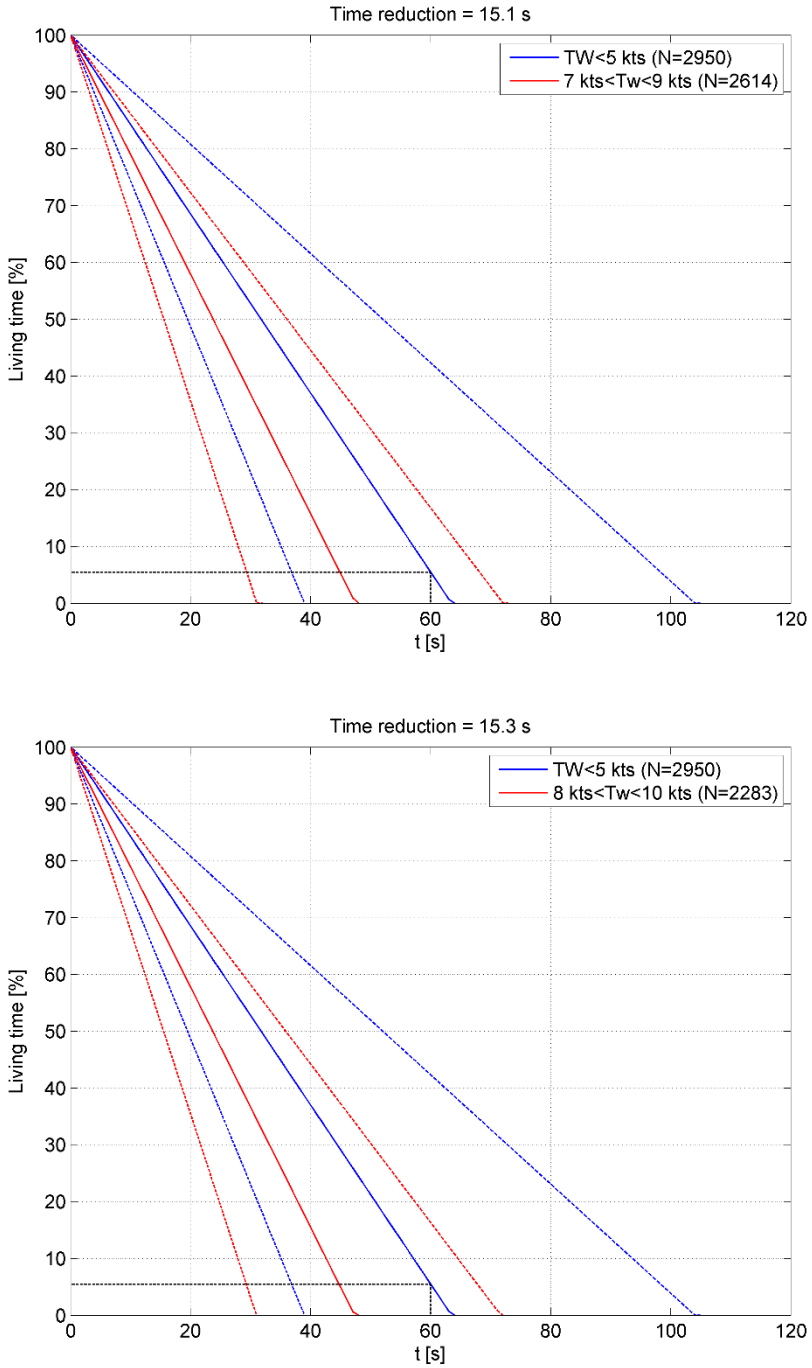

Figure 23: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 8 kts +/- 1 kt (red, top) and of 9 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

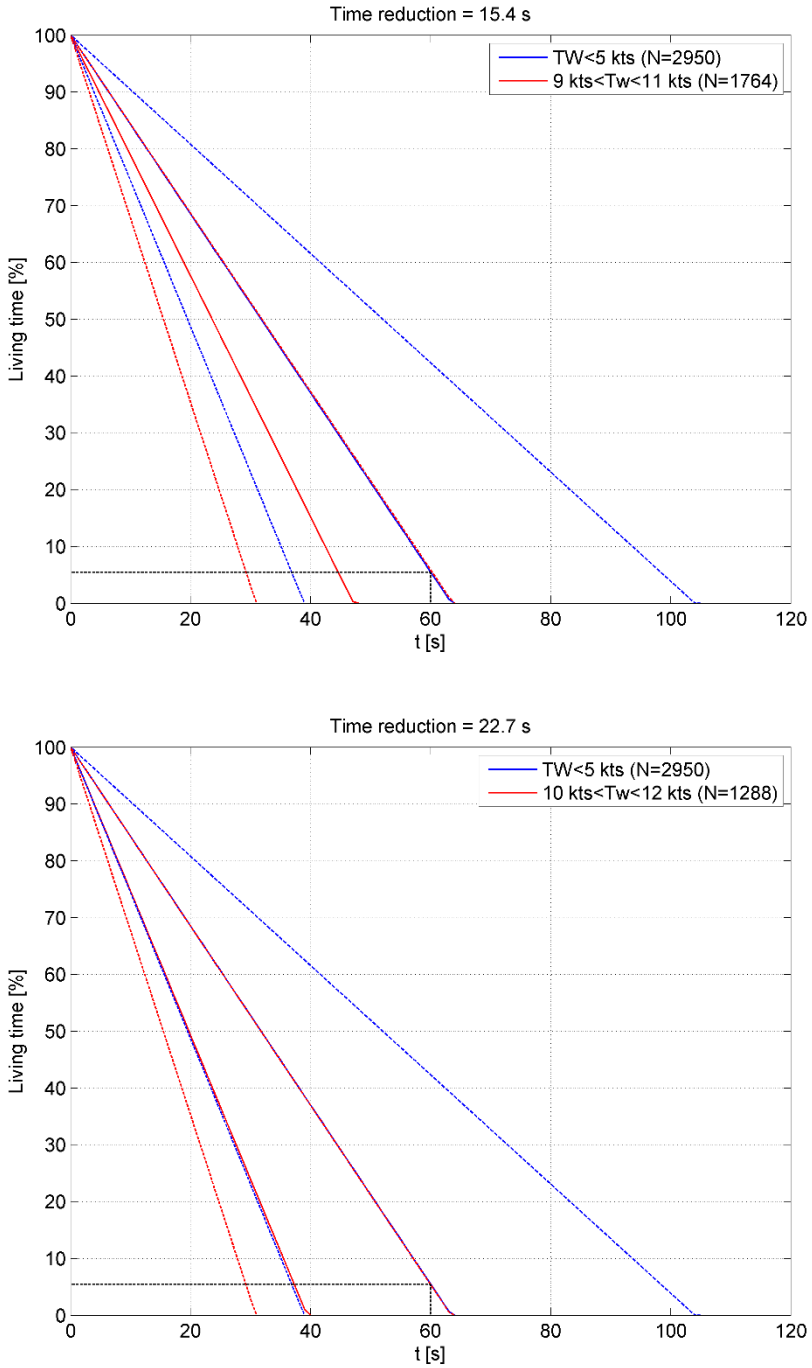

Figure 24: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 10 kts +/- 1 kt (red, top) and of 11 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

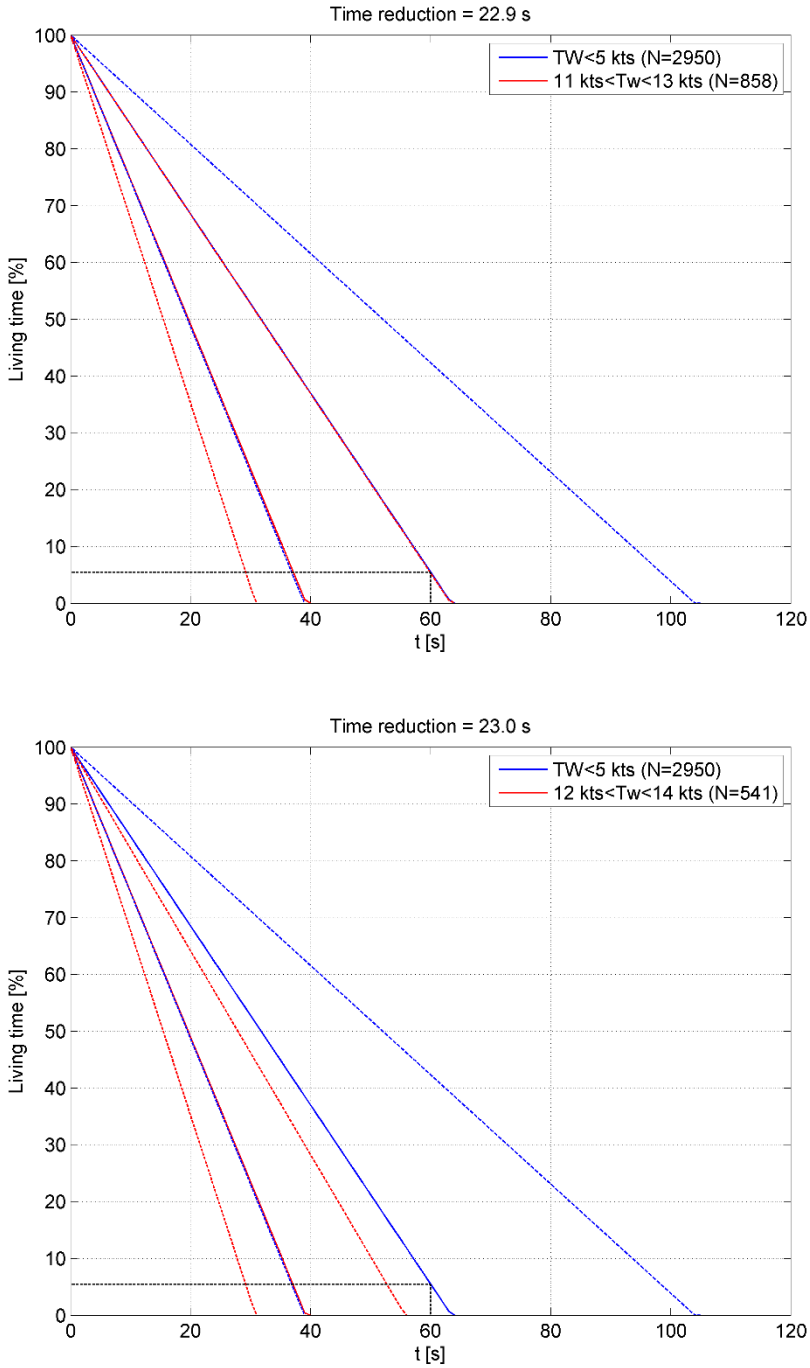

Figure 25: Statistics (median (solid), p10/p90 (dash)) of the living time for a total wind of 12 kts +/- 1 kt (red, top) and of 13 kts +/- 1 kt (red, bottom) compared to the baseline (blue)

4.3.4 Risk assessment results for vortices generated by SUPER-HEAVY aircraft types

In the available databases, no sufficient LiDAR tracks are available for SUPER-HEAVY aircraft generators. Therefore, the same analysis as that performed in Section 4.3.2, for HEAVY aircraft types, cannot be reproduced here. However, it is to be noted that since the time-separation to be applied behind SUPER-HEAVY aircraft are larger than those to be applied behind ICAO HEAVY aircraft types, the expected total wind thresholds are lower or equal to those found in Section 4.3.2.

