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NLR-CR-2016-131 | August 2016

Benefits analysis of RECAT-EU for Schiphol Airport

CUSTOMER: KDC Mainport Schiphol

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EXECUTIVE SUMMARY

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Benefits analysis of RECAT-EU for Schiphol Airport

Problem area

In today's operations, a limiting factor for runway throughput is the required minimum wake turbulence separation. These wake separations are static and applicable to broad categories of aircraft and have proven to be suboptimal and over-conservative for certain combinations of aircraft and in certain weather conditions. Therefore, new concepts for reduced, flexible and dynamic use of wake turbulence separations have been explored by EUROCONTROL and others in programmes like SESAR.

One of the concepts is the European Proposal for revised Wake Turbulence Categorisation and Separation Minima on Approach and Departure, "RECAT-EU". The RECAT-EU proposal is built up from 6 categories. Further ongoing developments aim at a pair-wise separation (RECAT-PWS-EU) scheme, where separation is defined for each combination of a leader and follower aircraft type.

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Description of work

An initial assessment of the capacity benefits when RECAT-EU separations are applied to arrivals at Schiphol airport has been conducted. Data is used of pairs of separation constrained arrival pairs in busy morning and afternoon peak hours in the years 2012 – 2015. For comparison, benefits of RECAT-PWS-EU have also been assessed. To support the decision-making process, relevant aspects regarding systems, humans and procedures have been identified and considerations are provided for the extension of the scope of the study and the set-up of a local safety case.

Results and conclusions

With RECAT-EU applied to arrivals at Schiphol, the estimated increase is 0.7 landings per hour on average in the inbound peaks considered. With RECAT-PWS-EU, this is 1.4 landings per hour. There are significant differences between morning and afternoon peaks: in the morning there is an expected increase of 1.1 landings per hour for RECAT-EU and 2.1 for RECAT-PWS-EU. In the afternoon increases are 0.2 and 0.5. This is the result of the differences in traffic mix with more Heavy traffic in the morning peak. In the afternoon peak there is predominantly Medium traffic for which no separation reduction is proposed.

RECAT-EU requires relatively little modifications of the systems and no additional system support to the controllers is needed. There is a slight increase in complexity.

With RECAT-PWS-EU more advanced system support is required and the working practices of controllers will change more significantly.

It seems a logical option to integrate RECAT-PWS-EU with the Time Based Separation concept as similar system support is needed and TBS is included in the European Commission Implementing Regulation (EU) No 716/2014 which is applicable to Schiphol.

It can be considered to extend the scope of this study to also analyse the effects on runway and airspace capacity when RECAT separation is applied to departures and in the whole TMA or even beyond to en-route.

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Summary

In today's operations, a limiting factor for runway throughput is the required minimum separation. This is either a minimum radar separation or a wake turbulence separation. The latter is based on ICAO's definition of wake turbulence categories and minima, sometimes with local adaptations. These wake separations are static and applicable to broad categories of aircraft and have proven to be suboptimal and over-conservative for certain combinations of aircraft and in certain weather conditions. Therefore, new concepts for reduced, flexible and dynamic use of wake turbulence separations have been explored by EUROCONTROL and others in programmes like SESAR.

FAA and EUROCONTROL jointly started the RECAT initiative to optimise the ICAO Wake Turbulence Categories by splitting the Heavy and Medium categories into 'upper' and 'lower' Heavy and Medium categories and reduce the separation between e.g., Lower Heavy leader and Upper Medium follower aircraft. The initial proposal was adopted by FAA and has been successfully implemented at several US airports. EUROCONTROL and European stakeholders further fine-tuned the categories, considering European traffic mix characteristics. This resulted in the RECAT-EU proposal.

The European Aviation Safety Agency (EASA) has reviewed the RECAT-EU proposal and confirmed in a letter to Member States that the RECAT-EU wake turbulence scheme can be used by States and Air Navigation Service Providers as a basis to update their current schemes. RECAT-EU has not yet been adopted in regulations. It is the intention of EASA to prepare with the RECAT-EU partners the revision of related standards in ICAO PANS-ATM.

According to EUROCONTROL, the runway throughput benefits can reach 5% or more during peak periods depending on individual airport traffic mix. RECAT-EU is first introduced at Paris Charles de Gaulle in March 2016. For Paris Charles the Gaulle, DSNA aims to increase peak hour arrival throughput using RECAT-EU in combination with High Intensity Runway Operations (HIRO) by 7% to 8% in 2017 and more than 10% by 2020. This further increase can be achieved when considering the evolution of traffic mix, with an increase of Heavy aircraft like B787 and A350.

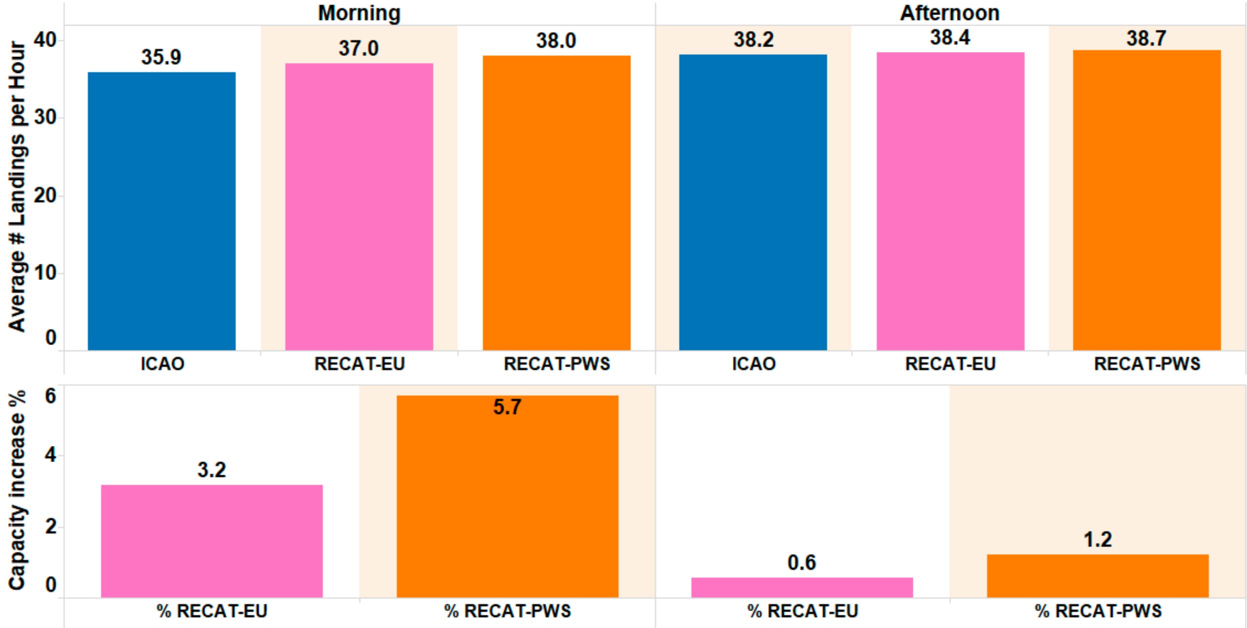
The RECAT-EU proposal is build up from 6 categories, which is relatively easy to implement and to adopt by controllers without the need for additional system support. Further on-going developments aim at a pair-wise separation (PWS) scheme where separation is defined for each combination of a leader and follower aircraft type and that can be used as a basis for defining a number of categories dedicated to the operational conditions of the airport. The RECAT-PWS-EU proposal has been under consultation in the EUROCONTROL Wake Vortex Task Force and has been offered to EASA for review recently.

In parallel, Time Based Separation (TBS) has been developed within the SESAR programme. The (TBS) concept defines a set of separation rules in terms of time rather than distance to improve runway throughput resilience to – in particular – strong headwind conditions. TBS has been included in European Commission Implementing Regulation (EU) No 716/2014, which requires ATS providers and airport operators at selected airports – including Schiphol – to operate TBS by January 2024.

To get insight in the potential benefits, an initial assessment of the efficiency and capacity benefits when RECAT-EU separations are applied at Schiphol airport has been made. Because the largest benefits can be expected for arriving traffic, the focus of the current study is on application of RECAT-EU to arrivals. To assess the local effects of such a generic concept, local characteristics including traffic mix, peak hours, separation practices, and runway operation modes are taken in to account. For comparison, the benefits of RECAT-PWS-EU have also been assessed.

In the analysis, the focus is on pairs of aircraft that are constrained by wake turbulence separation. Data is used of pairs of arrivals in busy morning and afternoon peak hours in the years 2012 – 2015, for which the actually achieved spacing is less than 130% of the separation minimum.

With RECAT-EU, the estimated increase is 0.7 landings per hour on average or 1.9%. With RECAT-PWS-EU, this is 1.4 landings per hour or 3.6%. When further distinguishing the morning and afternoon peak, as shown in the figure below, there are significant differences: in the morning there is an expected increase of 1.1 landings per hour (3.2%) and 2.1 landings per hour (5.7%) for RECAT-EU and RECAT-PWS-EU respectively. In the afternoon increases are 0.2 (0.6%) and 0.5 (1.2%). This is the result of the differences in traffic mix with more Heavy traffic in the morning peak. In the afternoon peak there is predominantly Medium traffic for which no separation reduction is proposed.



When comparing the estimated benefits for Schiphol with those for Paris Charles the Gaulle, the benefits for Schiphol are considerably lower. This is because of the higher amount - about 15% against 10% - of Heavy aircraft in the Paris traffic mix.

In strong headwind conditions, the potential gain in time – and therefore in runway throughput - is higher because of the lower ground speeds. For conditions with headwind exceeding 15 kts the expected benefits are indeed slightly higher: 1.2 (3.5%) and 2.1 (6.0%) landings per hour in the morning for RECAT-EU and RECAT-PWS-EU respectively.

The benefits are mainly created by reduction in separation behind aircraft in the RECAT-EU Upper Heavy (B) category, like A332, A333, B744, and B772. Next to that, there is a contribution because of separation reduction behind aircraft like B752, B763 and MD11 in the Lower Heavy (C) category. The numbers of these latter types appear to decrease over time. On the other hand, Upper Heavies like B772, B77W and B788 appear to visit Schiphol more and more frequently.

In addition to the benefits analysis and in view of the further decision-making process, relevant aspects regarding systems, humans and procedures have been identified and considerations on extension of the scope of this study and the set-up of a local safety case have been provided.

According to EUROCONTROL studies and experiences at Paris Charles de Gaulle airport, RECAT-EU requires relatively little modifications of the systems and no additional system support to the controllers is needed. There is an increase in complexity due to the six instead of four categories where for example the B737 family is split up into Upper and Lower Medium categories.

With RECAT-PWS-EU more advanced system support is required and the working practices of controllers will change more significantly. A 'separation indicator' is needed to display the targeted separation on the radar display. Development and integration of an indicator for the environment at Schiphol airport will require a dedicated study.

It seems a logical option to integrate RECAT-PWS-EU with the Time Based Separation concept as similar system support is needed. TBS has been included in European Commission Implementing Regulation (EU) No 716/2014, which requires ATS providers and airport operators at selected airports – including Schiphol – to operate TBS by January 2024.

It can be considered to extend the scope of this study to also analyse the effects on runway and airspace capacity when RECAT separation is applied to departures and in the whole TMA or even beyond to en-route.

For RECAT-EU and RECAT-PWS-EU, EUROCONTROL has developed generic safety cases to show that the wake turbulence encounter risk is acceptable in principle. At a local level, a complementary safety case needs to be developed to show that the proposed scheme is adequately deployed, applied and monitored. Such local safety case should also assess the effects on risks other than WTE risk: the risk of an increased number of runway incursions or go-arounds which in worst case conditions could evolve into a runway or mid-air collision.

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Contents

Abbreviations

ACRONYM	DESCRIPTION
ADS-B	Automatic Dependent Surveillance – Broadcast
AIC	Aeronautical Information Circular
AIP	Aeronautical Information Publication
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATS	Air Traffic Services
BZO	Bijzondere Zichtomstandigheden (Low visibility conditions)
DSNA	Direction des Services de la Navigation Aérienne
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
LoA	Letter of Agreement
LTI	Landing Time Interval
LVNL	Luchtverkeersleiding Nederland (ATC the Netherlands)
KDC Mainport Schiphol	Knowledge Development Centre Mainport Schiphol
Kts	Knots
MRS	Minimum Radar Separation
NATS	National Air Traffic Services of the UK
NLR	Netherlands Aerospace Centre
NM	Nautical Mile
OE	Operational Expert
PANS-ATM	Procedures for. Air Navigation Services - Air Traffic Management
PANS-OPS	Procedures for. Air Navigation Services - Aircraft Operations.
PWS	Pair Wise Separation
RECAT	Recategorisation of wake turbulence categories and separation minima
SERA	Standardised European Rules of the Air
TBS	Time Based Separation
TMA	Terminal Manoeuvring Area
UDP	Uniform Daylight Period
UTC	Universal Time Coordinated
WTC	Wake Turbulence Category
WV	Wake Vortex
WVTF	Eurocontrol Wake Vortex Task Force

1 Introduction

1.1 Background

In today's operations, a limiting factor for runway throughput is the required minimum separation. This is either a minimum radar separation or a wake turbulence separation. The latter is based on ICAO's definition of wake turbulence categories and minima, sometimes with local adaptations. These wake separations are static and applicable to broad categories of aircraft and have proven to be suboptimal and over-conservative for certain combinations of aircraft and in certain weather conditions. Therefore, new concepts for reduced, flexible and dynamic use of wake turbulence separations have been explored by EUROCONTROL and others in programmes like SESAR.

1.2 Concept development

One of the concepts is the European Proposal for revised Wake Turbulence Categorisation and Separation Minima on Approach and Departure, "RECAT-EU" [3][1].

RECAT started as a joint initiative of FAA and EUROCONTROL to optimize the ICAO Wake Turbulence Categories by splitting the Heavy and Medium categories into 'Upper' and 'Lower' Heavy and Medium categories and reduce the separation between e.g., Lower Heavy leader and Upper Medium follower aircraft. The initial RECAT proposal was adopted by FAA [1] and has been successfully implemented at several US airports. EUROCONTROL and European stakeholders further fine-tuned the categories, considering European traffic mix characteristics. This resulted in the RECAT-EU proposal.

The RECAT-EU proposal [3] is build up from 6 categories, requires relatively little modifications of the systems and no additional system support to the controllers is needed. Further on-going developments aim at a pair-wise separation (RECAT-PWS-EU, [5][2]) scheme, where separation is defined for each combination of a leader and follower aircraft type and that can be used as a basis for defining a number of categories dedicated to the operational conditions of the airport.

In parallel, Time Based Separation (TBS)[3] has been developed within the SESAR programme. The (TBS) concept defines a set of separation rules in terms of time rather than distance to improve runway throughput resilience to – in particular – strong headwind conditions.

1 http://www.eurocontrol.int/articles/recat-eu
2 http://www.eurocontrol.int/articles/pair-wise-separations-pws-recat-2
3 http://www.eurocontrol.int/articles/time-based-separation

1.3 Regulatory status

In the US, FAA has adopted the RECAT proposal in regulations [2].
In Europe, the European Aviation Safety Agency (EASA) has reviewed the RECAT-EU proposal and confirmed in a letter to Member States that the RECAT-EU wake turbulence scheme can be used by States and Air Navigation Service Providers as a basis to update their current schemes. RECAT-EU has not yet been adopted in regulations. It is the intention of EASA to prepare with the RECAT-EU partners the revision of related standards in ICAO PANS-ATM. In accordance with EU regulations (EU) No. 1034/2011 [14] and (EU) No. 1035/2011 [15], the Air Navigation Service Providers from EU Member States considering to implement RECAT-EU, shall perform a risk assessment covering the changes to the ATM functional system and their lifecycle and shall obtain approval of their competent authority. The RECAT-PWS-EU proposal has been under consultation in the EUROCONTROL Wake Vortex Task Force and has been offered to EASA for review recently.

