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Continuous climb and High altitude SIDs

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Date	20 December 2019
Version	V1.0
Document Nr	19.282.04
Executed by	To70

19.282.04 • December 2019

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Report

Aviation Consultants

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The Hague, December 2019

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1 Introduction

1.1 Background

As part of airspace redesign of the Dutch FIR, a redesign of the Amsterdam TMA is foreseen after 2023. This redesign provides the possibility to redesign the arrival and departure routes in such a way that these are free of conflict and provide an optimal balance in noise, emissions and capacity. An optimal SID achieves several objectives:

1. The aircraft climbs as quickly as possible to minimise noise, emissions and fuel burn.
2. The aircraft turns toward the destination as soon as possible to fly the minimal distance for minimum emissions and fuel burn.
3. The SID branches as late as possible for airspace complexity and to minimise the geographical area affected by noise.
4. The SID provides enough separation between consecutive flights for capacity.

These considerations are competitive and therefore need to be balanced. Above 6000ft, emission preferent routing is given priority. Below 6000ft, priority is given to noise preferent routing and reducing the number of SIDs per runway.

Choices must be made in designing new optimal SIDs. However, the consequences of several design choices are not exactly known. Keeping all traffic laterally combined on a single SID allows for noise optimal SIDs but is expected to reduce peak capacity. Flying a fixed vertical profile allows for the separation of inbound and outbound traffic but is expected to have effect on the noise footprint of the SID. This research focuses on both the lateral and vertical design choices and their consequences. The scope of this research is the exploration of possibilities and possible effects. The outcomes can be used as a guide to direct further research and policy development.

This research analyses the capacity effects of keeping all traffic laterally combined till 6000ft and the potential for mitigation of capacity loss through speed restrictions. A uniform design climb angle for 3D fixed departures is determined and the noise impact of this new climb angle is analysed. The analysis uses ADS-B data from Schiphol, which provides insights into the actual operation at Schiphol.

1.2 Conclusions

Keeping all traffic laterally combined on a single SID is likely to cause a drop in capacity of 4-7 movements per hour. Imposing a speed restriction of 230-250 knots starting at 3000ft provides a capacity gain of 2 movements per hour since aircraft can be sequenced more closely. ADS-B data shows 95% of the operation can operate at these restrictions. Tighter speed restrictions only provide marginal improvements and lower compliance in the operation. The effect of a speed restriction is limited since most spacing differences occur in the first 2000ft and the speed profile is not always the critical factor in separation.

Analysis of vertical profiles shows that 95% of the aircraft operating at Schiphol can fly a fixed angle of 8%. Using this angle, aircraft would perform a conventional NADP-2 departure until 2000ft, followed by a climb with a fixed angle to 6000ft located 12.3nm from the runway. Noise modelling shows that this new profile causes the noise footprint to narrow along the SID, due to a lower power setting. At the same time the noise footprint increases in length along the extension of the runway since aircraft fly at a lower altitude for a longer time.

1.3 Assumptions

The analyses conducted in this research focuses on departing traffic above an altitude of 2000ft. This demarcation has been made since the first part of the departure is limited by safety and performance limitations of the aircraft. Above 2000ft flight profiles are still limited by aircraft performance but more flexible. From this altitude, the exact profile is strongly based on operator choices.

This analysis is based on actual flight tracks departing from Schiphol performing a continuous climb. For this analysis a set of flight tracks of departures from Schiphol 2018 and 2019 were randomly drawn from To70's ADS-B database. The sample therefore closely reflects the current operation at Schiphol. Since the current operation covers a realistic technical envelope it is assumed that the current operation is a good indicator for performance of aircraft beyond 2030.

1.4 Reading guide

Chapter 2 analyses the capacity drop when introducing a single SID and how much introduction of the speed restriction can compensate for this capacity drop. Chapter 3 uses the ADS-B dataset to determine which realistic climb angle can be introduced given the current climbing performance of the aircraft at Schiphol. The noise consequences of this new climbing angle are compared to the current departure procedures in Chapter 4. Chapter 5 provides recommendations for additional research based on the conducted analysis.

2 Analysis: capacity consequences of single SID

Keeping all traffic laterally combined on a single SID is likely to cause a drop in capacity of 4-7 movements per hour. Imposing a speed restriction of 230-250 knots starting at 3000ft provides a capacity gain of 2 movements per hour since aircraft can be sequenced more closely. ADS-B data shows 95% of the operation can operate at these restrictions.