Indeed, as illustrated in Figure 26, if one considers various circulation decay curves (using a simple two-phase decay model[2]) for increasing wind conditions (wind 1< wind 2 < wind 3< wind 4) and various TBS to be applied:180 s, 150 s and 120 s, one notes that :

- in order to obtain the circulation value, observed for wind 1 conditions after 180 s, 30 s earlier (i.e., at t=150 s), a wind comprised between wind 2 and wind 3 is required; whilst
- in order to obtain the circulation value, observed for wind 1 conditions after 120 s, 30 s earlier (i.e., at t=90 s), a wind condition corresponding to wind 3 is required.

Therefore, the wind thresholds established for ICAO HEAVY constitute upper bounds for SUPER-HEAVY leader aircraft types.

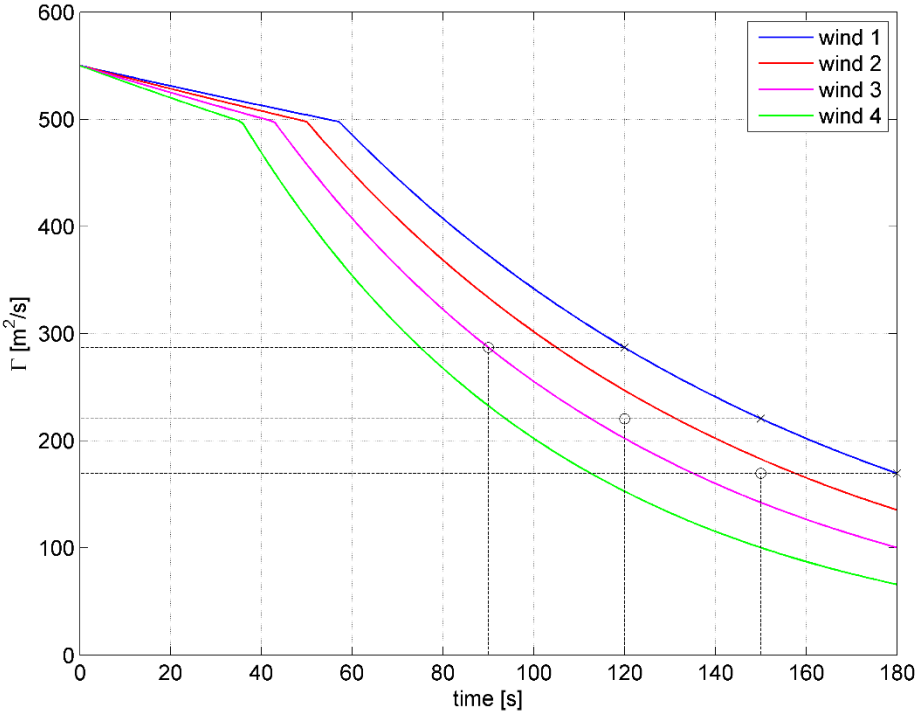

Figure 26: Illustration of the required wind threshold for a 30 s reduction depending on the baseline time spacing

4.4 TBS Wake vortex encounter risk assessment for Out-of-Ground Effect (OGE) long lasting wakes

As stated in RECAT-EU safety case[9]:

"When vortex transport and decay characteristics are influenced by the ground (usually on approach) then the vortex is said to be In Ground Effect (IGE). When a vortex is IGE the sink rate may be reduced or, in some circumstances, may be reversed leading

[2] $\Gamma = \Gamma_0 \exp\left(-\alpha_1 \frac{t}{t_d}\right)$ $if\ t < t_d$, $\Gamma = \Gamma_0 \exp\left(-\alpha_2 \frac{(t-t_d)}{t_d} - a_1\right)$ $if\ t > t_d$ with $a_2 > a_1$ and t_d decreasing with the wind.

to the vortex "stalled" in the final approach path of the generator or even rising above the final approach path of the generator. Wake vortices in IGE generally decay faster than those that are out-of-ground effect (OGE)".

The reasonable worst-case selected for the TBS design corresponds to NGE/IGE region for wake generation at altitude (around Heavy generator wingspan altitude above ground). Although in NGE/IGE, the wake decay is however significantly more rapid than higher on the glide, this altitude is identified as the highest WT risk location and relevant for separation design case, considering the possible stalling of WV in the final approach path and the remaining low altitude for WVE recovery.

In OGE, (hence, at higher altitude on the final approach path), while wake decay will be slower, the natural sink rate of the wake is likely to move the vortices below the following aircraft trajectory. However, before and during the ILS interception, the lateral and vertical variability in the aircraft trajectories can increase the frequency of occurrence of WVE while the potential strength of the encountered wake can also be up to 2 times more significant than close to ground, but with more margin for recovery.

It is worth to note that, in OGE situation, the WT risk is mitigated by the vortex transport. At those altitudes, the wind amplitude is on average higher and the vortices sink due to their mutual interaction (note that in RWC meteorological conditions the stratification is low, hence the stratification-induced rebound is here not considered). Due to its larger circulation, the sink rate of the vortices generated by the large aircraft types is larger than that of vortices generated by smaller aircraft types. Moreover, since the separations to be applied behind the strongest generators are larger than those to be applied behind weaker leaders, the vortices have "more time" to be transported by the wind and to descend bellow the ILS.

Since the risk must be acceptable at any location where the TBS are applicable, an analysis on the impact on risk (severity in RWC) is also developed hereafter for OGE region of flight.

4.4.1 OGE LiDAR database

For that purpose, the wake decay evolution for OGE conditions is determined using LiDAR measurements from London Heathrow (EGLL).

The Lockheed-Martin "WindTracer" LIDAR (Light Detection and Ranging) sensor equipment owned by EUROCONTROL has been used to capture wake vortices generated by aircraft on westerly approaches to London Heathrow airport. The LiDAR is the same as that used in the EGLL-1 IGE/NGE campaign.

For the OGE LIDAR data collection campaign the LIDAR was positioned ca. 1700m south of runway 27L centreline and ca. 3200m south of runway 27R centreline, and approximately 4Nm from the runway landing thresholds. For both runways (27L and 27R) the LIDAR scan plane intercepts the approach paths at ca. 1400ft above sea level (ca. 1320ft above ground level).

The campaign starts in January 2011 and last until end of 2013. Note that due to a series of LIDAR system failures, culminating in the LIDAR being returned to Lockheed Martin for repair, the LiDAR OGE campaign database does not contain two years of measurements. Further details on the data can be found in [17].

The database covers less generator leader aircraft types compared to the IGE database.

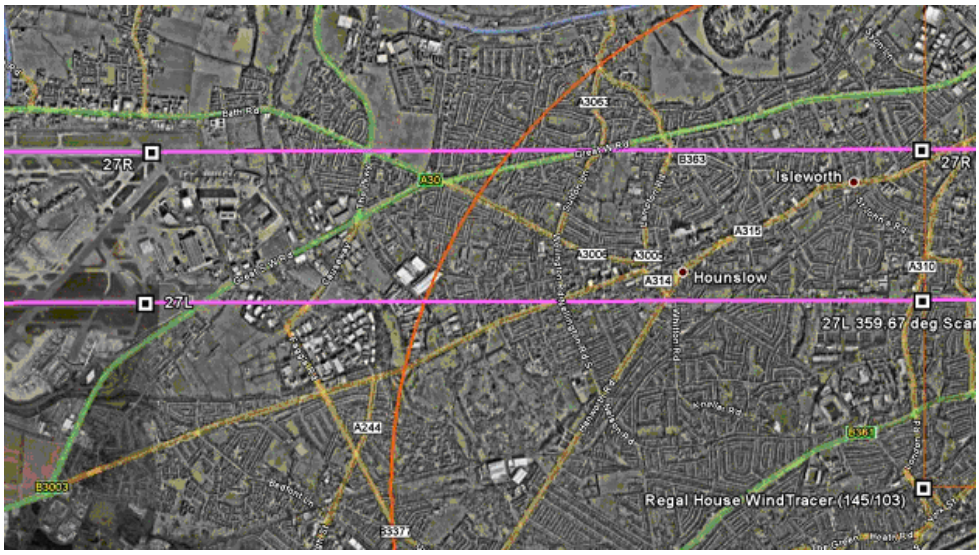

Figure 27: OGE LIDAR location

4.4.2 OGE wake turbulence risk assessment

In this section, the WVE risk related to the application of TBS on the glide is investigated. The analysis is performed in two steps.

First the WVE severity related to the application of TBS is compared to that of the baseline (i.e. DBS in low wind conditions). As what was performed for NGE/IGE region, since the TBS application should be valid for any aircraft pair, the severity is here only characterized by the circulation of the leader-generated vortices at any possible time separation. The follower characteristics (i.e., span, flight speed, aspect ratio, size of the vortex compared to the wing span) that have to be taken into account in a wake encounter severity metrics are indeed unchanged in TBS compared to DBS and can hence be neglected.