TBS has been included in European Commission Implementing Regulation (EU) No 716/2014 [17], which requires ATS providers and airport operators at selected airports – including Schiphol – to operate TBS by January 2024.

1.4 Benefits

In the US, RECAT was first implemented at Memphis Airport. The FAA estimates a more than 15 percent increase in capacity at Memphis. Overall, the FAA states it can accommodate nine additional flights per hour using the new separation standards. Lower fuel consumption and fewer emissions are added benefits of this newly gained efficiency.

According to EUROCONTROL, the runway throughput benefits of RECAT-EU can reach 5% or more during peak periods depending on individual airport traffic mix [3]. RECAT-EU is first introduced at Paris Charles de Gaulle in March 2016. For Paris Charles the Gaulle, DSNA aims to increase peak hour arrival throughput by 7% to 8% in 2017 and more than 10% by 2020. This further increase may be possible when considering the evolution of traffic mix, with an increase of Heavy aircraft like B787 and A350 [6].

TBS is in operation at London Heathrow airport since 2015 as a means to regain lost runway throughput in headwind conditions [22]. NATS reports over the period May – July 2015 an overall increase of 20 movements per day and a reduction of wind related ATFM delay of 62% [9].

As EUROCONTROL has assessed the capacity and safety effects of RECAT-EU and RECAT-PWS-EU at a generic level, EUROCONTROL has approached ANSPs like LVNL to assess the effects for their airport, taking into account the local traffic mix and ATC procedures.

1.5 This study

To get insight in the potential benefits, Knowledge Development Centre (KDC) Mainport Schiphol has asked NLR to conduct an initial assessment of the efficiency and capacity benefits when RECAT-EU separations are applied at Schiphol airport. Because the largest benefits can be expected for arriving traffic, the focus of the current study is on application of RECAT to arrivals.

To assess the local effects of such a generic concept, local characteristics including traffic mix, peak hours, separation practices, and runway operation modes are taken in to account.

The scope of the assessment is limited to arrivals and – in order to focus on high density traffic situations – further defined by:

- The summer period (April – October);
- The first and fifth inbound peak;
- Runway combinations with two runways available for landing with each runway a maximum capacity of 34 landings (“34+34”);
- All visibility conditions, except “Bijzondere Zichtomstandigheden” (BZO); and
- All headwind conditions with special attention for strong headwind conditions.

Although the main objective of this study is to provide insight in RECAT-EU benefits, RECAT-PWS-EU is considered as well.

To support the decision-making process, in addition to the benefits analysis, relevant aspects regarding systems, humans and procedures are identified. Furthermore, some thoughts are provided on the need to extend the scope of this study and to set-up a local safety case, complimentary to the generic RECAT-EU and RECAT-PWS-EU safety cases as developed by EUROCONTROL.

1.6 Set-up of this report

This report includes the following chapters:

- Chapter 2: Current practice of separation delivery;
- Chapter 3: RECAT separation scenarios;
- Chapter 4: Benefits analysis results;
- Chapter 5: Relevant aspects for deployment; and
- Chapter 6: Conclusions.

2 Current practice of separation delivery

2.1 Introduction

The main aim of Air Traffic Control is to expedite and maintain an orderly flow of air traffic. An important objective in this respect is to maintain a minimal separation between aircraft, in order to prevent accidents. Air Traffic Controllers therefore provide instructions to aircrew such that the distance between aircraft is more than the applicable separation minimum.

The separation minima to be applied in first instance depend on the surveillance means. According to [11], the Minimum Radar Separations (MRS) for aircraft flying in the TMA are at least 1000 ft vertical separation and at least a lateral distance of 3 NM to 5 NM, depending on the radar quality and coverage. Between succeeding aircraft which are established on the same final approach track within 10 NM of the runway end, a reduced separation minimum of 2.5 NM may be applied, provided certain requirements are satisfied, including requirements on runway occupancy time, braking action and radar accuracy.

Wake separation minima are applied to reduce the risk that an aircraft encounters severe wake turbulence of a predecessor. The PANS-ATM [11] states that the radar wake turbulence separation minima shall be applied in the approach and departure phases of flight when:
a) an aircraft is operating directly behind another aircraft at the same altitude or less than 1 000 ft below; or
b) both aircraft are using the same runway, or parallel runways separated by less than 2 500 ft; or
c) an aircraft is crossing behind another aircraft, at the same altitude or less than 1 000 ft.

The numerical values of the separation minima depend on the aircraft types of the leader and follower in a pair of aircraft. ICAO's definition of aircraft wake turbulence categories (Heavy, Medium, Light) and the corresponding separation minima [10],[11],[12] were initiated in the late sixties. The ICAO WTC of the involved aircraft are based on their Maximum Take-Off Weight (MTOW). A category SUPER with increased separation was established by ICAO for the Airbus A380 as a generator [13].

Table 2-1: ICAO WT separation distance minima scheme. Separations in Nautical Miles (NM). For certain combinations no WT separation minimum applies

ICAO Leader / Follower	Super	Heavy	Medium	Light
Super	-	6	7	8
Heavy	-	4	5	6
Medium	-	-	-	5
Light	-	-	-	-

For assessing the capacity benefits of an adapted separation scheme, it has to be considered that the spacing along the final approach fluctuates due to changes in ground speed of the leader and follower aircraft.

When looking at a particular point, e.g., at the runway threshold, the achieved spacing at that point has a distribution around the separation minimum which is the result of multiple factors: Controllers set up the sequence of aircraft adding a spacing buffer that is mainly based on experience, taking into account the leader and follower aircraft type and prevailing wind conditions. However, the wind evolves with altitude and with time introducing uncertainty. Furthermore, the Final Approach Speed (FAS) for a particular aircraft type, can vary significantly because of variation in landing weight and flap configurations and these are unknown to the controller.

It is therefore of interest to analyse the actually delivered spacing in view of the separation minima and wake turbulence categories. The following subsections therefore describe the minima and procedures applicable at Schiphol and provide a descriptive analysis of the spacing in the current practice.

2.2 Wake turbulence separation minima and procedures at Schiphol

The wake turbulence categories and minima as currently applied by LVNL at Schiphol airport follow the ICAO definitions as described above, though with the following exceptions [18]:

- For radar separation of a SUPER behind a SUPER or Heavy aircraft, preferably 4 NM is applied instead of MRS, in order to be consistent with Heavy behind Heavy and because of the runway occupancy time of SUPER and Heavy aircraft.
- Aircraft types B757-200 and B757-300 are in the Medium WTC when considered as follower and in the Heavy WTC when considered as leader aircraft.

Table 2-2: LVNL VDV WT separation distances scheme. Separations in NM. In grey the Minimum Radar Separation of 3.0 NM as applicable in the Schiphol TMA. For these combinations no WT separation minimum applies

VDV Leader/ Follower	Super	Heavy	Medium	Light
Super	4	6	7	8
Heavy	4	4	5	6
Medium	3	3	3	5
Light	3	3	3	3

2.3 Descriptive analysis of historical data

In view of the scope of the assessment as defined in section 1.5, the following data has been provided by LVNL as the basis for the analysis:

- The summer period (April – October) of years 2012, 2013, 2014 and 2015;

- For each day, the busiest 60 minutes period in the first and fifth inbound peak;
- Runway combinations with two runways available for landing with each runway a maximum capacity of 34 landings per hour ("34+34");
- All visibility conditions, except "Beperkt Zicht Omstandigheden" (BZO)[4]; and
- All headwind conditions.

The first inbound peak is in the morning, roughly between 5.00 and 7.00 UTC, and is characterized by relatively high percentage of Heavy aircraft, because of arriving transatlantic flights. The fifth inbound peak is in the afternoon, roughly between 16.00 and 18.00 UTC and consists of predominantly Medium traffic. The two peaks will be considered separately.

The characteristics of the data set is described in the following to provide insight in the distribution of flights over the ICAO WTC, the headwind and visibility conditions, the runway throughput and the actually achieved separation.

Figure 2-1 and Table 2-3 show the number of flights in the data set. For each year there are about 15,000 flights where around 89% belongs to the ICAO WTC Medium and the remainder to Heavy while less than 0.1% is Light. Please note the absence of the Super category, because in the current operation A380 flights are scheduled outside the considered peaks. In the first peak (morning), about 15% consists of Heavy aircraft, while in the afternoon this is about 5%.

Table 2-3: Number and percentage of flights per ICAO WTC in the data set

WTC	2012	2013	2014	2015	Overall %
Heavy	1,732 (11.0%)	1,564 (10.1%)	1,475 (10.0%)	1,523 (10.0%)	10.53%
Medium	13,957 (88.9%)	13,957 (89.9%)	13,230 (89.9%)	13,708 (89.9%)	89.39%
Light	13 (0.1%)	7 (0.0%)	12 (0.1%)	9 (0.1%)	0.08%
TOTAL	*15,702*	*15,528*	*14,717*	*15,240*	

[4] Low visibility, with visibility less than 1,500 meter and/or cloud base below 300 ft.

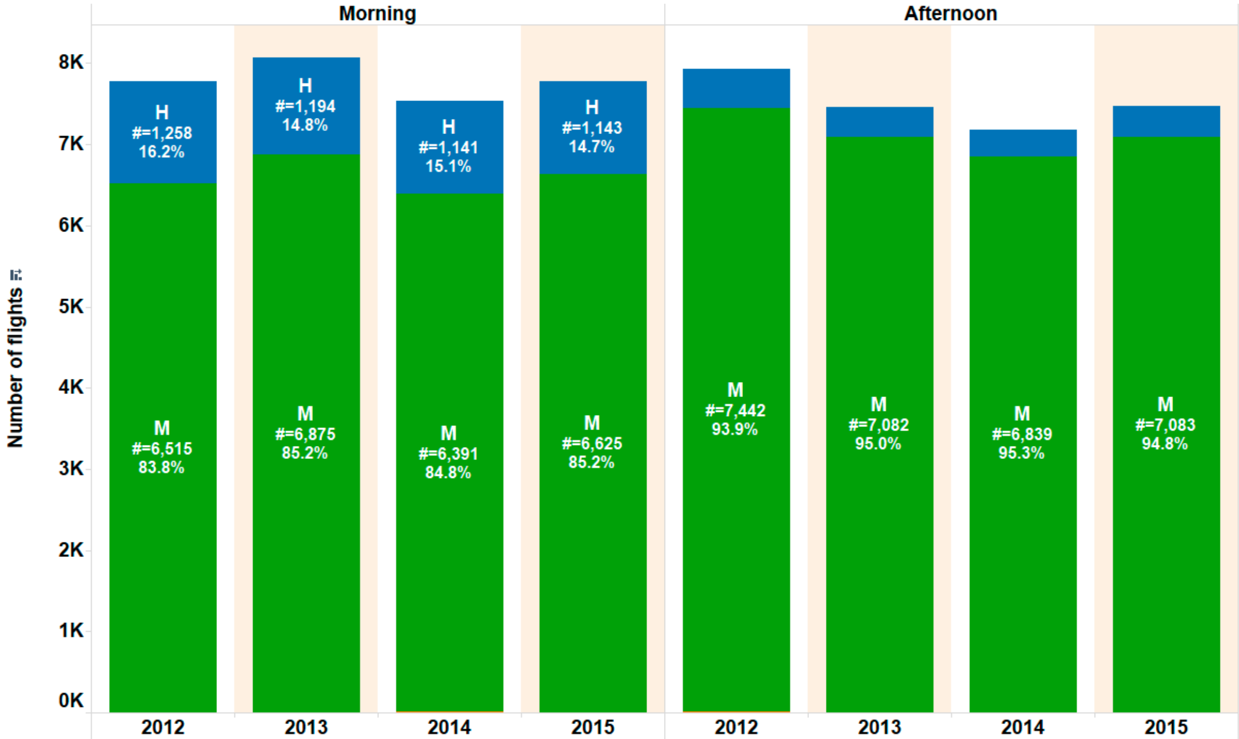

Figure 2-1: Number of flights per ICAO WTC in the data set, distinguishing peaks 1 (morning) and 5 (afternoon)

Figure 2-2 shows the distribution of aircraft pairs in the traffic mix over the combinations of ICAO WTC in the data set, distinguishing peaks 1 (morning) and 5 (afternoon). In the morning peak, about 74% concerns Medium – Medium traffic and about 12% Heavy – Medium. In the afternoon peak these percentages change to 90% and 5%.

Figure 2-3 shows the distribution of the headwind on the runway. The headwind the flights are exposed to is clustered in bins of 5 kts. The figure shows that around 40% of flights is exposed to headwind in between 0 and 5 kts (dark green bars). For less than 4% of flights, the headwind exceeds 15 kts. For less than 1% of flights, the headwind exceeds 20 kts.

According to Figure 2-4, showing the distribution of visibility conditions, marginal visibility applies to in between 6% and 19% of the flights in morning peaks. In the afternoon peaks this concerns 1% or 2%, except for 2014 where it concerns 6.8%.

Runway throughput is shown in Figure 2-5 expressed as the average number of landings per runway and per hour in the years considered. Here, only landings are included for which spacing is less than 130% of the separation minimum, as the same is done in the benefits analysis in chapter 4. In the morning peaks this increases over the years from 35.3 to 36.2 landings per hour. In the afternoon peak, there is an increase from 37.8 to 38.5 landings per hour. The higher numbers in the afternoon peaks can be explained by the traffic mix. A higher percentage of Medium - Medium traffic, for which less separation is required, results in a higher runway throughput.