Tighter speed restrictions only provide marginal improvements and lower compliance in the operation. The effect of a speed restriction is limited since most spacing differences occur in the first 2000ft and the speed profile is not always the critical factor in separation.

2.1 Capacity drop due to single SID

The minimum spacing between consecutive departures is governed by radar separation and wake turbulence separation. ATC provides this separation by timing consecutive departures.

To ensure sufficient separation between consecutive ATC has to apply a (0.5-1.0 NM) buffer above the minimum spacing requirements. This buffer provides assurance against loss of separation due to differences in flight speed between different aircraft and airlines and for sudden changes in speeds due to wind changes or engine failures.

When SIDs branch with an angle of more than 45 degrees, two consecutive aircraft are separated as soon as they are on their ‘own’ branch. Earlier branching therefore eliminates the need for the additional buffer. Ensuring that consecutive flights follow different SIDs is the primary means for LVNL to provide high capacity for departing aircraft.

An analysis of the departure capacity from a single runway at Schiphol with extra buffer shows a maximum rate of 50 departures per hour. Introducing the 0.5-1.0NM buffer reduces that capacity by 4-7 movements per hour. This analysis is further detailed in paragraph B .

The actual highest declared capacity for Schiphol is 40 departures per hour per runway. This is considerably lower than the 50 modelled departures. The main difference in departure rate are other factors than prevent ATC from reaching that average value. These differences will also apply in the envisioned further scenario with a single SID and therefore the loss of capacity will be comparable.

2.2 Capacity effects of speed restrictions

The capacity loss due to the usage of a single SID can partially be compensated by imposing speed restrictions. Speed restrictions improve uniformity in the departure stream, which limits the possibility of aircraft breaching separation requirements. Because of this, aircraft can be sequenced more closely and capacity can be increased.

Figure 1 shows the speeds of the Schiphol fleet at different altitudes, based on analysed ADS-B data. The figure shows the minimum speed (green) and the maximum speed (red) which 95% of the flights can fly at different altitudes. The blue line indicates the average speed at each altitude.

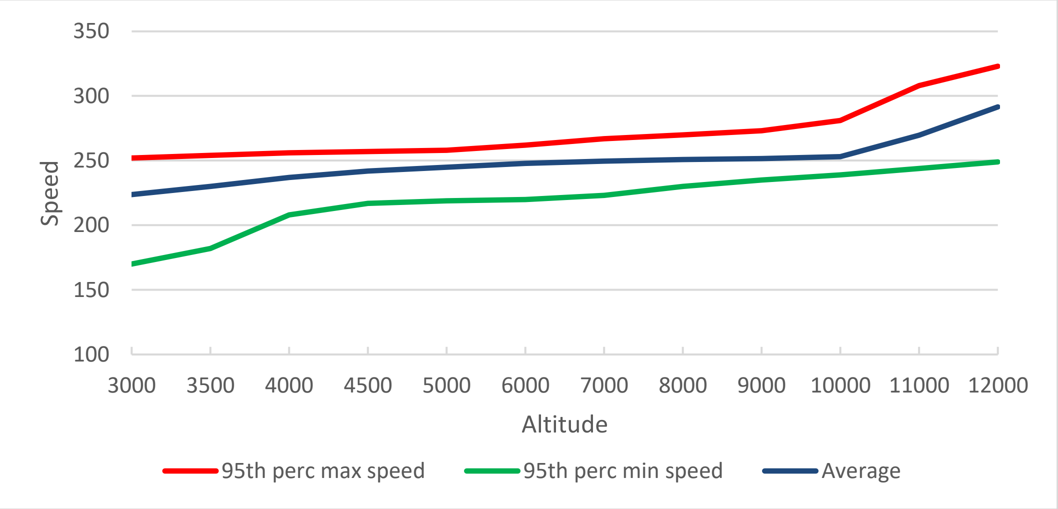

Figure 1: Analysis of operating speeds at Schiphol

Table 1 provides an overview of the capacity effects of different speed restrictions at different altitudes. From the table it is concluded that imposing a speed limit of minimal 230 knots at 3000ft is the most realistic option and allows for a capacity improvement of 2 movements/hour. This is concluded because:

- Imposing the same speed restriction at the higher altitude of 4000ft only improves capacity by 1 movement/hour since.
- A tighter speed restriction of 240 knots at 3000ft only provides marginal improvements and lower compliance in the operation.
- Speed restrictions of 250 knots at both attitudes are deemed not realistic in terms of compliance in the operation given the analysis presented in Figure 1.