As a second step, the probability of WVE in case of TBS application is compared to that when applying DBS in low wind conditions. This study is based on the investigation of the wake transport in case of strong wind conditions.

4.4.2.1 OGE wake decay depending on the wind

The analysis performed in this section is similar to that performed for IGE/NGE data.

In particular, as detailed in Section 4.2.1, some fitting and filtering of the LiDAR circulation data is performed.

As what was presented in Section 4.2.3.2 for IGE/NGE data, for each leader HEAVY aircraft for which sufficient LiDAR measurements are found in the database, and for various headwind values (measured at the ground) HW ranging from 7.5 kts to 17.5 kts by step of 5 kts the statistics (mean, 50th, 75th and 90th percentiles) of the circulation are computed. In order to obtain more statistically converged results, for each headwind value HW, all tracks for which the headwind was measured within a range HW +/- 2.5 kt are used. The baseline corresponds to the tracks for which the measured headwind was below 5 kts. The vortex circulation statistics are then compared for time separations ranging from 46 to 173 s (i.e., time covering all time separations behind HEAVY aircraft). The results are provided in Figure 28 for large Heavy-generated vortices and in Figure 29 for all Heavy-generated vortices.

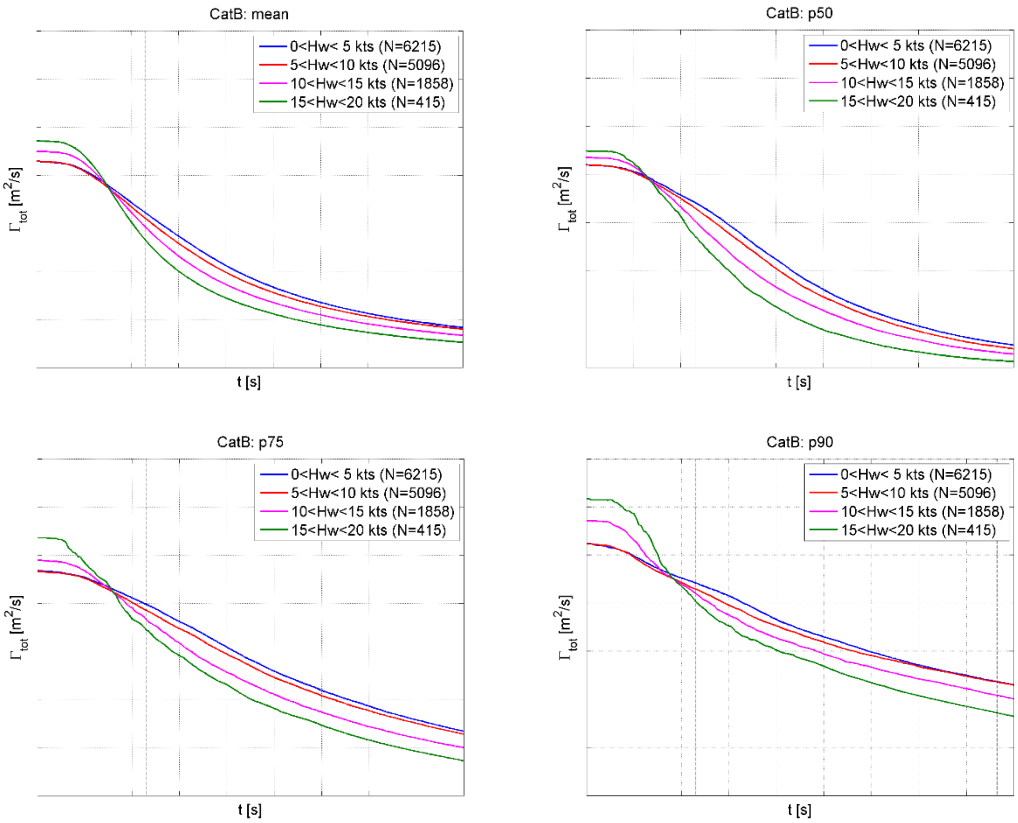

Figure 28: Wake circulation evolution depending on the headwind for large HEAVY (RECAT-EU Cat-B)- generated vortices

When considering vortices generated either by any HEAVY aircraft type or only by the larger ones, it is noticed that, for headwind values below 10 kts, the circulation evolutions are slightly below or equivalent to that of the baseline, for all considered statistics.

On the contrary, for headwind values larger of equal to 15 kts, the circulation decay is seen to be much enhanced. This can be explained by the fact that, for lower headwind levels, the atmospheric turbulence, which is the key parameter for wake decay OGE, is not strongly linked to the wind, whereas for stronger wind conditions, the atmosphere is also strongly turbulent.

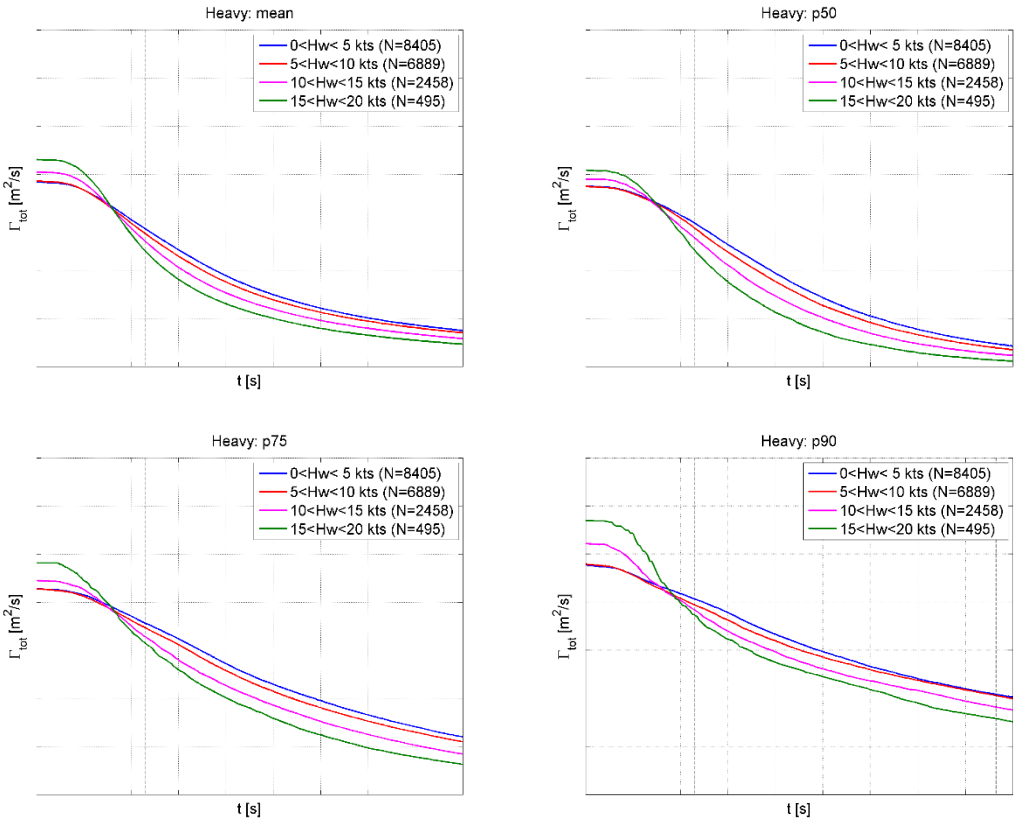

Figure 29: Wake circulation evolution depending on the headwind for HEAVY- generated vortices

Therefore, in terms of encounter severity (i.e., wake circulation), the application of TBS does not appear to lead to an increase of the WVE severity compared to that of the baseline (i.e., DBS in low wind conditions) also for OGE conditions.

4.4.2.2 OGE wake transport depending on the headwind

In out of ground region, the vortices are also transported by the wind reducing the probability for the follower to encounter a vortex. Moreover, it is known that, following a typical wind profile, the wind increases with the altitude and also rotates in altitude due to Coriolis effect. Hence, in presence of headwind close to the ground, the probability to have a significant crosswind component in altitude is high, which significantly reduces the probability to encounter a wake when applying either DBS or TBS.

This phenomenon is highlighted by looking at the percentage of tracks in the LiDAR dataset with at least a certain lasting time as a function of the lasting time and as for various ground (i.e., anemometer) headwind. Figure 30 provides the percentage of remaining tracks in the database for various ground headwind conditions (various intervals of 5 kts) and for vortices generated by large HEAVY or any HEAVY aircraft types. As the headwind increases, the percentage of remaining tracks decreases more rapidly. For example, after 60 s, about 65 % of the tracks are still measured in low wind conditions whereas only about 15% are still measured for headwind above 15 kts.

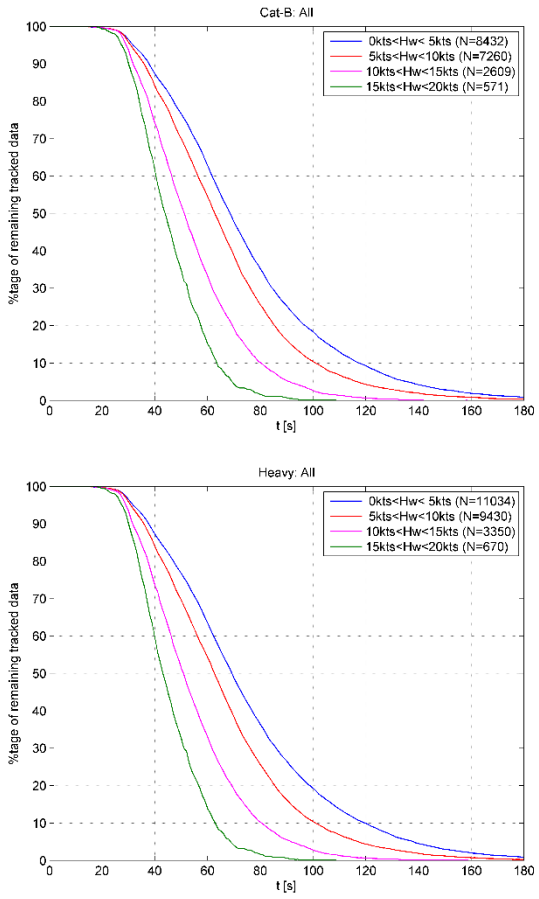

Figure 30: Evolution of the percentage of remaining tracks in the LiDAR dataset of large HEAVY- (left) and HEAVY- (right) generated vortices depending on the headwind.