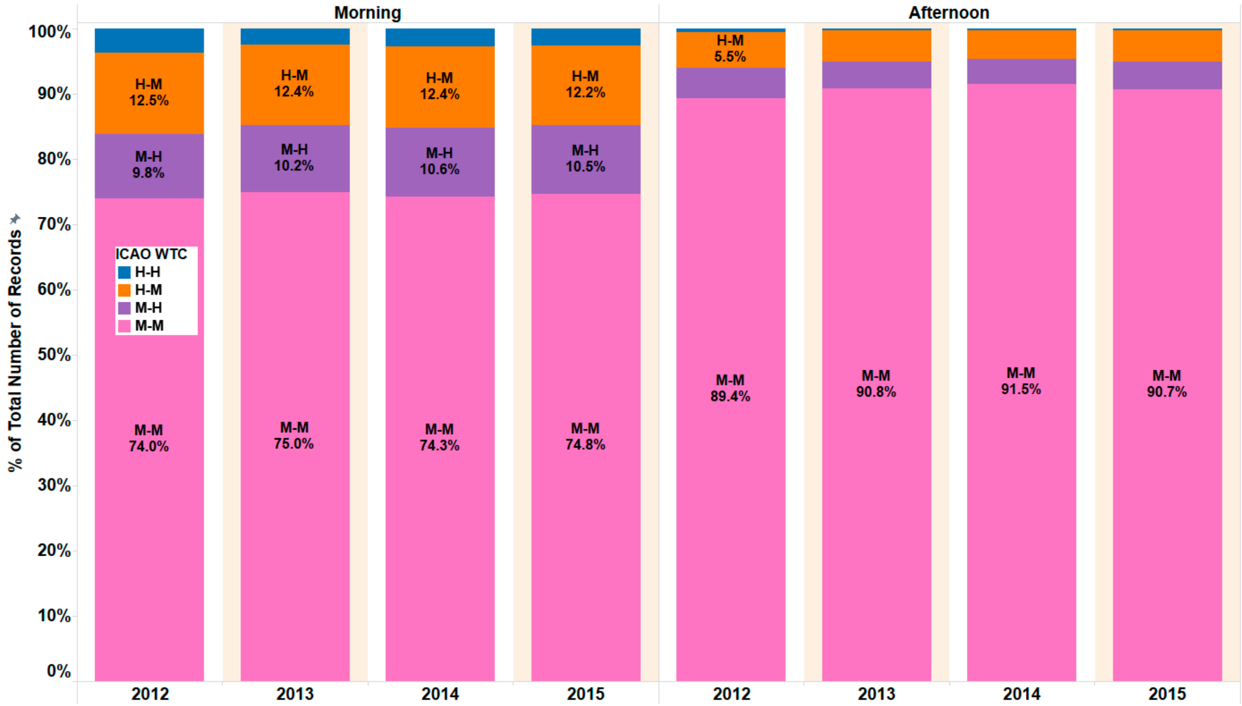

Figure 2-2: Distribution of aircraft pairs in the traffic mix over the ICAO WTC in the data set, distinguishing peaks 1 (morning) and 5 (afternoon)

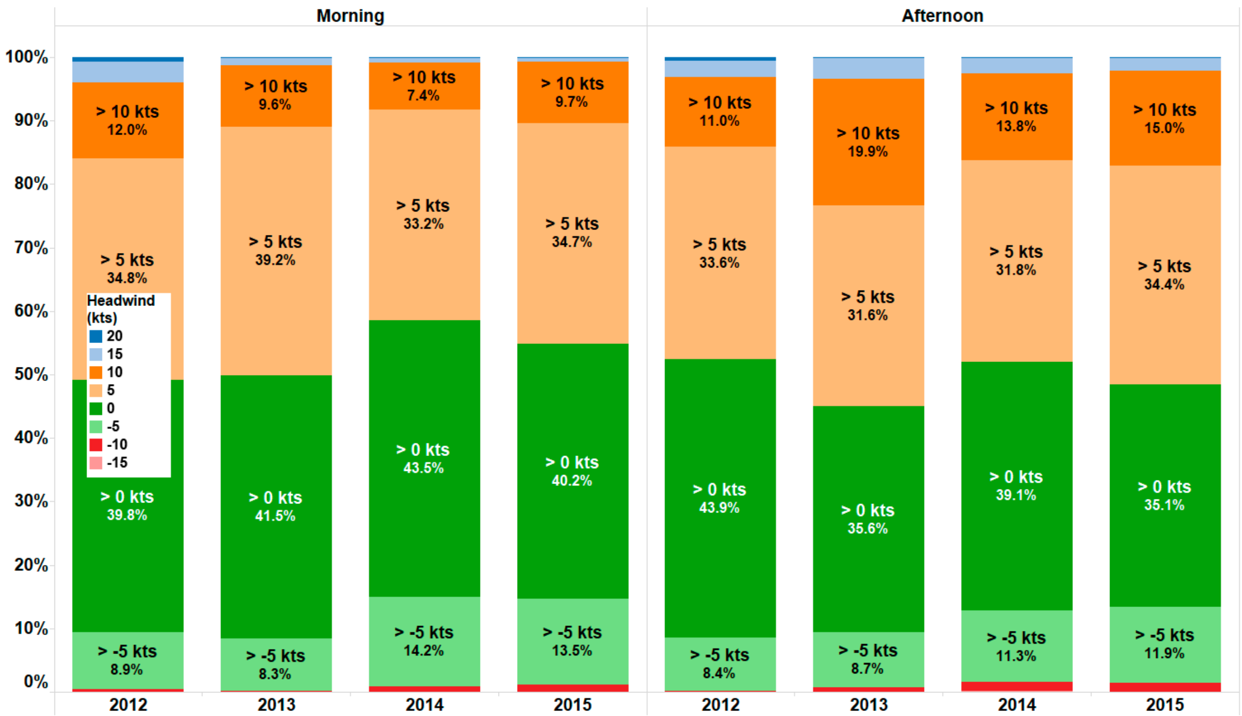

Figure 2-3: Distribution of the headwind to which the flights in the data set were exposed, distinguishing peaks 1 (morning) and 5 (afternoon)

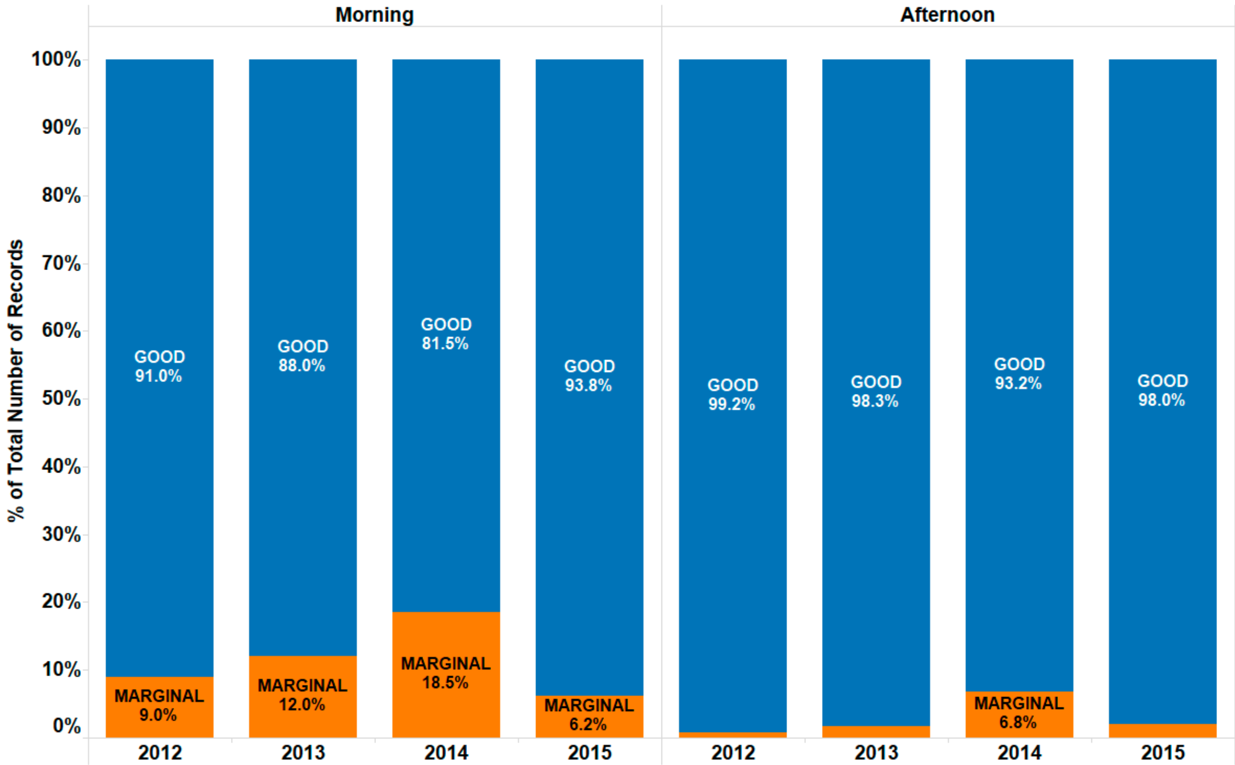

Figure 2-4 :Distribution of the visibility condition to which the flights in the data set were exposed, distinguishing peaks 1 (morning) and 5 (afternoon)

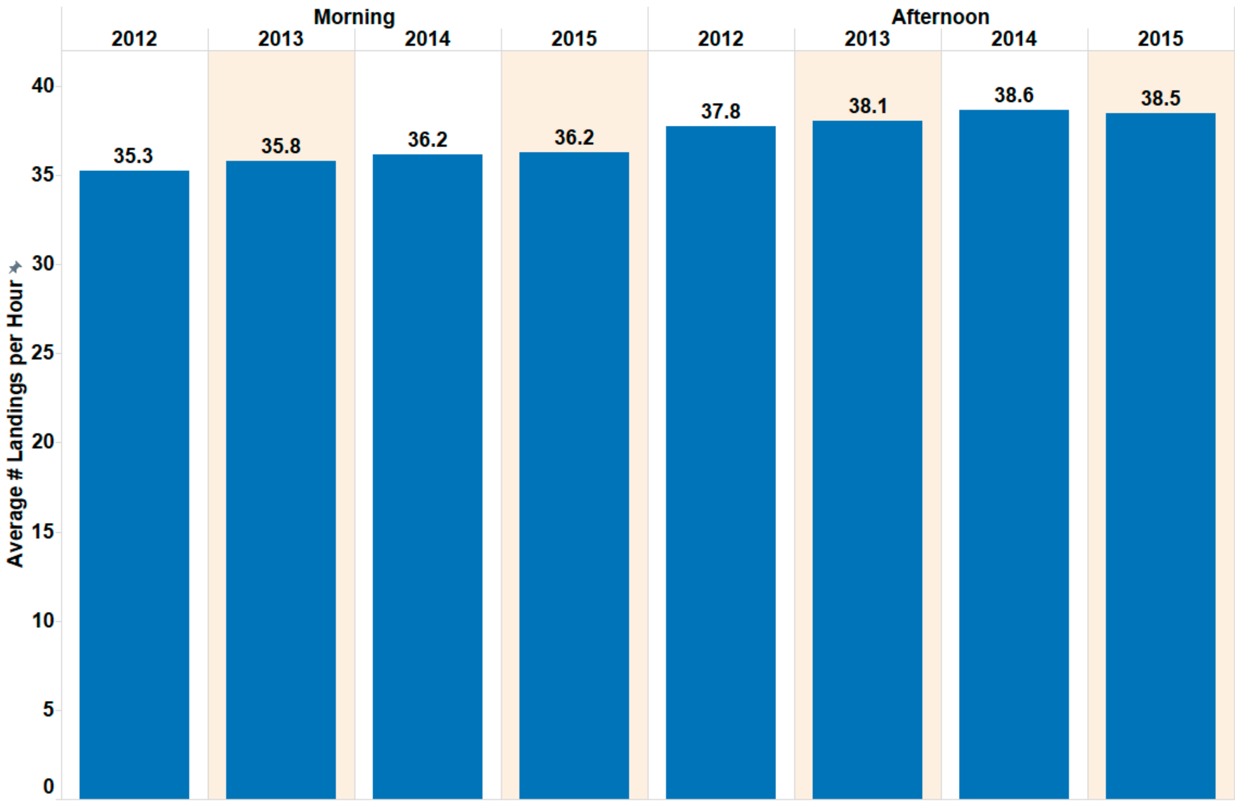

Figure 2-5: Average number of landings per hour per runway that are separation constrained (<= 130% of the separation minimum), distinguishing peaks 1 (morning) and 5 (afternoon)

Figure 2-6 shows the distribution of the distance spacing as achieved at the runway threshold, expressed as a percentage of the associated separation minimum, distinguishing the combinations of ICAO WTC. The vertical yellow lines indicate 100%. The vertical magenta dashed lines indicate the average values. E.g., for Heavy – Heavy traffic, the average spacing achieved is 120% of the associated separation minimum of 4 NM. In other words, on average there is a buffer of 0.64 NM. The figure also shows that there is a fraction of the flights for which the spacing achieved is less than 100%. These are not necessarily separation infringements as it could be that visual separation has been applied and as such the WT separation minimum was no longer applicable.

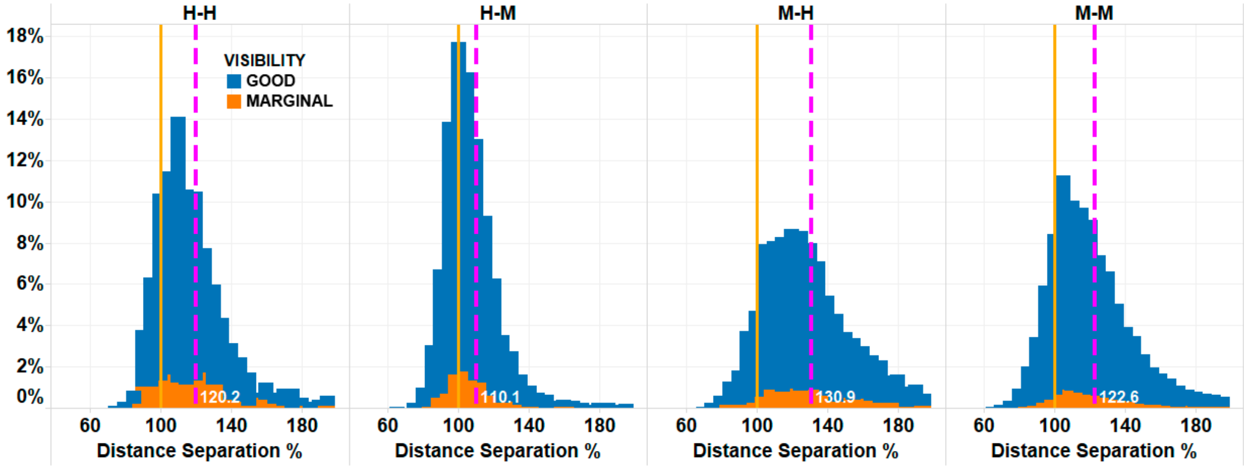

Figure 2-6 :Histograms of the distance spacing, expressed as a percentage of the applicable separation minimum for combinations of ICAO WTC, with in orange indication of 100% and in magenta indication of the average value

Figure 2-7 shows the distribution of the ground speed when the follower aircraft is at the actual spacing distance before the runway threshold. Depending on the actual spacing, this can vary from say 3 to 6 NM before the threshold. The blue bars indicate the range from 10% to 90% per aircraft type, for the most frequently occurring types in the traffic mix. The variation appears to be considerable, which is the result of variation in actual spacing distance and variation in Final Approach Speed of aircraft types. The magenta horizontal lines indicate the average speed per ICAO WTC, which appears to be around 145 to 160 kts. The magenta lines indicate the mean speed per ICAO WTC.

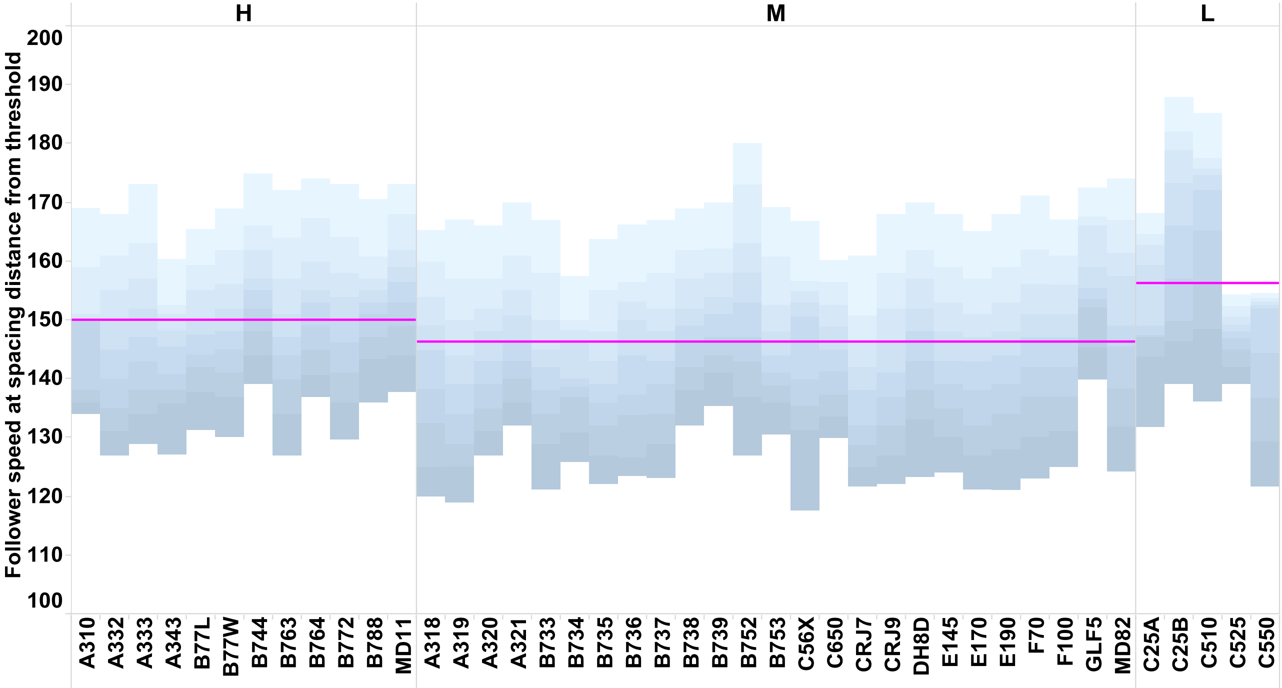

Figure 2-7: Distribution of ground speed of the follower aircraft at the spacing distance before the runway threshold. The blue bars indicate the range from 10% to 90%. The magenta horizontal lines indicate the average speed per ICAO WTC

3 RECAT separation scenarios

3.1 RECAT-EU and RECAT-PWS-EU

The aim of RECAT-EU is to optimize the wake turbulence separation classes with six categories. Roughly speaking, the ICAO Heavy and Medium categories have been split into an upper and lower Heavy and Medium category. Furthermore, Lower Heavy or C category has been extended to include also aircraft like the B757. The Light category has been extended to include the lightest Medium aircraft types like Cessna 650.