Imposing the speed restriction does not fully compensate for the capacity loss caused by a single SID since most spacing differences occur in the first part of the departure, below 2000ft. Furthermore, the speed profile is not always the critical factor in separation but rather the (time-) interval between consecutive take-offs.

Table 1: Effect of speed restrictions on capacity

ALT	IAS Restriction [knots]	Capacity (0.5 nm buffer)	Capacity improvement (base = 46 m/h)
4000ft	Minimal 250	48	+2
	Minimal 240	47	+1
	Minimal 230	47	+1
3000ft	Minimal 250	49	+3
	Minimal 240	48	+2
	Minimal 230	48	+2

Two aircraft types do not have sufficient ADS-B data in the data sample which comply with the speed limitation because their operating speed is too low. Within the analysed data, the CRJX has not reached any of the minimal speed restrictions at the different altitudes. The BCS3 only complies with the lowest speed limit at higher altitude. Given that these aircraft types are both small jets and relatively new, it is expected that they can meet the speed limitations.

3 Analysis: options for design climb angle

Analysis of vertical profiles shows that 95% of the aircraft operating at Schiphol can fly a fixed angle of 8%. Using this angle, aircraft would perform a conventional NADP-2 departure until 2000ft, followed by a climb with a fixed angle to 6000ft located 12.3nm from the runway.

A second climb angle which would allow arrival aircraft to pass between the two departure streams is not deemed realistic. Only an angle of approximately 23% would comply with separation requirements, which is deemed unrealistic for the fleet at Schiphol.

3.1 Analysis of climb angles at Schiphol

Figure 2 shows the climb angle of departing aircraft during take-off, based on analysed ADS-B data. The figure shows the minimum climb angle (purple) and the maximum climb angle (green) which 95% of the flights can fly at different distances from the runway. The blue line indicates the average climb angle at each distance. The graph shows that, while climb angles are high in the first part of take-off, a stable minimal climb angle of 8% is possible for 95% of the analysed flights.

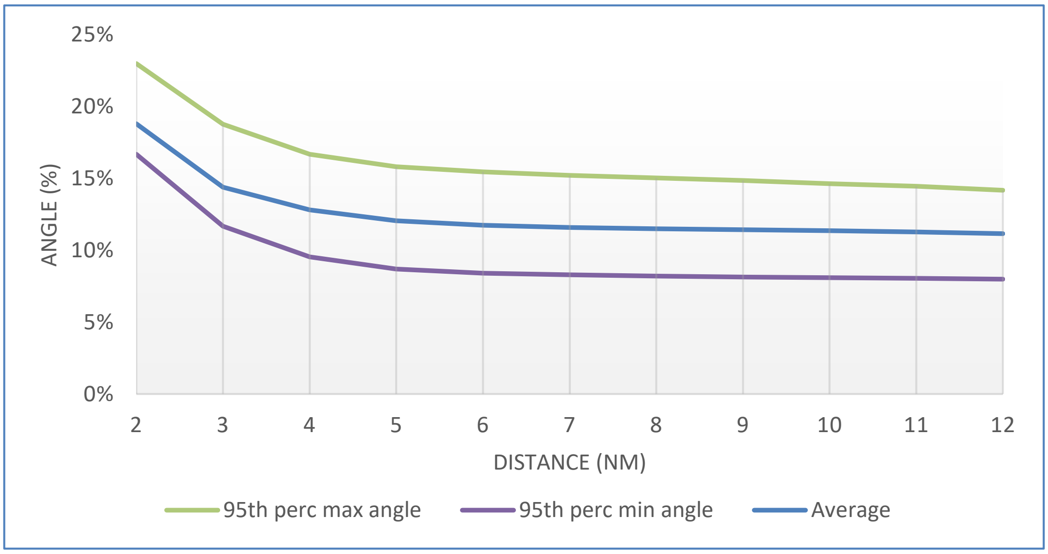

Figure 2: Climb angles at different distances from the runway

The ADS-B data sample includes three aircraft types (the A343, B742 and B744) which regularly have a climb angle lower than 8%. Table 2 shows that of these three types, the A343 performs worst and only rarely achieves an 8% climb angle between 7 and 12 nm from the runway. This can also be seen in Figure 3, which compares the climb angles of the A343 with three other aircraft types.