However, the reason for which the LiDAR tracks are no longer measured are not identified in the results of Figure 30. In order to isolate the transport effect, each "stopped" track is extrapolated at what would have been the next measurement time (i.e., last time + 8s). In case the obtained position is outside of the scanning area, the track is considered to be stopped because of transport of the vortices. An example of identified track is provided in Figure 31. The extent of the scanning area (also shown in Figure 31) has been identified based on the measured position for all vortex tracks.

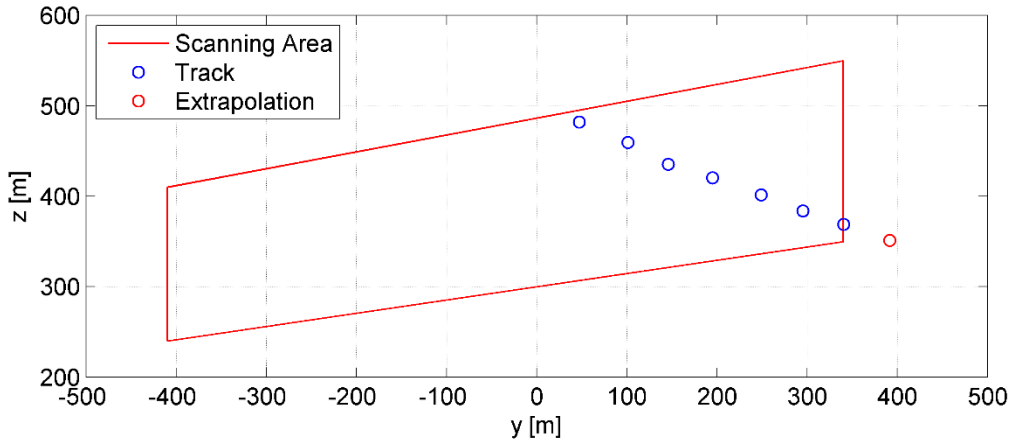

Figure 31: Example of LiDAR track stopped because of vortex transport outside of the scanning area

Using a reduced dataset solely composed of the tracks identified as stopped because of wake transport outside of the scanning area, the percentage of remaining tracks in the dataset is computed depending on the ground headwind. The results are provided in Figure 32. One observes that the wake transport is seen to be more significant for headwind above 5 kts and significantly more significant for headwind above 10 kts.

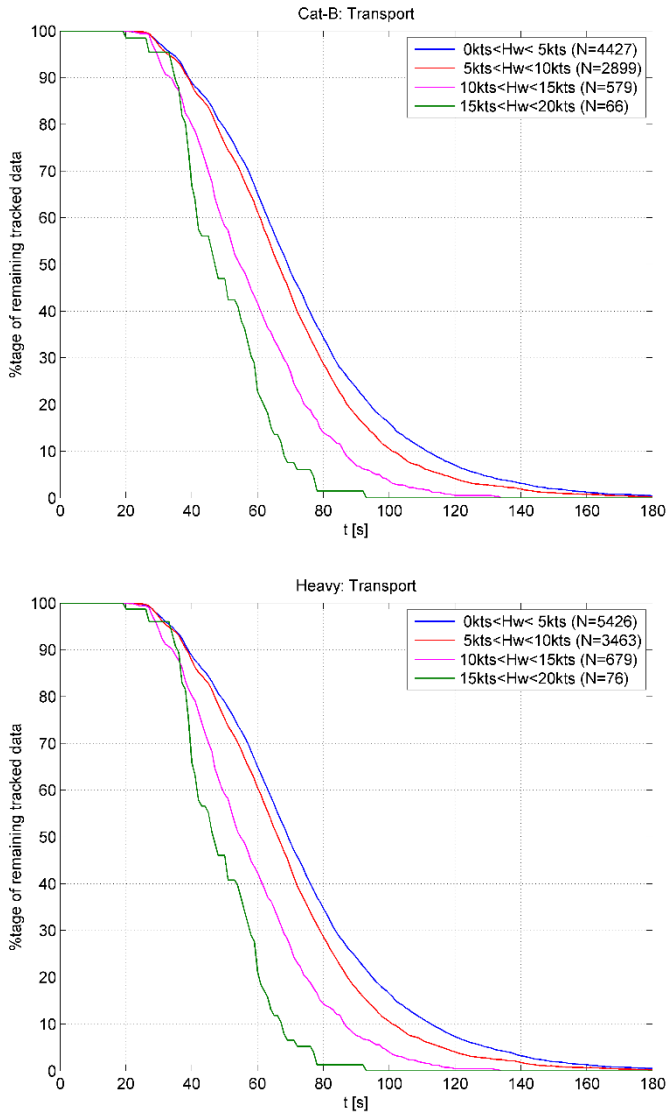

Figure 32: Evolution of the percentage of tracks not transported outside of the scanning area in the LiDAR dataset of large HEAVY- (top) and HEAVY- (bottom) generated vortices depending on the headwind.

If we consider that when the vortex has left the scanning area, it can no longer be encountered by a follower aircraft, the results of Figure 32 directly provides an image of the probability of wake vortex encounter.

It can hence be concluded that, in OGE region, because of the wake transport by the wind, for a given time separation, the probability to encounter a wake is lower in strong headwind conditions compared to the baseline case (low headwind conditions).

When applying TBS, the probability to encounter a wake is hence lower compared to that when applying DBS in low wind conditions.

5. Operational applications

5.1 TBS with support delivery tool: operational application and experience

5.1.1 Application

Equivalent time-based separation (TBS) to a selected applicable distance-based separation may be applied in the final approach phase when an ATS surveillance service is provided, subject to the approval of the competent authority.

(a) As an alternative to the wake turbulence separation minima prescribed in accordance with AMC6 and AMC7 ATS.TR.220, an ATS provider may decide to implement TBS supported by a dedicated traffic display integrated to ATS surveillance service or parts thereof.

(b) TBS minima should be derived from the applicable distance minima prescribed for wake turbulence and ATS surveillance service, using the local time-to-fly profiles on final approach measured in low wind conditions.

(c) The applicable minimum should be presented on the traffic situation display using:

- the sequence of arrival flight identified in the ATS system

- the flight plan data and TBS minima established under (b)

- the wind conditions in the final approach segment

- an appropriate graphical representation

- an alerting function for non-conformant final approach airspeed behaviour, cases of possible separation infringement and in case of a change to the aircraft sequence

The implementation of TBS is considered to be a change to the ATS provider functional system and, as such, is supported by a safety assessment, in accordance with ATS.OR.205 in Annex IV to Regulation (EU) 2017/373. Any such implementation should provide clear operational benefits.

Due to the effect of headwind on the decay and transport of wake turbulence, the principles of separation based on equivalent time minima (as described in AMC) for arrivals provide the same level of safety assurance as separation based on distance (AMC 6 and 7) and therefore should not be re-assessed.

5.1.2 London Heathrow TBS operation experience

TBS operations on final approach have been introduced at London Heathrow from March 2015.

It is reported in [16] that the introduction of TBS has delivered major benefits to Heathrow Airport, the airlines and the flying public. TBS is delivering a reduction in wind related ATFM delay of over 60%.

This is achieved by an average increase in the landing rate of 1.2 arrivals per hour over distance-based separations across all wind conditions, increasing to an average of 2.9 arrivals per hour in winds over 20kts.

As a result of this, there has been a marked reduction in weather related flight cancellations.

In delivering these benefits Wake Turbulence Encounter & Go-Around analysis has shown that there has been no increased risk to Wake Turbulence Encounters and no increase in the number of go-arounds following introduction of TBS.

5.2 Procedural Wind-Based Conditional Reduction of Separation: concepts and applications

5.2.1 Introduction

Procedural application of TBS as transitional step, without the use of a separation delivery tool, can also be developed and operated, on the basis of principles developed in this safety case.

Those procedural concepts are transitional steps proposing a change in the current ATM procedures that will enable controllers under specified wind conditions to apply reduced separation.

Two types of concepts are proposed:
(1) fixed reduction of the applicable wake turbulence distance-based separation minima for wind conditions above certain threshold, and
(2) delivery of the applicable wake turbulence and surveillance distance-based separation minima at a point located upstream the runway threshold.

These concepts of conditional reduction of separation shall be designed such as to maintain an acceptable level of safety using the TBS safety principles described in the above sections.

The wind threshold criteria are defined in terms of already available wind sensor information (e.g. surface wind, SODAR if available) in order to make the concept implementation easier (« quick win »).

5.2.2 Examples of derived concepts

5.2.2.1 WINDSEP with shifted Separation Delivery Point

Because of the deceleration profile of the aircraft down to their stabilized final approach speed, if delivering the separation at a displaced delivery point (DP), compression beyond the delivery point will be observed resulting in a reduction of spacing obtained at threshold. Therefore, by allowing to “deliver” separation at a shift delivery point, the obtained separation at runway threshold are reduced. This concept is illustrated in Figure 33.

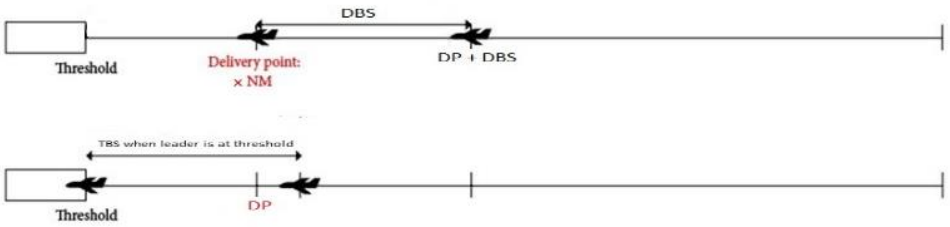

Figure 33: REDSEP scheme: separation delivery at a displaced delivery point

Operationally, this concept can be applied in two different ways.