The RECAT-EU categories in comparison to the ICAO WTC are illustrated for some typical aircraft types in Figure 3-1. Lists of frequently occurring aircraft types in the current traffic mix at Schiphol airport per RECAT-EU category are shown in Table 3-1.

Figure 3-1: ICAO and RECAT-EU Wake Turbulence Categories with typical aircraft in the categories

Table 3-1: List of aircraft types in the current traffic mix (2012-2015) per RECAT-EU Category

SUPER Heavy A	UPPER Heavy B	LOWER Heavy C	UPPER Medium D	LOWER Medium E	Light F
A380	A332	A306	A318	B712	C56X
	A333	A310	A319	B733/4/5	C510
	A343	B752	A320	CRJ2/7/9	H25B
	B77L	B753	A321	DH8D	SW4
	B77W	B763	B736	E145	
	B742	B764	B737	E170/E190	
	B744	MD11	B738	F2TH	
	B748		B739	F50	
	B772		MD82	F70/F100	
	B788			F900	
				GLEX	
				GLF4/5	
				RJ1H	
				RJ85	
				SB20	

The RECAT-EU separation minima for approach as used in the current study are listed in Table 3-2 with in brackets the (maximum[5]) difference in separation in NM compared to ICAO.

Table 3-2 :RECAT-EU Wake Turbulence Categories and separation minima, from [3]

RECAT-EU Leader/Follower	A	B	C	D	E	F
A	3	4 (-2)	5 (-1)	5 (-2)	6 (-1)	8
B	-	3 (-1)	4	4 (-1)	5	7 (+1)
C	-	3 (-1)	3 (-1)	3 (-2)	4 (-1)	6
D	-	-	-	-	-	5 (+2)
E	-	-	-	-	-	4 (-1)
F	-	-	-	-	-	-

In RECAT Phase 2 or Pair Wise Separations (PWS), the six categories from Phase 1 will be replaced by a regime under which each aircraft pair will have its own separation minima defined, focusing on optimisation for the approximately 100 aircraft types that constitute 99% of world-wide demand. States can decide by themselves on how to implement the static pair-wise separation minima. Grouping of aircraft may depend on local or national needs, and may be tailored to the local situations.

The RECAT-PWS-EU separation scheme for 96x96 aircraft combinations can be found in [5] and is illustrated for the Schiphol situation in the next section.

3.2 RECAT based separation scenarios for Schiphol

When RECAT-EU is taken as the basis, the six category scheme proposed for this analysis is listed in Table 3-3. Here, in view of the separation scheme currently applied at Schiphol, see section 2.2, it is proposed to maintain the exception for Super (A) behind SUPER or Upper Heavy (B) for reasons of consistency and runway occupancy time. The current exception for the B757 is no longer necessary, as B757 is categorized as a Lower Heavy (C) in RECAT. The distribution of the current traffic mix over combinations of the RECAT-EU categories is shown in Figure 3-2.

Alternatively, the RECAT-PWS-EU scheme can be applied. A comparison of the separation reduction in RECAT-EU and RECAT-PWS-EU for frequently occurring pairs in Schiphol traffic mix is presented in Figure 3-3. The size of the boxes indicates the percentage of a combination in the traffic mix. For example, for an A332 (B) followed by a B738 (D) the separation can be reduced by 1 NM in RECAT-EU and by 1.5 NM in RECAT-PWS-EU. Considering the size of the box, this is a relatively frequent combination. For a B788 (B) followed by an E190 (E), there is no separation reduction in RECAT-EU and 1 NM reduction in RECAT-PWS-EU. However, in the current traffic mix this combination occurs with a relatively low frequency. Note that there are also differences in minimum separation for pairs where

[5] For certain combinations, the difference is less than the number in between the brackets. E.g., for D – F pairs where the follower belonged to the Light category, there is no separation increase. The +2 applies to F follower aircraft that belonged to the Medium category.

the follower is Category F. However, these occur with such low frequency that these are not shown here.

Table 3-3: Proposed RECAT separation scheme for Schiphol for this analysis with differences in comparison to current scheme in brackets. Note that for D-F, there is an increase of +2 for those Cat F aircraft that used to be ICAO Medium

RECAT-SPL Leader/Follower	A	B	C	D	E	F
A	4	4 (-2)	5 (-1)	5 (-2)	6 (-1)	8
B	4	4	4	4 (-1)	5	7 (+1)
C	3	3 (-1)	3 (-1)	3 (-2)	4 (-1)	6
D	3	3	3	3	3	5 (+2)
E	3	3	3	3	3	4 (-1)
F	3	3	3	3	3	3

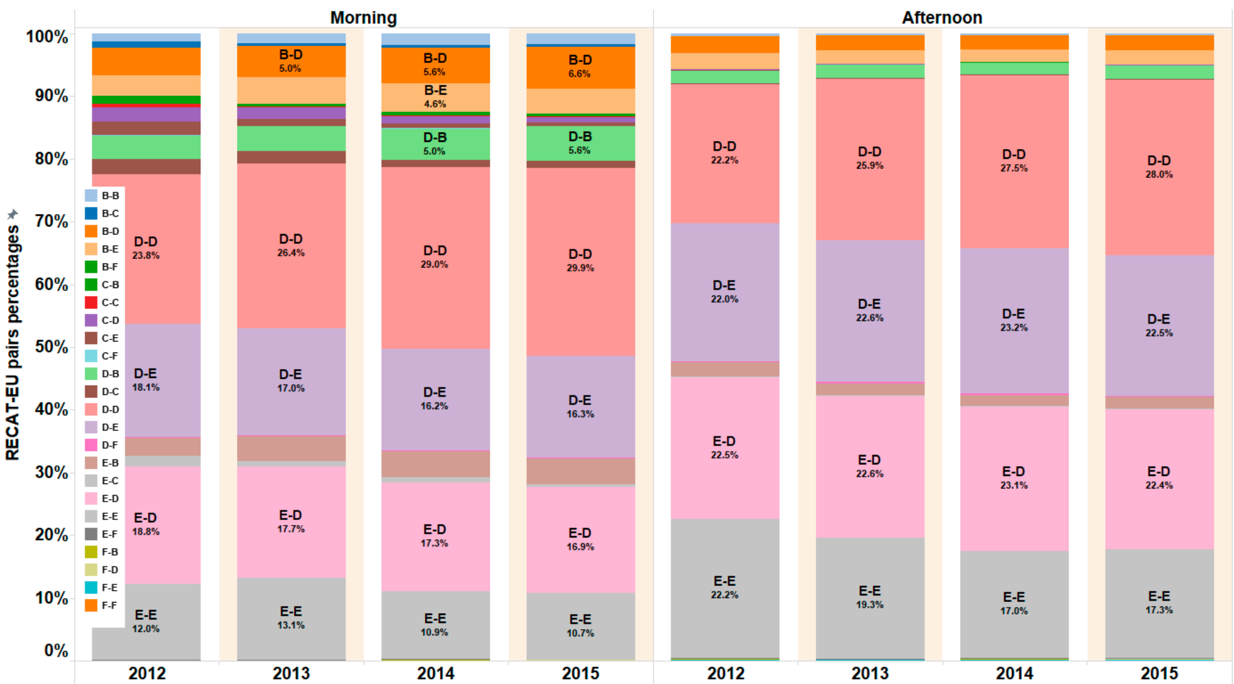

Figure 3-2: Distribution of Schiphol traffic over the combinations of RECAT-EU categories

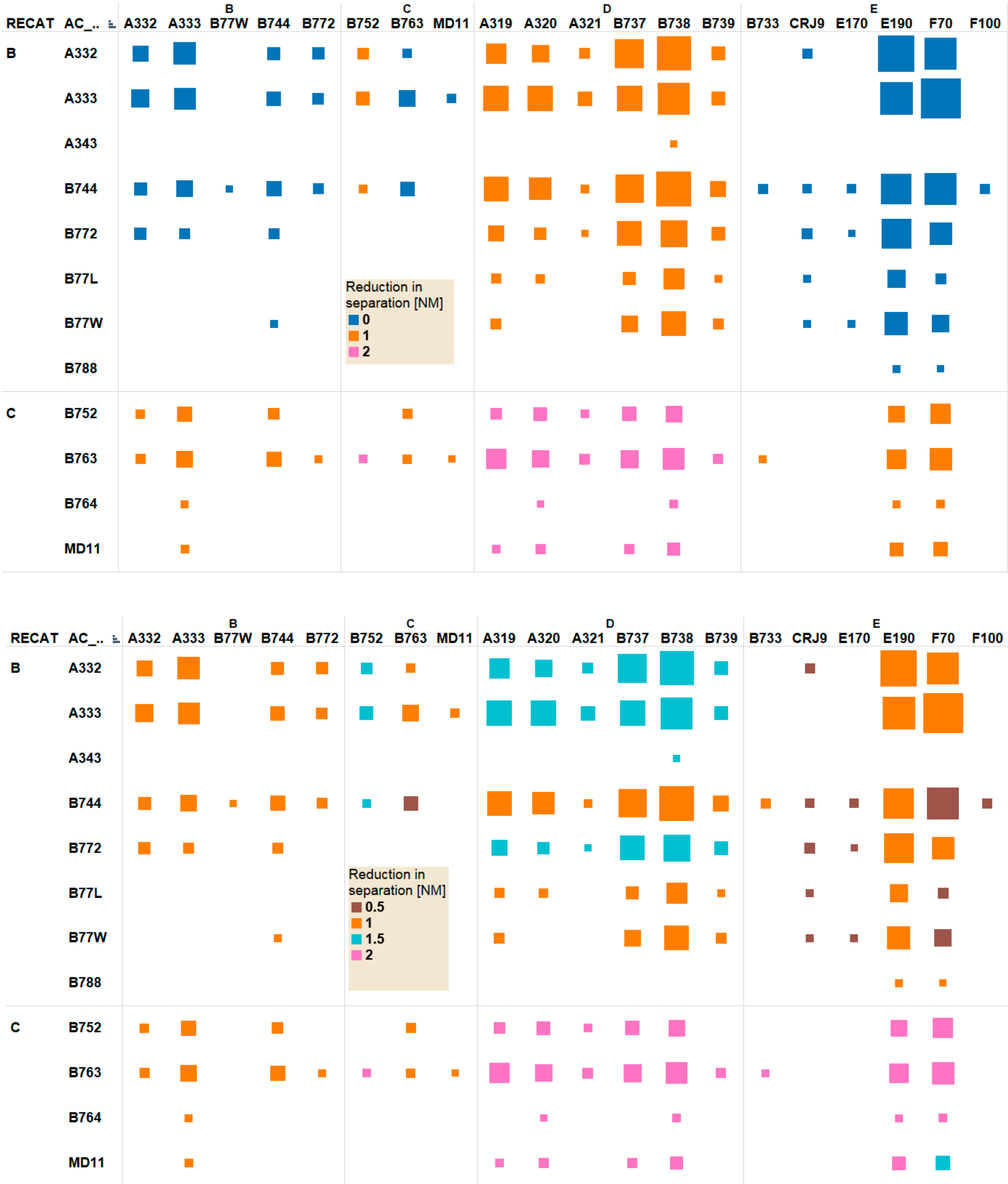

Figure 3-3: Illustration of separation reduction in RECAT-EU (top) and RECAT-PWS-EU (bottom) for frequently occurring pairs with B and C leaders in the Schiphol traffic mix, with the leader aircraft type on the vertical axis and the follower aircraft type on the horizontal axis. The size of the boxes indicates the percentage of a combination in the traffic mix. Note that in the bottom picture, showing RECAT-PWS-EU separation reductions, the legend differs from the one in the top figure. Note furthermore that there are also differences in minimum separation for pairs where the follower is Category F. However, these occur with such low frequency that these are not shown here

4 Benefits analysis results

4.1 Benefits analysis methodology

To assess the capacity benefits, the primary metric is defined as the percent change of the average number of landings that are constrained by separation, per hour and per runway.

In the compilation of the data set there is already a focus on separation constrained pairs. However, as shown in Figure 2-6, there may be pairs for which the actually achieved spacing is up to 200% of the minimum. Apparently, for these pairs there was no traffic pressure to aim at minimum separation and it is expected that in the future operation there would be no incentive for such pairs to aim at the reduced separation. Therefore, in order to get realistic results, the separation reduction because of the proposed scheme is only applied to pairs for which the actually achieved spacing is less than 130% of the separation minimum.

In the current operation the average number of separation constrained landings per hour and per runway is close to 36 in the morning and 38 in the afternoon peak, see section 2.3, Figure 2-5. An increase of 1 movement per hour would thus imply a percent change of about 3%.

A detailed description of the benefits analysis methodology is given in Appendix A. The main rationale is that the change in distance separation minimum is converted to a change in the Landing Time Interval (LTI) given the speed of the follower aircraft. The LTI is to be understood as the time spacing in seconds between two aircraft over the runway threshold. This is calculated for each pair in the data set as described in section 2.3. The average sum of all changes in LTI's per hour is divided by the average LTI to estimate the change in average number of landings.

As was shown in Figure 2-6, the achieved spacing varies from pair to pair and is usually larger than the separation minimum. The difference between the achieved spacing and the separation minimum is referred to as the spacing buffer. In some cases, the buffer is negative, i.e., the achieved spacing is less than the minimum. In this analysis, it is assumed that this buffer does not change. For example, consider a specific pair in the data set for which the ICAO separation minimum is 5 NM and the RECAT-EU minimum is 4 NM. The actually achieved separation is 5.4 NM, so with 0.4 NM buffer. For the benefits assessment, the separation reduction of 1 NM is applied and the actually achieved spacing is now assumed to become 4.4 NM, so with the same 0.4 NM buffer. To calculate the gain in LTI, the ground speed of the follower aircraft at 5.4 NM before the runway threshold is taken. With this ground speed, e.g., 140 kts, which is assumed to be constant over the 1 NM, this implies a reduction of the LTI of 26 seconds.

The assumptions are listed in Table 4-1.