All three aircraft types are old aircraft which are currently being phased out by several airlines operating at Schiphol. It is expected that in the upcoming years these aircraft types will no longer carry out operations at Schiphol.

Table 2: Percentage of flights above 8% climbing angle at different distances from the runway

NM	2	3	4	5	6	7	8	9	10	11	12
A343	100%	100%	100%	70%	50%	30%	20%	20%	20%	10%	10%
B742	100%	100%	100%	50%	50%	50%	50%	50%	50%	50%	50%
B744	100%	100%	100%	80%	60%	60%	50%	50%	50%	50%	50%

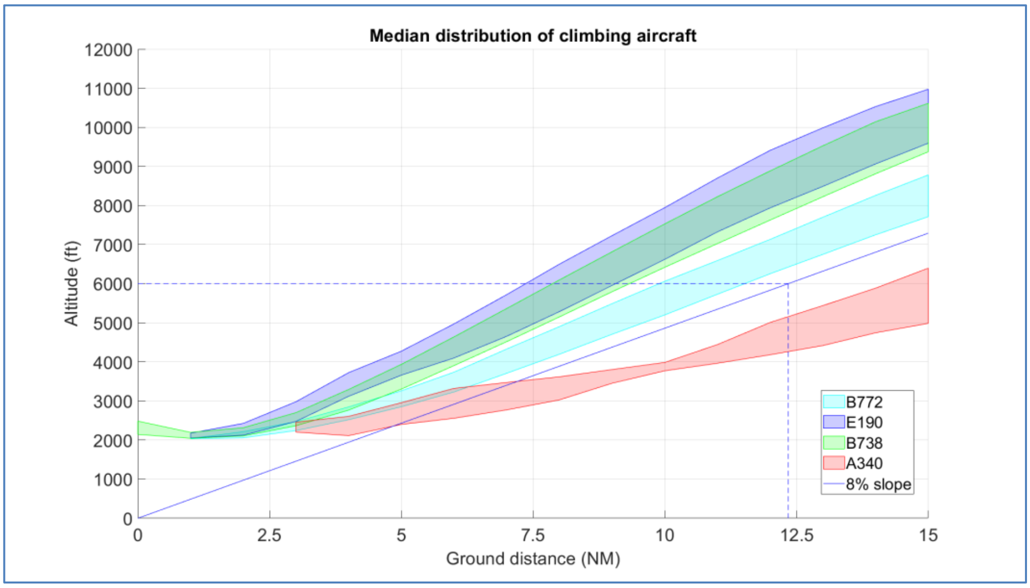

Figure 3: Median distribution of climbing aircraft compared with 8% fixed climb

3.2 Introduction of a second climb angle

The proposed 8% climb angle is a conservative climb angle achievable by 95% of the flights. The ADS-B data shows that a large amount of aircraft can climb at much higher angles. This opens the question if it is possible to create a second, higher climb angle for aircraft which can climb faster. This could improve fuel efficiency and reduce noise effects of the faster climbing aircraft.

A secondary minimum climb angle is relevant when an arrival route will cross the SID between the two vertical paths. This can only be done if these routes maintain at least 5 nm lateral or 1000 ft vertical separation from each other. Figure 4 shows the same climb angles as Figure 3 and a hypothetical arriving aircraft (blue dot). The yellow lines indicate the lateral separation requirements on both sides of the arriving aircraft, the red line indicates the vertical separation required above and below the arriving aircraft.

The result of these separation requirements is shown in **Error! Reference source not found.**. With a lower angle of 8%, a second higher angle has to be at least 23% to allow for an arriving aircraft to pass between the two at 12.3nm. By moving the crossing point further away from the runway the higher angle can be decreased. However, as Figure 2 shows, the maximum climb angle which 95% of the flights can fly at these distances is around 15%. A second climb angle to allow arrivals in between is therefore not considered to be operationally feasible.