In order to maximize the throughput benefits when the wind conditions are met, the concept can be applied strategically by the ATC. The Controller then “aims” to deliver the separation at the shifted delivery point. This procedure requires the use by the controller of a simple met tool indicating to the controller that the wind conditions are met for reduced separation and that a certain stability in the wind conditions is to be expected so that the concept can be safely applied. This stability condition will lead to select wind activation criteria above the wind threshold criteria leading in a reduction of the frequency of application but avoiding a toggling ON/OFF of the system.

Another option of application is to allow separation to be delivered below the minima between the shifted delivery point and the runway threshold if the wind conditions are met. This concept is allowed as soon as the wind criteria are met and shall avoid unnecessary go-around when wind effect compensate the wake risk. It can however not be used strategically to aim for reduced separation. Compared to the first version, the frequency of application is hence larger since no wind stability criterion has to be considered. This second concept could be operated with or without specific wind tool depending on the complexity of the defined wind criteria.

5.2.2.2 Wind-Based reduced distance separation delivery

The objective of those concepts is to allow for wind-based conditional wake separation reduction in very strong wind conditions. This would allow to reduce significantly the wake separation minima for the days of very strong wind conditions, for which significant delays are observed in airports.

The objective is to define wind threshold criteria above wind a fix reduction of separation (e.g. 1 NM for all wake pairs and not below surveillance and ROT minima) is allowed.

In order to apply such concept, a simple met tool is required indicating that the wind criteria are met and guaranteeing a certain wind stability.

5.2.3 Methodology for definition of local concept applicability conditions in support of local safety case

In the case of procedural application, the determination of the eligible pairs and of the local wind threshold criteria for its conditional application shall account for three possible risks:

(1) the wake turbulence encounter related risk,

(2) the risk of provision of spacing below minimum runway occupancy times and,

(3) the wind uncertainty and evolution risk.

The risk assessment is then based on the characterisation of the time-to-fly for aircraft pairs on final approach depending on the wind conditions using local traffic and wind data.

The wake turbulence encounter safety assessment analysis to be performed is based on the TBS principles. It thus consists in verifying that, when applying the procedural concept at minima with wind conditions above the wind threshold criteria, the obtained time separations delivered at runway threshold do not fall below the weather (i.e head- and/or cross and/or total wind)-dependent minima that are function of the wind. The analysis shall be based on local surveillance and wind data covering at least one year of operation and with wind information that correspond to what will be used when operating the procedural concept.

The risk of provision of time-spacing below minimum runway occupancy times and the related risk of go-arounds (due to still blocked runway) is assessed by verifying that when applying the procedural concept at minima and with wind conditions above the wind threshold criteria, the obtained time separations at threshold are above standard runway occupancy times (ROT) of the leading aircraft applicable in the considered airport and runway.

Finally, the risk related to the wind temporal evolution, between the decision time to apply procedural TBS and the actual time of aircraft landing, is assessed by considering, in the wind threshold determination, only wind information as available at the procedural concept “decision” time (typically 5 to 15 minutes before landing

depending on the arrival local procedure). The wind measurement possible evolution between this decision time and the actual wind experienced by the landing aircraft under procedural concept operation is hence accounted for. The risk related to wind measurement error uncertainty is accounted for by using only measurements gathered locally by the measurement devices that will be used operationally.

The wind threshold criteria are to be determined locally and per QFU also considering (in the analysis) the evolution of the wind with altitude.

6. Assumptions and operational limitations

6.1 Operational limitations log

The following Operational Limitations were raised during the safety assessment:

Ref	Operational Limitations	Resolution
L001	The operational application of TBS minima, with the display of equivalent distance to Air Traffic Controllers through a dedicated ATC separation delivery tool is not addressed in this safety case, and must be subject to a dedicated analysis, covering in particular the performance, accuracy and reliability of wind prediction, time-to-fly forecast and the ATC support tool. This will be supported by a EUROCONTROL Specification.	Develop a local safety case covering the local TBS minima, and local TBS separation delivery tool and / or local operating procedures

Table 18: Operational Limitations log

7. Conclusions

This document presents the safety case on Time-Based Separation principles on Final Approach ('TBS Principles) as alternative to Distance-Based Separation, focusing on wake turbulence risk.

With the application of fixed TBS minima between successive arrivals, introducing possible dynamic variation of DBS minima as a function of head wind, some aircraft pairs will be exposed to different wake age compared to their current situation under distance-based separation scheme, and TBS may impact the wake strength that can be potentially encountered.

Safety criterion has been set to assure that the probability per approach of wake turbulence encounter of a given severity for a given traffic pair at TBS minima on final approach segment under any headwind conditions shall not increase compared to the same traffic pair spaced at DBS minima in reasonable worst conditions recognized for WT separation design.

The wake vortex encounter risk related to the application of TBS is therefore evaluated by the comparison of the potential encounter severity in strong headwind conditions to that in low headwind conditions and for the same separation time.

Since the TBS application should be valid for any aircraft pair, the severity is here only characterized by the strength of the leader-generated vortices at any possible time separation.

The wake turbulence risk assessment is based on wake vortex data and operational traffic data, built on around 100.000 wake tracks collected by LiDAR technology. The wake decay is characterised per generator aircraft type and compared between low wind and headwind conditions.

The decay characterisation has first been made at in-ground effect/near-ground effect altitude (close to the ground), which constitutes the reference design case as reasonable worst-case conditions for wake turbulence encounter. A database has been used for characterisation of the wake decay for HEAVY category generator types, and another dataset for the MEDIUM category generator types. The comparative results show the expected effect of the headwind on the vortex decay allowing the satisfaction of the safety criterion.

The decay has also been characterised for out-of-ground effect to complement the analysis for other altitude range on final approach. In terms of encounter severity (i.e., wake circulation), the application of TBS does not appear to lead to an increase of the WVE severity compared to that of the baseline (i.e., DBS in low wind conditions) also for OGE conditions. In OGE region, because of the wake transport by the wind, for a given time separation, the probability to encounter a wake is lower in strong headwind conditions compared to the baseline case (low headwind conditions).

On this basis, the wake turbulence encounter risk assessment has verified that TBS minima converted from DBS minima in low wind conditions are acceptably safe in principle due to the effect of wind on wake decay.

Moreover, in case of strong wind conditions, the positive impact of the total wind on the wake decay allows for further reduction of the time separations even below the TBS minima. The allowed time separation reductions below TBS minima, called TBS margins, have also been determined depending on the leader type and on the surface total wind condition using the two LiDAR databases described above.

The statistics of TBS minima will need to be established on a local basis, based on local characterisation of the time-to-fly for aircraft pairs on final approach. This will be supported by a EUROCONTROL Guidance material.

Example of median TBS minima obtained from speed profile measurements, and corresponding time-to-fly, are provided in Annex.

The operational application of TBS minima, with the display of equivalent distance to Air Traffic Controllers through a dedicated ATC support tool is not addressed in this safety case, and must be subject to a dedicated analysis, covering in particular the performance, accuracy and reliability of wind prediction, time-to-fly forecast and the ATC support tool. This will be supported by a EUROCONTROL Specification.

Procedural application of TBS as transitional step, without the use of a separation delivery tool, can also be developed and operated, on the basis of principles developed in this safety case.

ANNEX A TBS Minima examples

A.1 TBS minima calculation method

The time separations to be applied at threshold (or another reference delivery point (e.g. 1NM from threshold)) are calculated using a Distance-Based Separation (DBS) table (here ICAO and RECAT-EU DBS schemes are used as example) and the approach speed profile in low wind conditions (here lower than 5 kts). The latter is expressed as the time-to-fly ($T2F$) profile, namely the time for the aircraft to travel a certain distance to threshold.

The time separations are computed as follows:

- for an application at threshold:

$$TBS(lead, foll) = T2F_{foll}\big(DBS(lead, foll)\big)$$

- for an application at 1NM from threshold:

$$TBS(lead, foll) = T2F_{foll}(DBS(lead, foll) + 1NM) - T2F_{foll}(1NM)$$

Where $DBS(lead, foll)$ is either the RECAT-EU DBS or the ICAO DBS, and $T2F_{foll}(x)$ is the time-to-fly in low wind conditions of the follower aircraft at a distance x from threshold. In what follows, and because of the availability of T2F measurements down to 1 NM from thresholds, a delivery point corresponding to 1NM from threshold is used.

Note that because a distribution of T2F is observed in low wind conditions, the distribution of TBS minima have to be determined based on some statistics of the T2F distribution. As an example, in what follows, the median TBS minima are established. The same approach shall be applied to characterized e.g. the 10th and 1st TBS quantiles using the 10th and 1st T2F quantiles, respectively.

A.2 Low wind time-to-fly database

The RADAR measurements database initially used for the determination of typical speed profiles was collected as part of the EUROCONTROL ORD study [13].

This database provides distance against time separations for a large range of aircraft types and wind conditions measured in 5 different European airports. The data sets per airport cover at least several months of data in 2012 and 2013. In total, the data set counts about 130,000 flights. The number of flights per airport is provided in Table 19.

Airport	APT1	APT2	APT3	APT4	APT5
Total number of flights	28,395	35,724	2,524	36,921	25,521

Table 19: Number of flights per airport

The data includes more than 160 aircraft types, though the 25 most frequently occurring types that represent 95% of the traffic. Figure 34 provides the histograms of aircraft types for the various airports.