Table 4-1: Assumptions in the benefits analysis methodology

#	Assumption
1	Separation reduction is only applied to pairs that are spaced less than 130% of the current separation minimum.
2	For a specific pair in the data set, the spacing buffer in the future operation is the same as in the current operation.
3	The ground speed of the following aircraft at the current spacing distance before the runway threshold is constant over the reduction in separation distance.

4.2 What are the overall benefits of RECAT-EU and RECAT-PWS-EU?

The estimated overall benefits for arrivals at Schiphol, expressed as the increase in average number of landings per hour, are shown in Figure 4-1. With RECAT-EU the expected increase is 0.7 landings per hour or 1.9%. With RECAT-PWS-EU, this is 1.4 landing per hour or 3.6%.

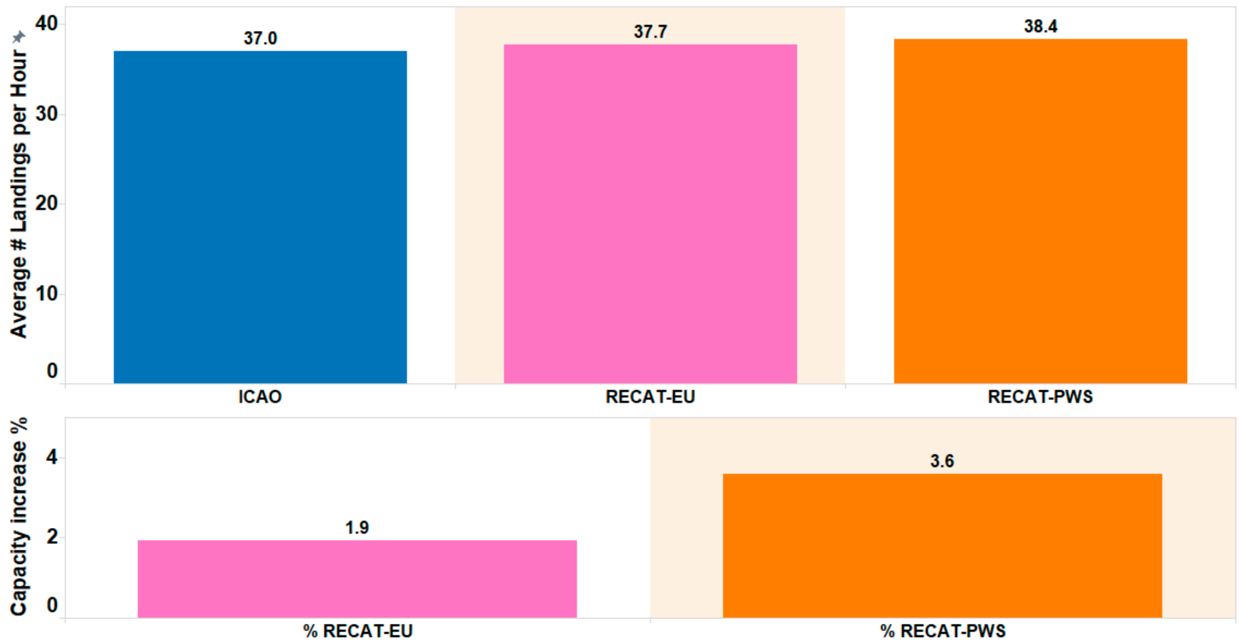

Figure 4-1: Overall benefits of RECAT-EU and RECAT-PWS

When further distinguishing the morning and afternoon peak, as shown in Figure 4-2, there are significant differences: in the morning there is an expected increase of 3.2% and 5.7% for RECAT-EU and RECAT-PWS-EU respectively. In the afternoon the increases are 0.6% and 1.2%. This is explained by the differences in traffic mix with more Heavy traffic in the morning peak. In the afternoon peak there is predominantly Medium traffic for which no separation reduction is proposed.

When comparing the estimated benefits for Schiphol with those for Paris Charles the Gaulle, the benefits for Schiphol are considerably lower. This is because of the higher amount - about 15% against 10% - of Heavy aircraft in the Paris traffic mix.

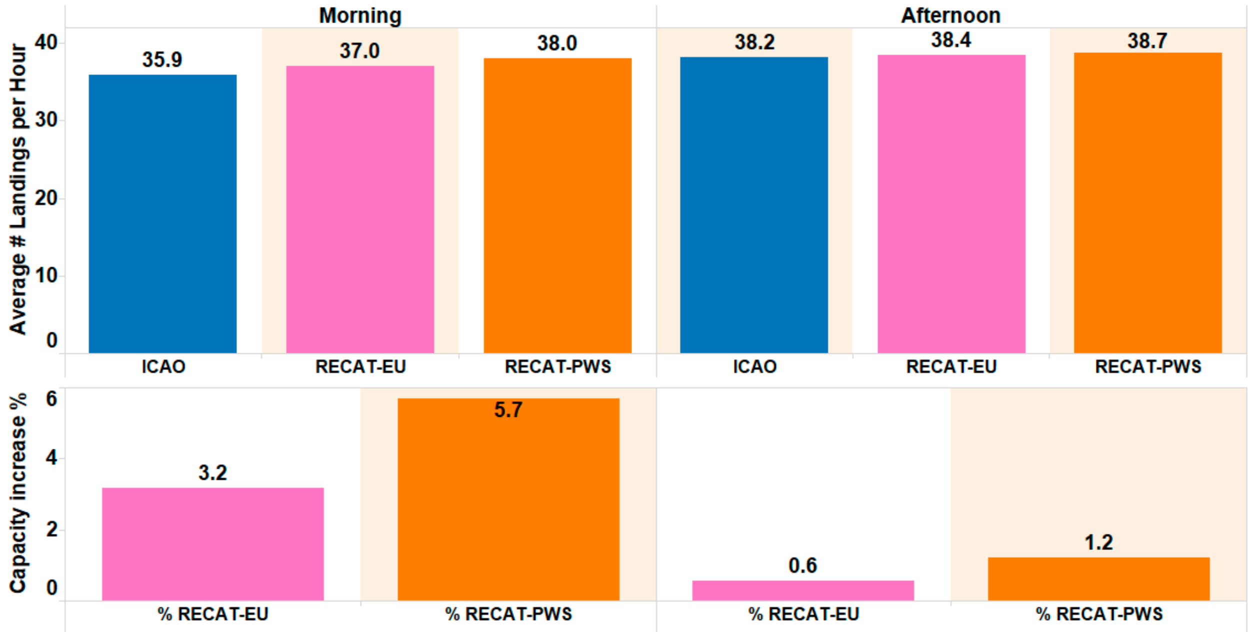

Figure 4-2: Benefits of RECAT-EU and RECAT-PWS, distinguishing Morning and Afternoon peaks

4.3 What are the benefits in strong headwind conditions?

In strong headwind conditions, the potential gain in time – and therefore in runway throughput - is higher because of the lower ground speeds. This is illustrated in Figure 4-3 for conditions with headwind exceeding 15 kts. In these conditions, the expected benefits are indeed slightly higher than in all headwind conditions. The figure also shows that in strong headwind conditions, the average number of landings per hour is considerably less (e.g., 32.5 versus 35.9 in the morning with the current ICAO separation scheme).

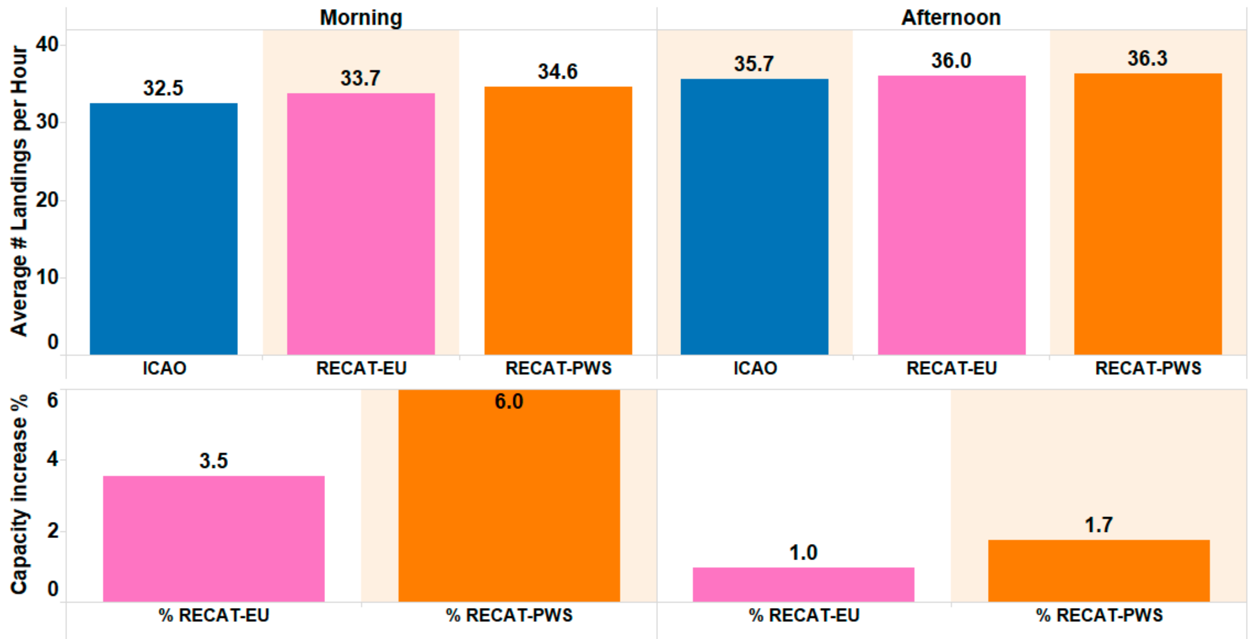

Figure 4-3 :Benefits of RECAT-EU and RECAT-PWS, distinguishing Morning and Afternoon peaks in conditions with headwind exceeding 15 kts

4.4 Which aircraft types contribute to the benefits?

Figure 4-4and Figure 4-5 show what the positive (reduced separation) or negative (increased separation) effect is of aircraft pairs in the current traffic mix. This is shown for the morning (left) and afternoon (right) peak with per column the combination of RECAT-EU WTC and within the column the leader (Figure 4-4) or follower (Figure 4-5) A/C type indicated by colours.

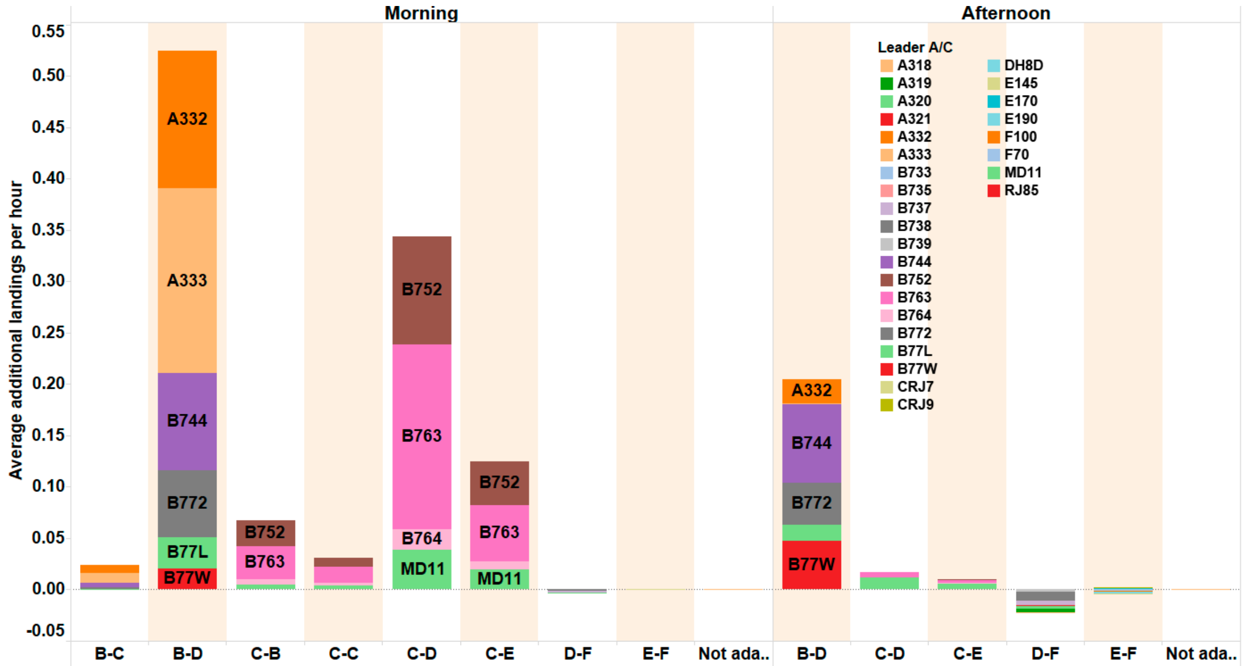

Figure 4-4 :Contribution (positive or negative) of the RECAT-EU WTC combinations to the total benefits. Within the pairs, the distribution of the leader A/C types is indicated by the colours.

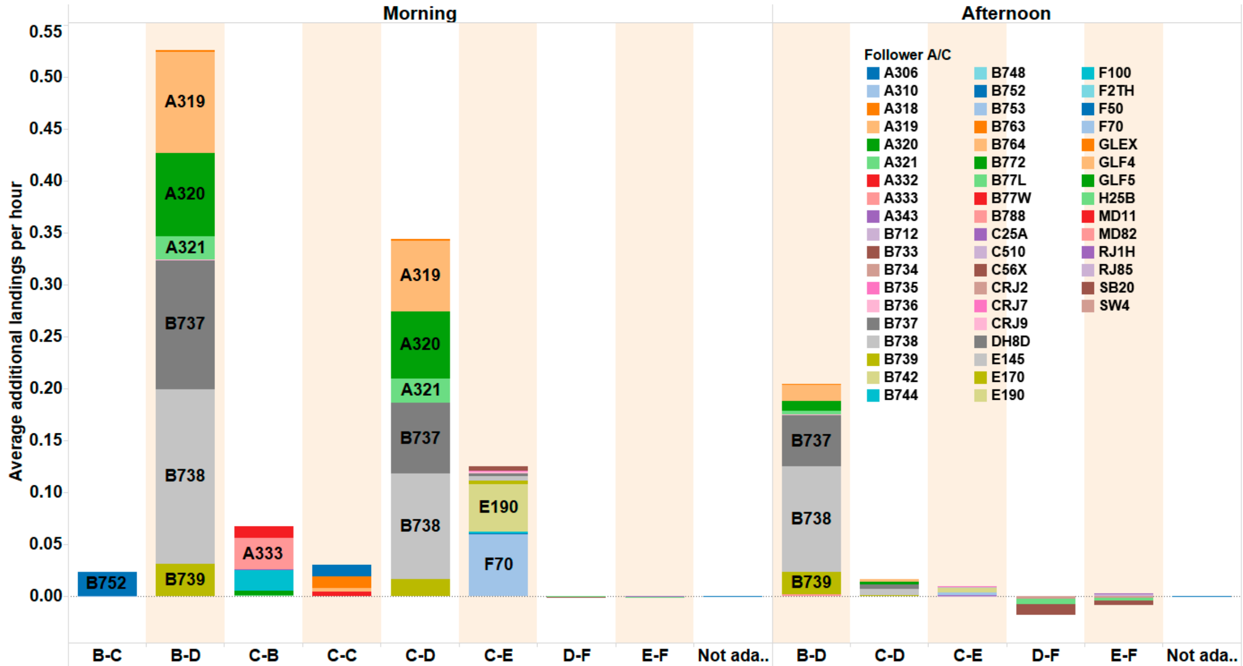

Figure 4-5: Relative contribution (positive or negative) of the RECAT-EU WTC combinations to the total benefits. Within the pairs, the distribution of the follower A/C types is indicated by the colours

The numbers sum up to the total increase of average landings per hour, see Figure 4-2: 1.1 landings for the morning peak and 0.2 landings for the afternoon peak.