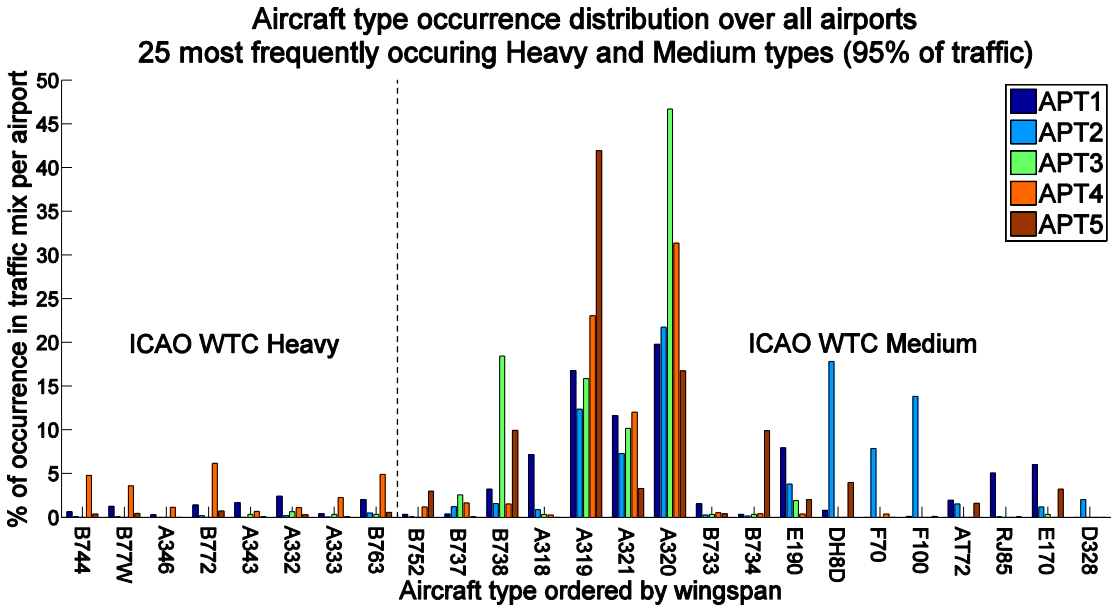

Figure 34: Histograms of RADAR tracks collected per aircraft type and per airport

For each flight, time, lateral and longitudinal position coordinates, altitude, ground speed, and aircraft type were available. The position data has been converted to distance to threshold. For this, the coordinates of the runway thresholds have been used. The runway concerned for a certain track – if not available in the data – is determined based on course of the track and the distance of the track points to the runway threshold. To limit the data to the area of interest, being the final approach where the approach path follows the extended runway centreline, the data per flight is limited to the last 20 NM before the runway threshold and only flights for which the ground speed in all data points exceeds 50 kts and for which these data points are complete are taken into account.

From the RADAR measurements were extracted the time at which the aircraft reaches various distances from threshold. From those reference times, the times required for the aircraft to travel those various distances from threshold are determined building a 'time-to-fly' profile from each RADAR track. The time-to-fly profile allows the transposition of distance separations to corresponding time separations and hence vortex age.

The database contains more than 50.000 flight tracks measured in low wind conditions used to derive final approach speed profiles. In order to derive time separation equivalent to distance separation, only RADAR measurements collected under low head-wind condition were considered: lower than 5 kts headwind measured at the runway threshold. Those measurements were available for 91 aircraft ICAO types.

Example time-to-fly profiles for various aircraft type are provided as illustration in Figure 35.

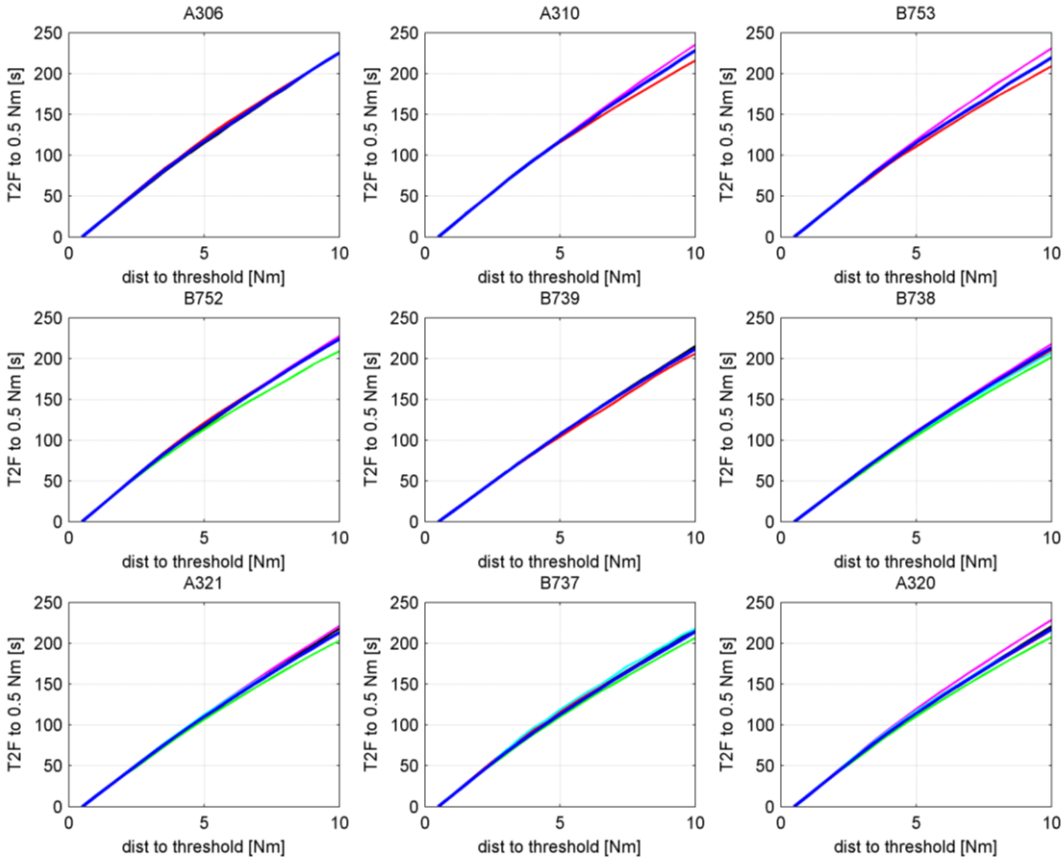

Figure 35: Example for some aircraft type of P50 of the Time-to-fly to 0.5 NM from runway threshold measured in low headwind conditions (<5 kts) in various airports and p50 of all data (blue)

In this figure, the p50 (50th percentile of data) profiles collected in various airports are also shown. One observes that for aircraft types for which sufficient amount of data are collected in various locations, the p50 profiles are consistent.

The T2F profiles are also compared to those that were used in the framework of RECAT-EU. For time-to-fly from 6NM to 1 NM, the p50 difference between the two databases is lower than 2 s.

For two aircraft types of the 96 list (i.e. the MD83 and SF34), no sufficient measurement of speed profiles are found in the database.

Given the good consistency between this database and that from RECAT-EU, the RECAT-EU speed profiles are eventually used therefore.

For one aircraft type (i.e. BE40), no sufficient measurements are available in low headwind conditions (i.e., headwind<5 kts), but a sufficient amount is available for moderate headwind conditions (i.e., <10 kts). For that aircraft, the time-to-fly profile is obtained from that measured in moderate wind conditions corrected to account for the effect of the headwind on the time-to-fly (i.e., increase of the time-to-fly caused by the decrease of the ground speed).

Using the complete dataset, it is found that the time-to-fly in moderate wind condition is 0.56 s/NM larger than that measured in low wind conditions. This correction is therefore used for the BE40.

Finally, for the A350 family aircraft types (i.e., A35K, A359), no time-to-fly profile measurements are available. Therefore, as performed in the A350 wake turbulence categorisation safety case [22], the time-to-fly profile is created based on that

measured for the roughly similar sized A340-300 aircraft type albeit adjusted for the higher final approach speeds of the A350-900 and -1000 aircraft types by adapting the final phase (i.e. the last 3.5 NM) of constant approach speed while retaining the initial approach speed as well as the speed reduction, since these are not specific to the aircraft type. The correction was made using a landing speed based on the manufacturer's reference landing speeds, MLW and typical operational weight.

A.3 Example of median TBS Minima for 96 follower aircraft types

The time-based separations to be applied at 1NM from threshold are here computed using as input:

- the times to fly in low wind conditions, measured in RECAT-EU PWS Safety Case for a selection of 96 aircraft covering CAT-A to F, and
- either the RECAT-EU separation matrix (with mrs=2.5 NM),.
- or the ICAO separation matrix (with mrs=2.5 NM).

A.3.1 Median TBS minima for RECAT-EU scheme

The RECAT–EU WT separation scheme for Approach under surveillance service is provided in Table 20, together with a list of frequent aircraft types assigned into the RECAT-EU categories in Table 21:

RECAT-EU scheme Leader / Follower		*"Super Heavy"* "A"	*"Upper Heavy"* "B"	*"Lower Heavy"* "C"	*"Upper Medium"* "D"	*"Lower Medium"* "E"	*"Light"* "F"
"Super Heavy"	"A"	3 NM	4 NM	5 NM	5 NM	6 NM	8 NM
"Upper Heavy"	"B"		3 NM	4 NM	4 NM	5 NM	7 NM
"Lower Heavy"	"C"		(*)	3 NM	3 NM	4 NM	6 NM
"Upper Medium"	"D"						5 NM
"Lower Medium"	"E"						4 NM
"Light"	"F"						3 NM

Table 20: RECAT-EU WT distanced-based separation minima on approach and departure

(*) means minimum radar separation (MRS), set at 2.5 NM, is applicable as per current ICAO doc 4444 provisions.

A388	A332	A306	A318	AN32	FA10
A124	A333	A30B	A319	AT43	FA20
(…)	A342	A310	A320	AT45	D328
	A343	B703	A321	AT72	E120
	A345	B752	AN12	B462	BE40
	A346	B753	B736	B712	BE45
	A359	B762	B737	B732	H25B
	AN22	B763	B738	B733	JS32
	B744	B764	B739	B734	JS41
	B748	B783	C130	B735	LJ35
	B772	C135	IL18	CL30	LJ60
	B773	DC10	MD81	CL60	SF34
	B77L	DC85	MD82	CRJ1	P180
	B77W	IL76	MD83	CRJ2	C650
	B788	MD11	MD87	CRJ7	C525
	IL96	TU22	MD88	CRJ9	C180
	(…)	TU95	MD90	DC93	C152
		(…)	T204	DH8D	(…)
			TU16	E135	
			(…)	E145	
				E170	
				E175	
				E190	
				E195	
				F70	
				F100	
				GLF4	
				RJ85	
				RJ1H	
				(…)	

Table 21: Example list of aircraft types assigned to RECAT-EU categories (Category names and letters are indicative)

Table **22** to Table **28** provide the time-based separations computed using as input:

- the times to fly in low wind conditions, described here above, and
- the RECAT-EU separation matrix (with mrs=2.5 NM) applied at 1NM from threshold.

	CAT- A	CAT-B														
L/F	A388	B744	A345	A346	B77L	B77W	A351	B773	A342	A359	A343	A358	B772	A333	A332	B788
A	80.3	96.8	95.7	96.1	97.5	95.1	98.5	101.3	103.2	100.8	102.2	102.2	100.6	100.9	104.1	96.9
B	67.1	73.6	72.9	72.9	74.5	72.6	74.9	76.4	80.7	77.2	78.6	78.6	77.3	77.6	80.1	74.2
C	67.1	61.6	61.5	61.1	62.6	60.8	62.3	63.4	67.4	64.6	66.0	66.0	64.9	65.6	67.3	62.8
D	67.1	61.6	61.5	61.1	62.6	60.8	62.3	63.4	67.4	64.6	66.0	66.0	64.9	65.6	67.3	62.8
E	67.1	61.6	61.5	61.1	62.6	60.8	62.3	63.4	67.4	64.6	66.0	66.0	64.9	65.6	67.3	62.8
F	67.1	61.6	61.5	61.1	62.6	60.8	62.3	63.4	67.4	64.6	66.0	66.0	64.9	65.6	67.3	62.8

Table 22: median time separations [s] for CAT-A to Cat-B followers

	CAT- c								
L/F	MD11	B764	B763	B762	A306	A30B	A310	B753	B752
A	116.6	117.0	122.1	128.7	125.4	124.9	126.2	123.4	126.8
B	93.7	94.4	99.7	106.0	103.2	101.5	103.9	102.0	104.3
C	70.9	71.7	76.5	81.2	79.7	78.7	80.1	78.2	80.9
D	59.4	60.2	64.3	68.8	67.4	68.1	67.2	66.4	68.5
E	59.4	60.2	64.3	68.8	67.4	68.1	67.2	66.4	68.5
F	59.4	60.2	64.3	68.8	67.4	68.1	67.2	66.4	68.5

Table 23: median time separations [s] for CAT-C followers

	CAT- D									
L/F	A321	B739	A320	B738	MD83	A319	B737	A318	MD82	B736
A	119.0	117.4	122.7	118.7	124.5	126.8	120.8	125.0	120.8	123.2
B	97.2	95.3	100.8	96.9	103.1	104.8	99.4	103.7	99.3	101.3
C	74.5	71.9	78.0	74.2	80.3	81.7	77.0	80.9	77.3	78.7
D	62.6	60.6	65.8	62.4	67.5	69.1	65.2	68.6	65.4	66.5
E	62.6	60.6	65.8	62.4	67.5	69.1	65.2	68.6	65.4	66.5
F	62.6	60.6	65.8	62.4	67.5	69.1	65.2	68.6	65.4	66.5

Table 24: median time separations [s] for CAT-D followers

	CAT-E																
L/F	B734	B733	B735	B712	E190	RJ1H	B463	GL5T	GLEX	A148	F100	RJ85	GLF5	E170	F70	CRJ9	GLF4
A	147.2	143.6	145.9	145.3	146.0	147.3	148.6	143.4	141.7	139.7	136.9	147.0	141.0	147.8	139.6	143.1	137.5
B	125.3	122.9	124.6	125.6	125.2	127.5	128.6	123.4	122.1	119.5	117.3	126.5	119.7	126.3	119.7	122.6	118.7
C	102.9	101.7	103.3	105.0	103.4	104.4	105.8	102.1	101.0	98.9	96.7	105.1	98.5	104.1	99.2	100.6	97.9
D	66.0	65.7	67.5	68.9	68.2	67.9	71.2	68.0	67.4	65.4	63.7	69.0	64.6	68.9	66.0	64.8	63.4
E	66.0	65.7	67.5	68.9	68.2	67.9	71.2	68.0	67.4	65.4	63.7	69.0	64.6	68.9	66.0	64.8	63.4
F	66.0	65.7	67.5	68.9	68.2	67.9	71.2	68.0	67.4	65.4	63.7	69.0	64.6	68.9	66.0	64.8	63.4

Table 25: median time separations [s] for CAT-E followers (1/2)

	CAT-E																		
L/F	CRJ7	FA7X	DH8D	AT75	AT72	CRJ2	F900	E145	F50	F27	CL60	E135	AT45	FA50	CL30	AT43	F2TH	GALX	J328
A	149.6	146.8	142.9	151.0	153.3	140.2	148.3	145.6	149.4	141.9	142.8	135.6	157.2	133.5	137.4	161.4	144.6	141.9	141.8
B	129.1	124.5	122.7	129.7	132.0	119.8	126.3	123.8	128.2	121.9	120.5	115.8	136.7	112.4	118.3	138.7	122.8	119.9	121.1
C	106.7	101.1	101.6	108.6	109.7	98.2	104.0	101.6	107.2	100.0	99.4	95.8	112.2	91.7	97.8	115.5	102.0	98.9	100.3
D	69.3	67.9	67.5	72.3	73.4	63.8	67.9	65.6	74.3	65.7	66.3	62.9	74.1	61.2	64.7	77.7	68.1	63.3	67.3
E	69.3	67.9	67.5	72.3	73.4	63.8	67.9	65.6	74.3	65.7	66.3	62.9	74.1	61.2	64.7	77.7	68.1	63.3	67.3
F	69.3	67.9	67.5	72.3	73.4	63.8	67.9	65.6	74.3	65.7	66.3	62.9	74.1	61.2	64.7	77.7	68.1	63.3	67.3

Table 26: median time separations [s] for CAT-E followers (2/2)

	CAT-F												
L/F	H25C	D328	C680	SF34	H25B	E120	LJ60	LJ40	LJ45	C56X	LJ35	C25C	BE40
A	159.4	178.9	176.0	193.7	176.8	195.4	174.6	179.3	182.7	179.0	169.8	166.8	179.6
B	141.9	160.5	156.5	172.3	157.3	173.8	156.1	160.6	161.5	161.4	151.6	152.1	160.9
C	123.7	140.6	136.9	151.0	139.2	152.8	135.9	140.1	140.5	142.1	133.2	135.0	141.5
D	105.6	119.9	116.5	129.6	118.2	131.0	114.8	118.7	119.5	121.5	114.0	116.6	121.5
E	87.7	98.7	94.7	108.2	98.5	108.3	94.0	98.5	98.3	99.6	92.9	95.6	100.5
F	68.5	76.2	73.5	85.6	75.8	83.2	71.9	74.5	76.4	78.3	72.1	74.4	78.3

Table 27: median time separations [s] for CAT-F followers (1/2)

	CAT-F											
L/F	C560	C550	C25B	B350	C25A	C501	C525	PC12	C510	P46T	PA34	C10T
A	175.3	184.3	179.0	182.7	177.2	173.9	177.9	196.2	184.9	186.9	195.2	186.4
B	156.3	166.3	159.0	161.4	158.9	154.2	160.0	174.6	167.0	163.5	172.4	165.6
C	137.3	147.2	138.0	140.5	139.4	132.2	140.6	152.7	147.2	140.0	149.7	144.7
D	116.9	126.7	117.4	118.8	119.1	110.8	119.0	134.1	125.4	117.7	127.1	124.2
E	95.2	104.7	97.0	95.9	98.0	89.2	96.5	111.6	102.6	94.8	105.3	103.1
F	73.5	81.4	74.9	72.3	75.9	67.7	74.1	87.4	80.3	72.4	81.4	79.8

Table 28: median time separations [s] for CAT-F followers (2/2)

A.3.2 Median TBS minima for ICAO legacy scheme

The ICAO legacy WT separation scheme for Approach under surveillance service (Doc 4444 PANS-ATM and A380 State Letter on wave vortex) is provided in Table 29:

	A388 follower	HEAVY follower	MEDIUM follower	LIGHT follower
A388 leader		6 Nm	7 Nm	8 Nm
HEAVY leader		4 Nm	5 Nm	6 Nm
MEDIUM leader				5 Nm
LIGHT leader				

Table 29: ICAO PANS-ATM wake turbulence distance-based separation minima on approach and departure

These wake turbulence separation minima are based on a grouping of aircraft types into three categories according to the maximum certificated take-off mass as follows:

HEAVY ("H"): all aircraft types of 136000 kg or more;

MEDIUM ("M"): aircraft types less than 136000 kg but more than 7000 kg;

LIGHT ("L"): aircraft types of 7000 kg or less."

Table 30 to Table 36 provide the time-based separations computed using as input:

- the times to fly in low wind conditions, described here above, and
- the ICAO separation matrix (with MRS=2.5 NM) applied at 1NM from threshold.