For example, in the morning peak, the main contribution (0.52 of the 1.1) comes from the separation reduction between Upper Heavy (B) followed by Upper Medium (D). Most frequently occurring Upper Heavy leading aircraft include A332, A333, B744, and B772. Regarding benefits because of separation reduction behind Lower Heavy (C), the frequently occurring leading aircraft types are B752, B763 and MD11.

Figure 4-6 shows the evolution of the percentages of Upper and Lower Heavy aircraft types in the traffic mix over the years 2012-2015. The numbers of the Lower Heavy (C) types appear to decrease over time as these are being phased out.

According to Figure 4-6, frequencies of Upper Heavies (B) B772, B77W and B787 appear to increase. This fits in a more general trend that the overall fleet mix evolves towards larger aircraft as a mitigation for the lack of runway capacity as forecasted in EUROCONTROL's Challenges of Growth 2013 study [19]. The introduction of the A350 in 2016 further contributes to this.

Most frequently occurring Upper Mediums as follower are – according to Figure 4-5 – A319, A320, A321, B737, B738 and B739. The figures also show there is reduction in runway throughput for combinations of D followed by F. This concerns aircraft like C56X and H25B that used to be ICAO Medium WTC and are now in the RECAT-EU Category F for which separation is increased with 2 NM.

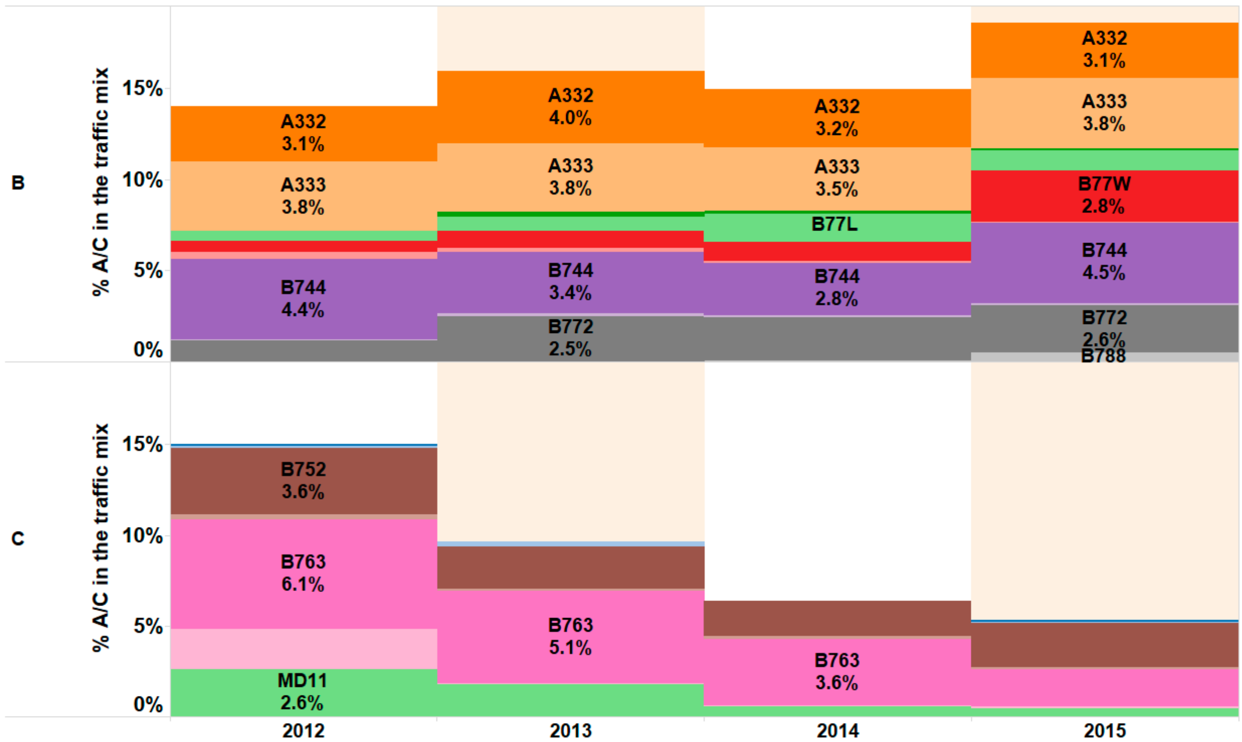

Figure 4-6: Evolution of the percentages of Upper and Lower Heavy aircraft types in the traffic mix over the years 2012-2015

4.5 Which runways contribute to the benefits?

Figure 4-7 shows the distribution of pairs over the runway combinations in use, distinguishing the morning and afternoon peak. The contribution of a runway mode to the benefits scales with the percentage that this runway mode is in use. There appear not to be runway modes for which the benefits are relatively higher or lower. The further distribution of which pairs contribute to the benefits given a runway mode does vary.

For example, the figure shows that about 50% of the pairs considered occurs when runway combination 18R+18C/24 is in use. In terms of the contribution to the benefits, about half of this is because of the separation reduction between B – D pairs and the other half because of separation reduction behind aircraft in the Lower Heavy category (C-E, C-D, C-C-, C-B). In the afternoon, the benefits are predominantly caused by B-D combinations.

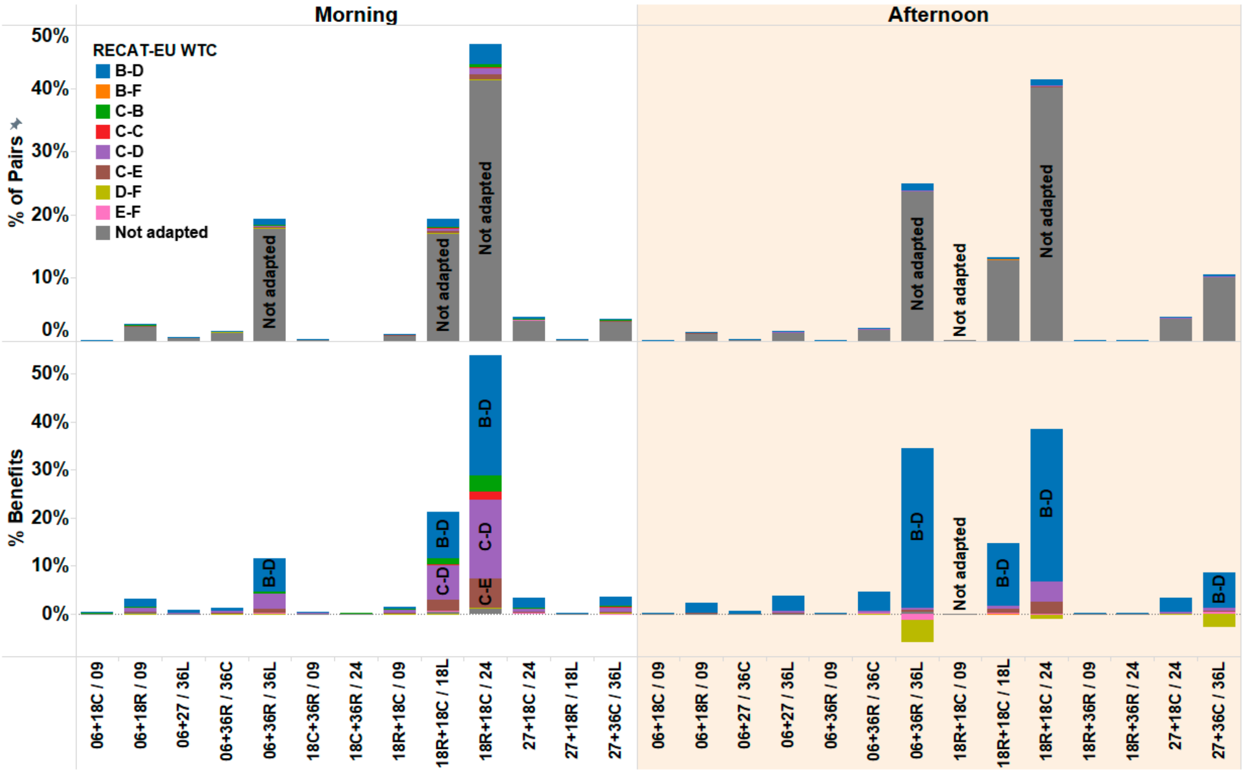

Figure 4-7: Distribution of pairs over the runway combinations per peak (top) and distribution of benefits over the runway combinations and RECAT-EU WTC combinations (bottom)

Figure 4-8 further displays the distribution of pairs over the runways used. In line with Figure 4-7, runways 18C and 18R are most frequently used in the morning peak. In the afternoon peak, runway 36R is also relatively frequently used. It is remarkable that traffic on runway 18R contributes more to the benefits than traffic on runway 18C. This can be explained by trans-Atlantic Heavy traffic that is more likely to make use of 18R than 18C.

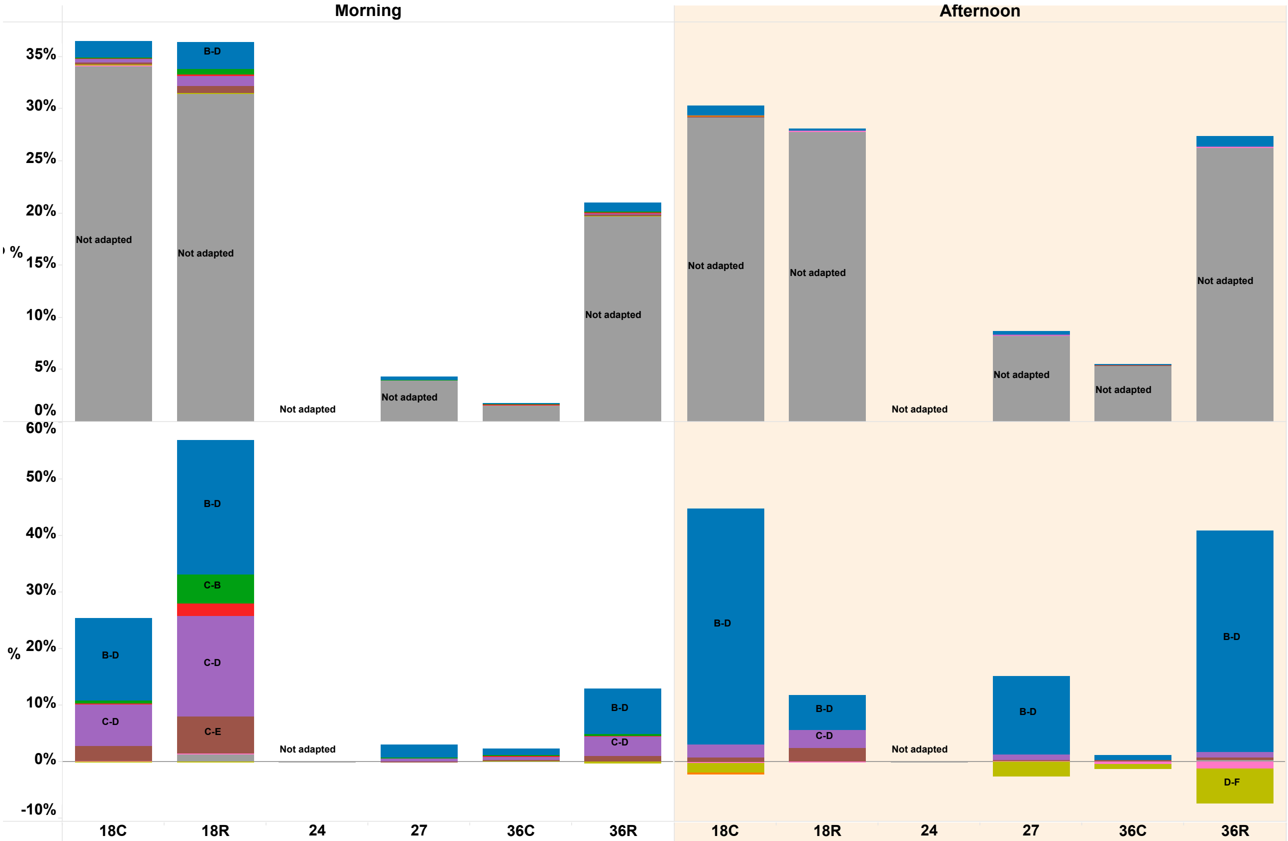

Figure 4-8: Distribution of pairs over the runways per peak (top) and distribution of benefits over the runways and RECAT-EU WTC combinations (bottom)

5 Relevant aspects for deployment

5.1 Introduction

This chapter discusses relevant aspects when it is decided to deploy RECAT-EU or RECAT-PWS-EU at Schiphol airport. Focus is first on aspects related to the System, the Human and Procedures. Furthermore, some thoughts are provided on the need to extend the scope of this study and to set-up a safety case. Inputs for this chapter are a discussion with an Operational Expert Capacity and an OE Strategy of LVNL Schiphol TWR/APP, and available documentation on RECAT-EU and TBS.

5.2 System aspects

In the current operation, the WTC of an aircraft is – or can be – displayed in the label on the radar display of the aircraft and on the flight progress strip. The associated separation minimum is known by the air traffic controller by heart. He assesses the actual spacing between a pair of aircraft based on the aircraft positions on the radar display.

With RECAT-EU the number of categories changes to six and the associated separation minima change as well.

As RECAT-EU and the classification is a local implementation, the information systems at Schiphol airport / LVNL need to be adapted to derive the appropriate category on the basis of the aircraft type.

According to EUROCONTROL [3], "RECAT-EU will mean a minimum system update, as it only requires updating local flight plan in the strip, adaptations to the Approach and Tower traffic surveillance display with new wake turbulence category designations, and publications of new applicable minima". It is believed that for RECAT-EU no further system support is needed for the controllers – with adequate training (see section 5.3) – to obtain the appropriate separation minimum.
EUROCONTROL [3] further substantiates this with the fact that Approach and Tower ATS in the UK have operated on a wake turbulence scheme with 6 categories for some years. Moreover, during Approach and Tower ATC real-time simulation exercises recently conducted at the EUROCONTROL Experiment Centre (EEC), ATC Controllers have confirmed that they were able to adequately apply RECAT-EU scheme without an automated support tool, quickly adapting to the 6-category system.

In the generic RECAT-EU concept as described by EUROCONTROL, the categories are referred to as A to F. Instead, it can be discussed what the best option is to name the categories for the local situation at Schiphol airport / LVNL. E.g., for Charles de Gaulle airport, DSNA has chosen letters S, G, H, K, M, L instead of A to F. By doing so, letters S for Super, H for Heavy, M for Medium, and L for Light remain in use [7].

With RECAT-PWS-EU more advanced system support is required. As explained in the RECAT-PWS-EU Safety Case, it is possible to construct a number of categories based on the pair-wise separation table. Nevertheless, it is believed that with more than six categories it is no longer possible for air traffic controllers to know the categories of aircraft and associated separation minima by heart. Therefore, a ‘separation indicator’ is needed to display the targeted separation on the radar display.

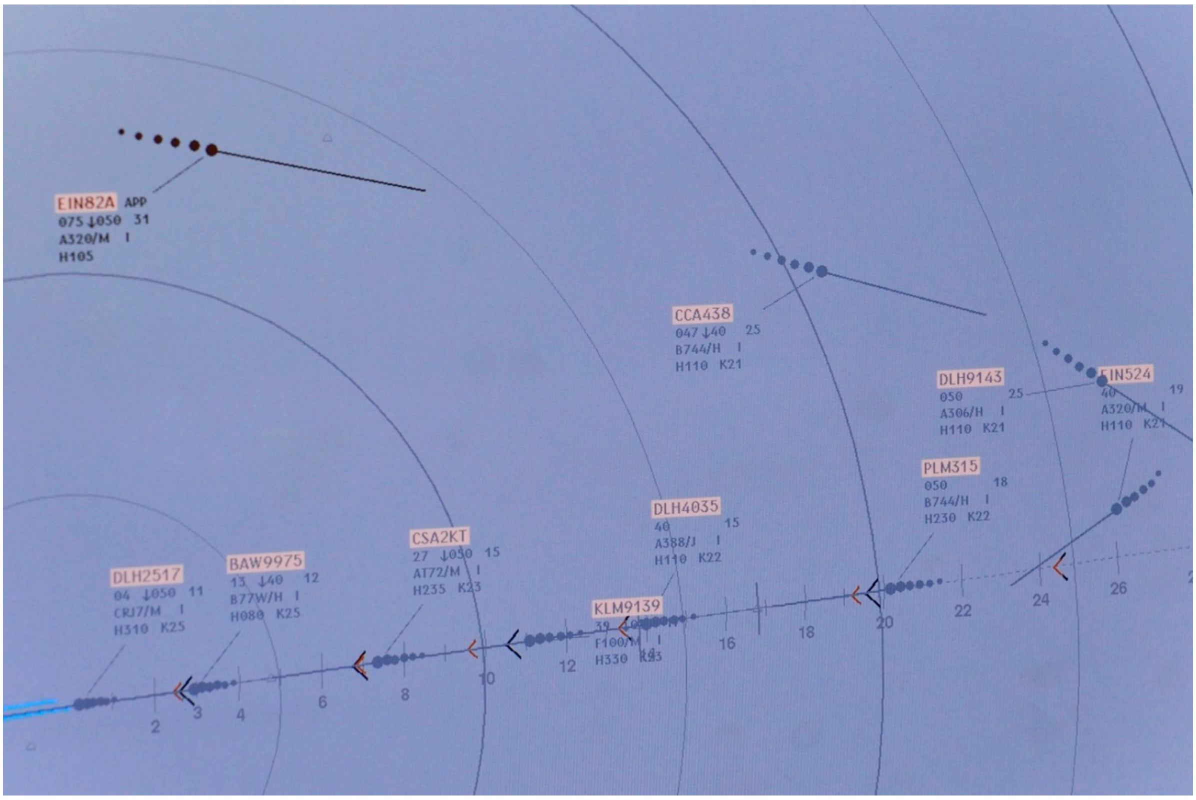

Figure 5-1 :Radar display with separation indicators for Initial Targeted Distance (ITD) in black and Final Targeted Distance (FTD) in red, as developed by EUROCONTROL

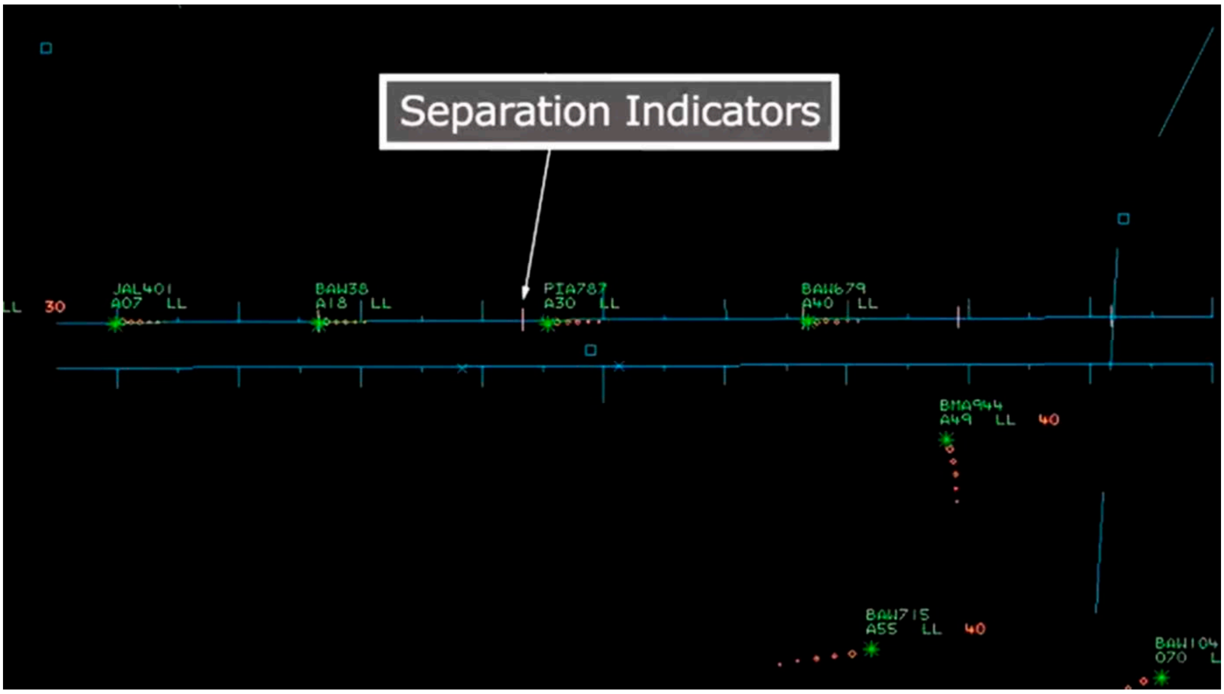

Figure 5-2: Radar display with separation indicator (red bar) as developed by NATS in the context of TBS

Such separation indicator has been prototyped and tested by EUROCONTROL in the context of the SESAR Time Based Separation (TBS) project (see Figure 5-1) and has been implemented by NATS and Lockheed Martin at London Heathrow airport (see Figure 5-2). Although TBS and RECAT-PWS-EU are somewhat different concepts, the need for system support is the same. The EUROCONTROL prototype, referred to as Leading Optimised Runway Delivery (LORD) distinguishes an Initial Targeted Distance (ITD) and a Final Targeted Distance (FTD). The latter one is the applicable separation minimum. The ITD is the FTD plus a buffer which takes into account the compression effect due to differences in speed of two succeeding aircraft; when the first one starts to decelerate, the second one still has a higher speed resulting in decreasing distance spacing.

Development and integration of an indicator in the local situation will require a dedicated study on how it is to be displayed (e.g., colour, size, shape, intensity) from where to where it is to be displayed (e.g., whole TMA, final approach only). While with RECAT-PWS-EU the computation of the indicator location is rather straightforward, as it is in principal a distance based solution. However, underlying the RECAT-PWS-EU distance based separation matrix is a time based matrix. This time based matrix has been converted and rounded off to the distance based matrix using average aircraft speed profiles. It can be beneficial to directly use the time based matrix and convert it to distances to be displayed on the radar screen using local and actual speed information. It can also be foreseen that with the introduction of such system, other concepts like TBS – which is a time based solution – are integrated. This will require further analysis on the use of wind information, its accuracy, reliability etc.

5.3 Human aspects

Regarding RECAT-EU, the working practices of controllers to separate aircraft will not change. However, controllers will need to become familiar with the new six categories and separation minima. Means to do so can include promotion and communication, e-learning and simulator training. For Charles de Gaulle airport, where RECAT-EU has been implemented in 2016, controllers received 2 to 3 hours simulator training [7].

One particular comment by the interviewed OE's concerns the split up of the B737 family over Upper and Lower Medium categories: the fact that B737-300, -400, and -500 are assigned to the Lower Medium (E) category while the B737-600, -700, -800, and -900 are Upper Mediums (D) is considered an increase of the complexity of the separation scheme.

In case of RECAT-PWS-EU, the working practices of controllers will change more significantly because of the use of the separation indicator. Obviously more training is required to become experienced in using such support tool.

In the context of the SESAR TBS project, NATS and EUROCONTROL conducted real-time simulations of the TBS concept at London Heathrow airport. Results of this experiment show that controllers did experience similar workload with TBS as with ICAO distance based separations. There was a slight increase of R/T usage by the final approach controller, apparently linked to the higher aircraft landing rates achieved with TBS. Furthermore, the accuracy of the spacing improved significantly using the separation indicator.

For pilots, EUROCONTROL has developed an e-learning module. This is available through the EUROCONTROL training zone [21]. In the module the RECAT-EU concept is explained and pilots can familiarise themselves with the separation minima associated to their aircraft type (e.g., see Figure 5-3). NATS also has developed crew briefing material, see [22].

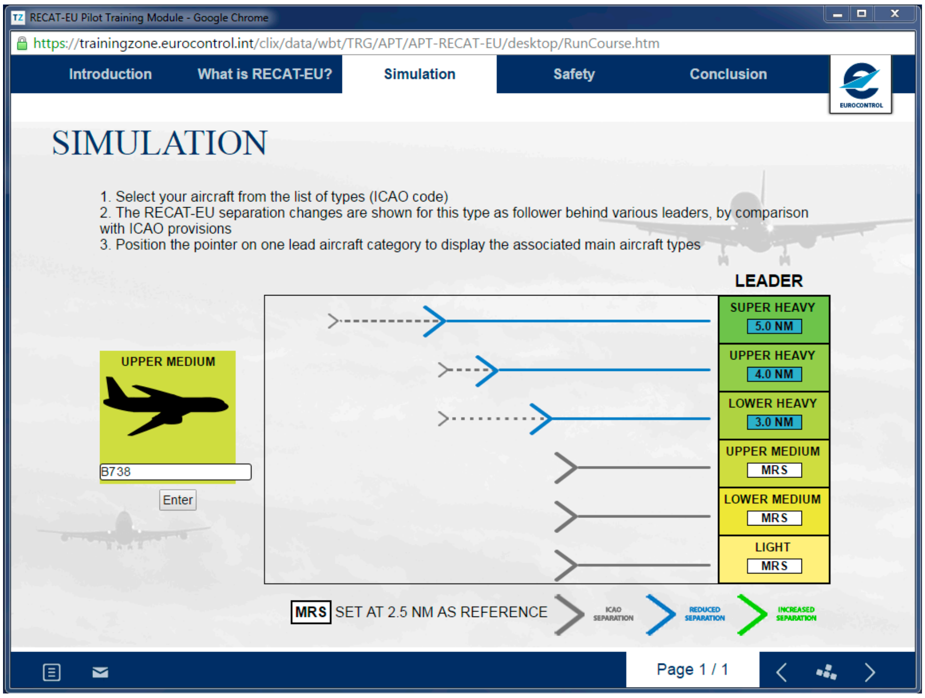

Figure 5-3: EUROCONTROL e-learning module for pilots [21]

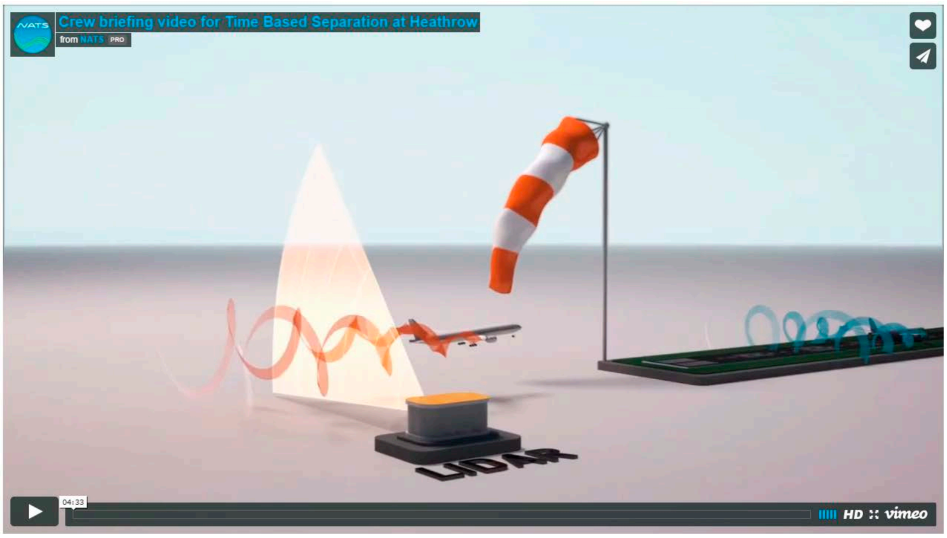

Figure 5-4 :NATS Crew briefing video for TBS at Heathrow [22]

5.4 Procedural aspects

At a high level, implementation of RECAT-EU or RECAT-PWS-EU is to be considered as an adaption of the separation minima. PANS-ATM [11] states that: *"The separation ....minima based on radar and/or ADS-B to be applied shall be prescribed by the appropriate ATS authority..."*

Furthermore, SERA [16] states that: *"The selection of separation minima for application within a given portion of airspace shall be made by the ANSP responsible for the provision of air traffic services and approved by the competent authority concerned."*
It is advised to contact the relevant authorities in a sufficiently early phase.

At an operational level, the relevant sections of the Operations Manual [18] need to be adapted. In addition to the more straightforward changes of separation categories and minima, it may need to be considered how the reduced separation scheme for arrivals fits in the larger scope of arrival and departure management.

Regarding phraseology, PANS-ATM section 4.9.2 [11] prescribes that "for aircraft in the Heavy wake turbulence category the word "Heavy" shall be included immediately after the aircraft call sign in the initial radiotelephony contact between such aircraft and ATS units". With RECAT-EU no change is needed since ICAO "Heavy" types remain "Heavy" in RECAT-EU.

Furthermore, the Aeronautical Information Publication (AIP) needs to be adapted and/or an Aeronautical Information Circular (AIC) can be issued. E.g., for the introduction of RECAT-EU at Charles de Gaulle airport, DSNA issued an AIC [23].

5.5 Scope considerations

While the focus of the current study is on application of RECAT separation to arrivals on final approach, it is noted that the distance based separation scheme is to be applied in the whole TMA and even beyond to the en-route phase and also to departing traffic. As such, it is recommended to consider extension of the scope from runway capacity to airspace capacity.

The interviewed OE's expressed a concern when reduced separation is applied to departures. E.g., when a B737-900 departs behind an A330 at 4 NM instead of 5 NM, the spacing between the two will decrease too much due to differences in speed and climb profile.

The RECAT-EU and RECAT-PWS-EU offer the possibility to create a quick win by starting with an implementation of only one of the new categories. From the discussion with OE's, such quick win could be achieved if it would be possible to maintain the current categorisation. This is the case for the separation behind the Super category with the A380. However, the number of A380 movements is currently such low that there are no significant benefits yet.

Moreover, it can be considered to integrate RECAT-EU or RECAT-PWS-EU with deployment of TBS. TBS has been included in European Commission Implementing Regulation (EU) No 716/2014, which requires ATS providers and airport operators at selected airports – including Schiphol – to operate TBS by January 2024 [17].

5.6 Safety case considerations

When it is decided to implement RECAT-EU or RECAT-PWS-EU, a local safety case will need to be made to show that the operations after introduction are sufficiently safe. For both RECAT-EU and RECAT-PWS-EU, EUROCONTROL has developed a generic safety case. These generic safety cases have a rather technical character, with the main focus on wake vortex decay, wake encounter metrics, and the statistical analysis of wake measurements and aircraft speed profile measurements. The main argument for which evidence is provided reads *"WT risk is acceptable with the proposed separation scheme in principle"*. At a local level, evidence needs to be collected for the argument that the *"Proposed separation scheme is adequately deployed, applied and monitored" [4]*.