	S	H														
L/F	A388	B744	A345	A346	B77L	B77W	A351	B773	A342	A359	A343	A358	B772	A333	A332	B788
S	67.1	141.3	137.6	140.7	140.3	137.9	143.6	149.2	146.7	145.9	147.3	147.3	144.6	145.4	148.2	140.7
H	67.1	96.8	95.7	96.1	97.5	95.1	98.5	101.3	103.2	100.8	102.2	102.2	100.6	100.9	104.1	96.9
M	67.1	61.6	61.5	61.1	62.6	60.8	62.3	63.4	67.4	64.6	66.0	66.0	64.9	65.6	67.3	62.8
L	67.1	61.6	61.5	61.1	62.6	60.8	62.3	63.4	67.4	64.6	66.0	66.0	64.9	65.6	67.3	62.8

Table 30: median time separations [s] for SUPER and HEAVY (1/2) followers

	H						
L/F	MD11	B764	B763	B762	A306	A30B	A310
S	137.5	139.0	143.6	150.8	147.5	145.2	150.0
H	93.7	94.4	99.7	106.0	103.2	101.5	103.9
M	59.4	60.2	64.3	68.8	67.4	68.1	67.2
L	59.4	60.2	64.3	68.8	67.4	68.1	67.2

Table 31: median time separations [s] for HEAVY followers (2/2)

	M											
L/F	B753	B752	A321	B739	A320	B738	MD83	A319	B737	A318	MD82	B736
S	165.2	169.6	161.0	159.4	164.5	160.6	167.2	168.9	161.6	165.1	164.8	164.7
H	123.4	126.8	119.0	117.4	122.7	118.7	124.5	126.8	120.8	125.0	120.8	123.2
M	66.4	68.5	62.6	60.6	65.8	62.4	67.5	69.1	65.2	68.6	65.4	66.5
L	66.4	68.5	62.6	60.6	65.8	62.4	67.5	69.1	65.2	68.6	65.4	66.5

Table 32: median time separations [s] for MEDIUM followers (1/4)

	M																
L/F	B734	B733	B735	B712	E190	RJ1H	B463	GL5T	GLEX	A148	F100	RJ85	GLF5	E170	F70	CRJ9	GLF4
S	168.6	163.8	166.3	164.0	166.3	168.4	167.1	163.1	162.3	160.4	156.1	167.1	161.2	168.4	158.5	162.3	156.5
H	125.3	122.9	124.6	125.6	125.2	127.5	128.6	123.4	122.1	119.5	117.3	126.5	119.7	126.3	119.7	122.6	118.7
M	66.0	65.7	67.5	68.9	68.2	67.9	71.2	68.0	67.4	65.4	63.7	69.0	64.6	68.9	66.0	64.8	63.4
L	66.0	65.7	67.5	68.9	68.2	67.9	71.2	68.0	67.4	65.4	63.7	69.0	64.6	68.9	66.0	64.8	63.4

Table 33: median time separations [s] for MEDIUM followers (2/4)

	M																	
L/F	CRJ7	FA7X	DH8D	AT75	AT72	CRJ2	F900	E145	F50	F27	CL60	E135	AT45	FA50	CL30	AT43	F2TH	GALX	J328
S	169.5	167.4	162.6	171.0	174.8	159.6	169.5	165.7	169.6	161.7	165.0	153.6	177.5	153.0	156.6	182.5	166.4	162.7	160.8
H	129.1	124.5	122.7	129.7	132.0	119.8	126.3	123.8	128.2	121.9	120.5	115.8	136.7	112.4	118.3	138.7	122.8	119.9	121.1
M	69.3	67.9	67.5	72.3	73.4	63.8	67.9	65.6	74.3	65.7	66.3	62.9	74.1	61.2	64.7	77.7	68.1	63.3	67.3
L	69.3	67.9	67.5	72.3	73.4	63.8	67.9	65.6	74.3	65.7	66.3	62.9	74.1	61.2	64.7	77.7	68.1	63.3	67.3

Table 34: median time separations [s] for MEDIUM followers (3/4)

	M													
L/F	H25C	D328	C680	SF34	H25B	E120	LJ60	LJ40	LJ45	C56X	LJ35	C25C	BE40	C560
S	141.9	160.5	156.5	172.3	157.3	173.8	156.1	160.6	161.5	161.4	151.6	152.1	160.9	156.3
H	105.6	119.9	116.5	129.6	118.2	131.0	114.8	118.7	119.5	121.5	114.0	116.6	121.5	116.9
M	58.5	64.9	62.8	73.0	64.2	69.6	59.9	64.7	65.2	66.6	61.0	62.6	66.5	62.2
L	58.5	64.9	62.8	73.0	64.2	69.6	59.9	64.7	65.2	66.6	61.0	62.6	66.5	62.2

Table 35: median time separations [s] for MEDIUM followers (4/4)

	L										
L/F	C550	C25B	B350	C25A	C501	C525	PC12	C510	P46T	PA34	C10T
S	184.3	179.0	182.7	177.2	173.9	177.9	196.2	184.9	186.9	195.2	186.4
H	147.2	138.0	140.5	139.4	132.2	140.6	152.7	147.2	140.0	149.7	144.7
M	126.7	117.4	118.8	119.1	110.8	119.0	134.1	125.4	117.7	127.1	124.2
L	69.3	63.7	60.3	64.5	57.1	62.3	72.3	69.0	61.2	69.6	67.4

Table 36: median time separations [s] for LIGHT followers

References

[1] ICAO, Doc 4444, Procedures for Air Navigation Services - Air Traffic Management (PANS-ATM), Fifteenth Edition, 2007

[2] ICAO, Doc 8643, Aircraft Type Designators

[3] ICAO State Letter on update guidance for wake turbulence aspects of Airbus A380-800 aircraft, July 2008

[4] ICAO International Working Group, Safety Case on WVE risk behind A380-800, edition 4.0, July 2008

[5] ICAO International Working Group, Safety Case for Wake Vortex Separation Minima for the B747-8, edition 1.0, August 2011

[6] LMCT set of documents describing the LIDAR functioning and data post-processing, 2003

[7] "LMCT WindTracer® System Performance Determinations", LMCT, 2006

[8] LMCT, WindTracer® Terminal Doppler Solution, 2009

[9] EUROCONTROL, European Proposal for revised Wake Turbulence Categorisation and Separation Minima on Approach and Departure, "RECAT – EU", Safety Case Report, 2013.

[10] EASA Executive Director letter to the EASA Management Board – 2014(D)54308, 10th of October 2014

[11] University support to Project P6.8.1 Wake vortex data analysis and modelling LIDAR Data Analysis, 2011

[12] N. Bourgeois, P. Choroba, and G. Winckelmans, Conditional reduction of ICAO wake turbulence separation minima on final approach, 5th International Conference on Research in Air Transportation (ICRAT 2012), May 2012

[13] SESAR Project 6.8.1 Flexible and Dynamic Use of Wake Turbulence Separations, D11, ed 00.01.01, 11th April 2013

[14] EUROCONTROL, Optimised Runway Delivery (ORD) study, Deliverable D6B Final Report, March 2015

[15] SESAR Project 6.8.1 Flexible and Dynamic Use of Wake Turbulence Separations, Input to D46 - Time Based PWS for Arrivals - Safety Assessment Report (SAR), ed 00.01.01, 1st October 2015

[16] IHS Jane's ATC Awards 2016 Nomination form, Time-based separation (TBS), November 2015

[17] SESAR P06.08.01, D11 Internal exercise results: Human performance, LiDAR, Benefit and Safety assessment reports - Appendix II: TBS Data Collection Campaign and LIDAR Data Analysis report, Edition 00.01.00, 01st March 2013

[18] UCL, DLR, AIRBUS, EDDF-2 database analysis and performance assessment of the Wake Vortex Models on the EDDF-1 and EDDF-2 databases, CREDOS Deliverable D2-5, 2009

[19] I. De Visscher, G. Winckelmans and V. Treve, Characterization of Aircraft Wake Vortex Circulation Decay in Reasonable Worst Case Conditions, AIAA SciTech, 54th AIAA Aerospace Sciences Meeting, 4-8 January 2016, San Diego, California, USA, AIAA 2016-1603

[20] Lai, D., Jacob, D., Lo, F. A., & Delisi, D. P., Assessment of Pulsed Lidar Measurements of Aircraft Wakes Using a Lidar Simulator: Vortex Position Estimates for IGE, Linking, and Oblique Viewing, and Dependence of Vortex Lifetime on SNR., (pp. AIAA 2011-3197). Honolulu, Hawaii, 2011

[21] Lai, D., Jacob, D., & Delisi, D. P., Assessment of Pulsed Lidar Measurements of Aircraft Wake Vortex Positions Using a Lidar Simulator., (pp. AIAA 2010-7988). Toronto, Ontario, 2010

[22] AIRBUS & EUROCONTROL A350 Wake Turbulence Categorisation Safety Case report, ed. 1.0, 30th June 2014

[23] De Visscher, I., Winckelmans, G. & Treve, V., A Simple Wake Vortex Encounter Severity Metric – Rolling Moment Coefficient due to Encounter of an Aircraft with a Wake Vortex, *Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)*, Lisbon, April **2015,**

Abbreviations

Term	Definition
ANSP	Air Navigation Service Provider
APP	Approach
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Services
CAA	Civil Aviation Authority
CSPR	Closely spaced parallel runway
DBS	Distance-Based Separation
EASA	European Aviation Safety Agency
ECAC	European Civil Aviation Conference
ft	feet
ICAO	International Civil Aviation Organization
IGE	In-ground effect
kg	Kilogram
kts	knots
lbs	Pounds
LiDAR	Light detection and ranging
MLM/MLW	Maximum landing mass / Maximum landing weight
MRS	Minimum Radar Separation
MTOM / MTOW	Maximum take-off mass / Maximum take-off weight
NGE	Near-ground effect
NM	Nautical Miles
OGE	Out-of-ground effect
PWS	Static Pair-Wise Separation
RMC	Rolling Moment Coefficient
RWC	Reasonable Worst Case
t	Metric tonne (equals 1000 kilograms)
T2F	Time-to-Fly
TAS	True Air Speed
TBS	Time-Based Separation
TBS-PW	Time-Based Pair-Wise Separation
TMA	Terminal Maneuvering Area
VAPP	Approach Air Speed
WT	Wake turbulence
WV	Wake vortex

WVE	Wake vortex encounter
WTE	Wake turbulence encounter

EUROCONTROL

SUPPORTING EUROPEAN AVIATION

© **EUROCONTROL - 2020**

This document is published by EUROCONTROL for information purposes. It may be copied in whole or in part, provided that EUROCONTROL is mentioned as the source and it is not used for commercial purposes (i.e. for financial gain). The information in this document may not be modified without prior written permission from EUROCONTROL.

www.eurocontrol.int