Considering the scope of the generic safety case, the following aspects need to be addressed additionally at a local level:

- Reduced WT separation can lead to a conflict with an aircraft that hasn't yet vacated the runway. This may lead to an increased number of runway incursions and go-around and may – in worst case conditions – have an effect on mid-air and runway collision risk. These are not addressed in the generic safety case.
- The generic safety assessment is made based on a traffic sample in a reference scenario, representative of the reasonable worst conditions, assuming this applies to all airports in Europe and for "conditions within the normal range of operating conditions". It may need to be checked if the reference scenario and conditions are representative for the local situation.

In view of safety monitoring, in the generic safety cases an estimate is made for the increase in wake vortex encounters and the increase in go-arounds. These estimates are based on historical data of WVE reports, traffic mix data, and the estimated increase in WVE risk. For RECAT-EU, it is estimated that the total number of WVE reports on approach will increase with 5% and an increase of go-arounds with 0.5% [4]. At a local level, these estimates can be reviewed and can be used as a reference in monitoring the evolution of local WVE reports.

Furthermore, the separation performance can be monitored. As shown in Figure 2-6, the actually achieved separation varies around the separation minimum. It is of interest to monitor how this distribution develops when RECAT is implemented. In the current benefits analysis it is assumed that the shape of this distribution remains the same.

5.7 Summary of aspects

In the following tables, the system, human, procedural, and safety related aspects are summarised.

Table 5-1: Summary of systems related aspects

Systems related aspects	RECAT-EU	RECAT-PWS-EU
WTC names	To be defined, or following A to F	To be defined depending on local categories made on the basis of the pair-wise separation matrix
WTC in label on radar display	To be adapted	To be adapted
WTC on flight progress strip	To be adapted	To be adapted
Separation indicator	Not required	To be implemented
Relation to other systems (e.g., AMAN)	Not expected	To be checked which systems are affected

Table 5-2: Summary of human related aspects

Human related aspects	RECAT-EU	RECAT-PWS-EU
Knowledge of separation scheme	Controllers should be trained such that they know categories and minima by heart. E.g., by e-learning and real-time simulation. Awareness campaign, briefing material, e-learning for pilots	Controllers should be aware of the new scheme Awareness campaign, briefing material, e-learning for pilots
Use of separation indicator	Not required	To be trained in real-time simulator

Table 5-3: Summary of procedure related aspects

Procedure related aspects	RECAT-EU	RECAT-PWS-EU
Adaptation of separation minima	To be approved by appropriate ATS authority	To be approved by appropriate ATS authority
Adaptation of VDV	Required	Required
Adaptation of AIP / Issue of AIC	Required	Required

Table 5-4: Summary of scope related aspects

Scope related aspects	RECAT-EU	RECAT-PWS-EU
Application of RECAT separations	Extend scope to TMA and departures, possibly also en-route	Extend scope to TMA and departures, possibly also en-route
Assessment of benefits	Extend scope from runway capacity to airspace capacity	Extend scope from runway capacity to airspace capacity
Identification of quick wins	Could be interesting to reduce separation behind A380	Could be interesting to reduce separation behind A380
Integration with TBS	Can be considered	Is logical to consider, given the similar requirements for system support

Table 5-5: Summary of safety related aspects

Safety related aspects	RECAT-EU	RECAT-PWS-EU
Wake vortex encounter risk	Assessed in EUROCONTROL generic safety case, which can be adopted	Assessed in EUROCONTROL generic safety case, which can be adopted
Mid-air and runway collision risk	To be assessed in a local safety case	To be assessed in a local safety case
Representativeness of generic traffic sample, speed profiles, and operating conditions	To be checked in a local safety case	To be checked in a local safety case
Monitoring of WVE reports and separation performance	To be described in a local safety case	To be described in a local safety case

6 Conclusions

An analysis has been made of the runway capacity benefits that can be expected when RECAT-EU or RECAT-PWS-EU would be applied at Schiphol airport to arrivals.

In the analysis, the focus is on pairs of aircraft that are constrained by wake turbulence separation. Data is used of pairs of arrivals in busy morning and afternoon peak hours in the years 2012 – 2015 for which the actually achieved spacing is less than 130% of the separation minimum.

With RECAT-EU, the estimated increase is 0.7 landings per hour on average or 1.9%. With RECAT-PWS-EU, this is 1.4 landings per hour or 3.6%. When further distinguishing the morning and afternoon peak, as shown in Figure 6-1, there are significant differences: in the morning there is an expected increase of 1.1 landings per hour (3.2%) and 2.1 landings per hour (5.7%) for RECAT-EU and RECAT-PWS-EU respectively. In the afternoon increases are 0.2 (0.6%) and 0.5 (1.2%). This is explained by the differences in traffic mix with more Heavy traffic in the morning peak. In the afternoon peak there is predominantly Medium traffic for which no separation reduction is proposed.

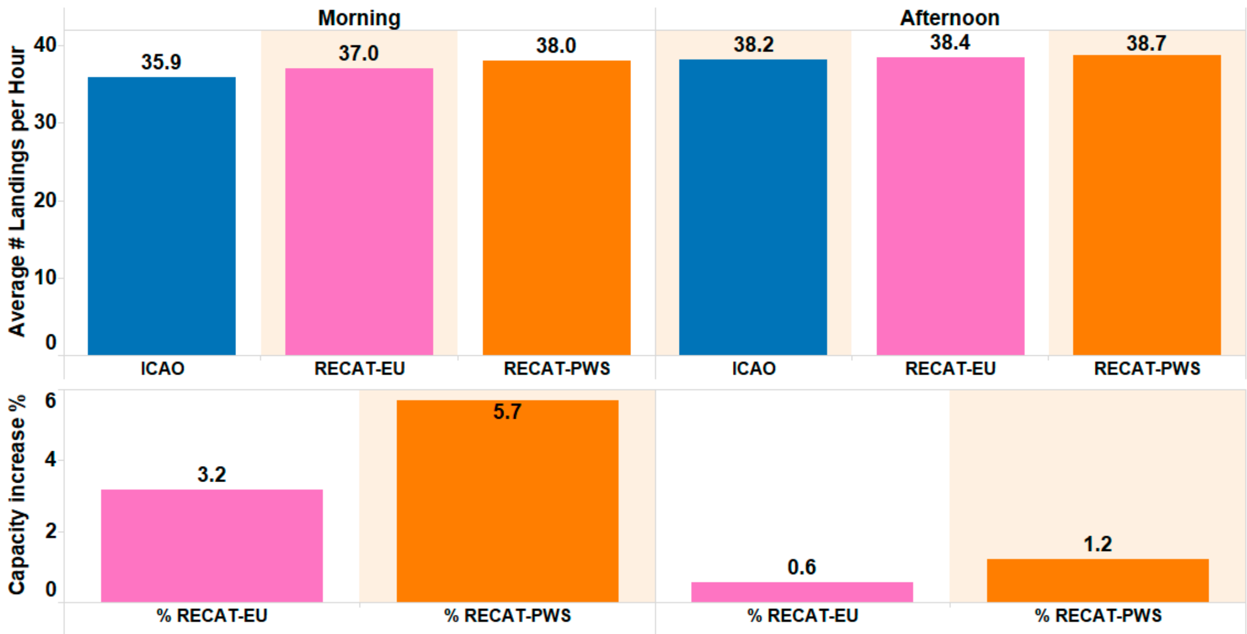

Figure 6-1: Benefits of RECAT-EU and RECAT-PWS, distinguishing Morning and Afternoon peaks

When comparing the estimated benefits for Schiphol with those for Paris Charles the Gaulle, the benefits for Schiphol are considerably lower. This is because of the higher amount - about 15% against 10% - of Heavy aircraft in the Paris traffic mix.

In strong headwind conditions, the potential gain in time – and therefore in runway throughput - is higher because of the lower ground speeds. For conditions with headwind exceeding 15 kts the expected benefits are indeed slightly higher: 1.2 (3.5%) and 2.1 (6.0%) landings per hour in the morning for RECAT-EU and RECAT-PWS-EU respectively.

The benefits are mainly created by reduction in separation behind aircraft in the RECAT-EU Upper Heavy (B) category, like A332, A333, B744, and B772. Next to that, there is a contribution because of separation reduction behind aircraft like B752, B763 and MD11 in the Lower Heavy (C) category. The numbers of these latter types appear to decrease over time. On the other hand, Upper Heavies like B772, B77W and B788 appear to visit Schiphol more and more frequently.
In addition to the benefits analysis and in view of the further decision-making process, relevant aspects regarding systems, humans and procedures have been identified and considerations on extension of the scope of this study and the set-up of a local safety case have been provided.

According to EUROCONTROL studies and experiences at Paris Charles de Gaulle airport, RECAT-EU requires relatively little modifications of the systems and no additional system support to the controllers is needed. There is an increase in complexity due to the six instead of four categories where for example the B737 family is split up into Upper and Lower Medium categories.

With RECAT-PWS-EU more advanced system support is required and the working practices of controllers will change more significantly. A 'separation indicator' is needed to display the targeted separation on the radar display. Development and integration of an indicator for the environment at Schiphol airport will require a dedicated study.

It can be considered to extend the scope of this study to also analyse the effects on runway and airspace capacity when RECAT separation is applied to departures and in the whole TMA or even beyond to en-route.

Furthermore, it seems a logical option to integrate RECAT-PWS-EU with the Time Based Separation concept as similar system support is needed. TBS has been included in European Commission Implementing Regulation (EU) No 716/2014, which requires ATS providers and airport operators at selected airports – including Schiphol – to operate TBS by January 2024.

For RECAT-EU and RECAT-PWS-EU, EUROCONTROL has developed generic safety cases to show that the wake turbulence encounter risk is acceptable in principle. At a local level, a complementary safety case needs to be developed to show that the proposed scheme is adequately deployed, applied and monitored. Such local safety case should also assess the effects on risks other than WTE risk: the risk of an increased number of runway incursions or go-arounds which in worst case conditions could evolve into a runway or mid-air collision.

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Appendix A Benefits assessment methodology

To assess the capacity benefits, the primary metric is defined as the percent change of the average number of landings within an hour:

$$Capacity\ benefit = \frac{\tilde{L}_{RECAT} - \tilde{L}_{VDV}}{\tilde{L}_{VDV}} * 100\% = \frac{\widetilde{\Delta L}}{\tilde{L}_{VDV}} * 100\%$$

where $\tilde{L}$ is the average of the number of landings in each of the H hours considered:

$$\tilde{L} = \frac{1}{H}\sum_{h=1}^{H} L_h$$

A landing is defined as an aircraft passing the runway threshold.

To assess $L_{h,VDV}$ is rather straightforward using historical data. For windows of 1 hour, the number of aircraft passing the runway threshold can be counted.

To assess what could be the number of landings using the new separation scheme, $L_{h,RECAT}$, requires the following steps:

1) For each pair of aircraft the distance spacing at a certain point (e.g., the threshold or at 1 NM) is defined as:

$$D_{i,j,VDV} = SM_{i,j,VDV} + SB_{i,j,VDV}$$

where $SM_{i,j,VDV}$ is the Separation Minimum applicable to the pair of aircraft according to the VDV and $SB_{i,j,VDV}$ is the Spacing Buffer associated to this pair of aircraft when applying VDV separation.

2) For this pair of aircraft, the distance spacing with the new separation scheme would be:

$$D_{i,j,RECAT} = SM_{i,j,RECAT} + SB_{i,j,RECAT}$$

The $\mathrm{SB}_{\mathrm{i,j,RECAT}}$ has to be estimated, taking into account different considerations:

- It can be assumed that $\mathrm{SB}_{\mathrm{i,j,RECAT}} = \mathrm{SB}_{\mathrm{i,j,VDV}}$, i.e., the buffer remains the same for a pair of aircraft;

- It can be assumed that the buffer is a function of the separation minimum. E.g., the buffer applied with RECAT separation of 3 NM for Cat C – Cat C pairs is the same as the buffer applied with VDV separation of 3 NM for Medium – Medium.

- The $\mathrm{SB}_{\mathrm{i,j,RECAT}}$ will be estimated for the proposed separation scheme for each combination of categories and associated separation minimum in section X.

- The difference in distance spacing (in meters) is then defined as:

$$\Delta D_{i,j} = SM_{i,j,RECAT} + SB_{i,j,RECAT} - SM_{i,j,VDV} - SB_{i,j,VDV}$$

3) The difference in time to fly (in seconds) this distance is computed with the actual ground speed (in meters per second) of the follower aircraft at its actual position when the leading aircraft is passing the reference point X_{ref}:

$$GS_j = GS\left(x = X_{ref} + SM_{i,j,VDV} + SB_{i,j,VDV}\right)$$

$$\Delta T_{i,j} = \frac{\Delta D_{i,j}}{GS_j}$$

4) The average gained time in seconds per hour then is:

$$\widetilde{\Delta T} = \frac{1}{H}\sum_{h=1}^{H}\sum_{i=1}^{N}\Delta T_{i,j}$$

5) To estimate the average number of additional flights $\widetilde{\Delta L}$ that can be accommodated in $\widetilde{\Delta T}$, we need to know the average time per landing in seconds:

$$\widetilde{T_L} = \frac{3600}{\tilde{L}} = 3600/\left(\frac{1}{H}\sum_{h=1}^{H}L_h\right)$$

$$\widetilde{\Delta L} = \frac{\widetilde{\Delta T}}{\widetilde{T_L}}$$

In the picture below, the different spacings are sketched.

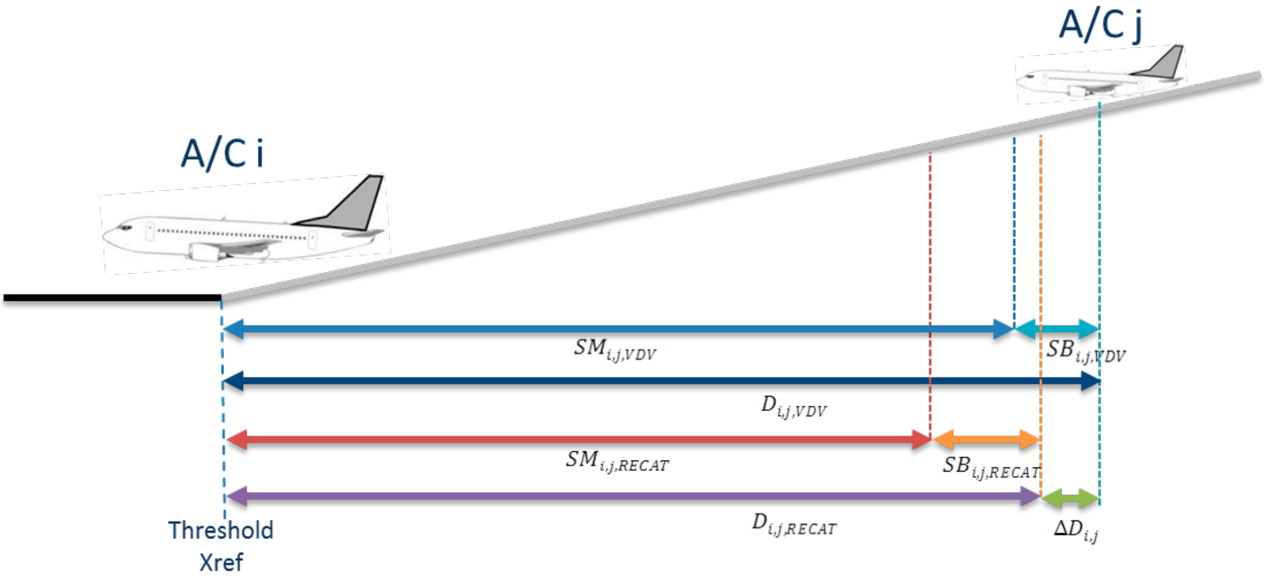

Figure 6-2: Different spacings (separation minima and buffers) between a pair of aircraft

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