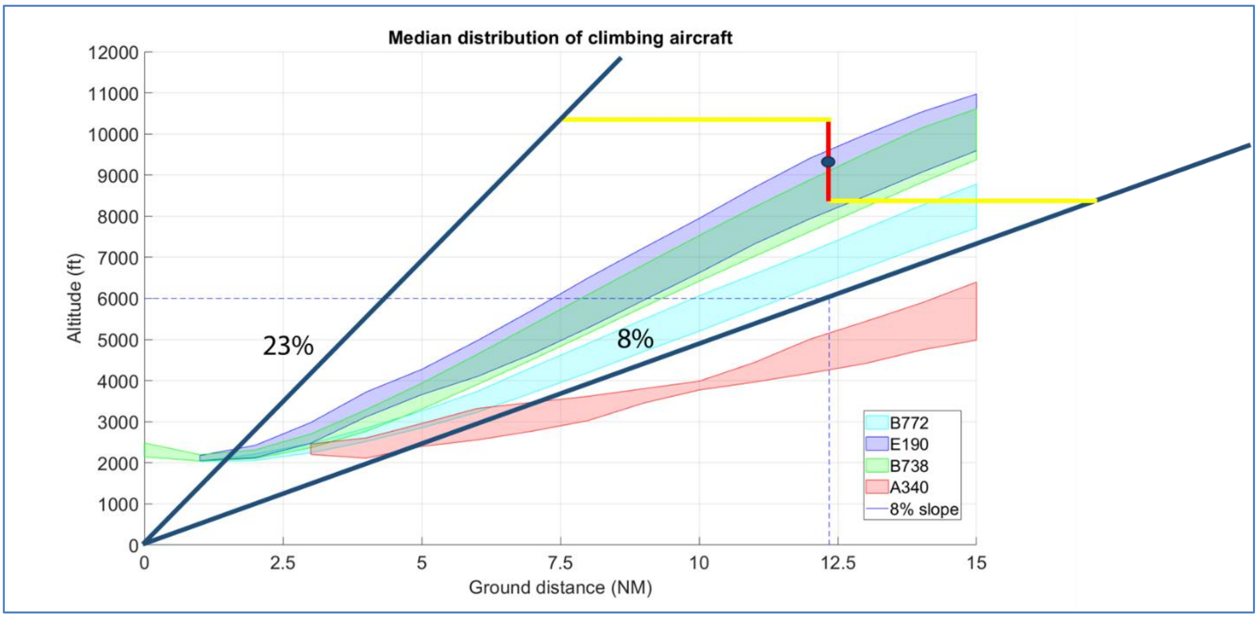

Figure 4: Analysis of second climbing angle

4 Noise impact of design climb angle

The proposed climb angle of 8% is based on a minimum performance. Therefore, most flights will climb slower compared to the current operations. This implies that these aircraft will fly lower for a longer period but also that engine power during the climb is reduced.

The lower altitude increases noise levels surrounding departure track, the lower power setting reduces the noise levels. An initial exploration of expected noise profiles shows that with a fixed 8% climb angle the noise levels will be reduced closer to the runway and along the SID, but noise levels will increase further away in the extension of the runway.

4.1 LAmax noise profiles

The analysis of noise effect focusses on three aircraft types which represent the different kind of aircraft which operate in the fleet at Schiphol:

- The Embraer E190, representing the smaller feeder aircraft
- The Boeing 737-800, representing the medium aircraft
- The Boeing 777-300, representing the large aircraft

Noise calculations were conducted with the FAA's INM model (version 7.0d). The reference case are the noise contours of the three aircraft flying a conventional NADP 2 departure. These contours are compared with the noise contours of the three aircraft flying a conventional NADP 2 departure until 2000ft, followed by the fixed climb angle to reach 6000ft at 12.3 nm. Figure 5 compares the LAmax contours of the different procedures for the three aircraft types. All three comparisons show a similar consequence of the fixed climbing angle: the noise footprint becomes narrower and longer.

The different aircraft types reach the altitude of 2000ft at different distances from the runway. The small E190 reaches 2000ft around 3nm from the runway while the heavy B777 reaches it around 5nm from the runway. After reaching 2000ft, the fixed climb angle causes the aircraft to reduce power compared to the current operation, which causes the noise contours to narrow. The noise contours become wider again after the aircraft passes the 6000ft point at 12.3 nm, as aircraft then increase their climb angle to 8%.

The fixed climb angle causes the aircraft to fly at a lower altitude for a longer time, which causes the noise contours to become longer. This effect is largest for the smaller E190 and B737 aircraft which climb much steeper than 8% in the current operation. For these two aircraft the 40 dB LAmax contours extends by 6 nm (B737) to 9 nm (E190) compared to the current operation. For the heavy B777 the differences in the length of the noise contours are smaller since the B777's current climb angle is closer to the fixed 8% angle in the current operation.

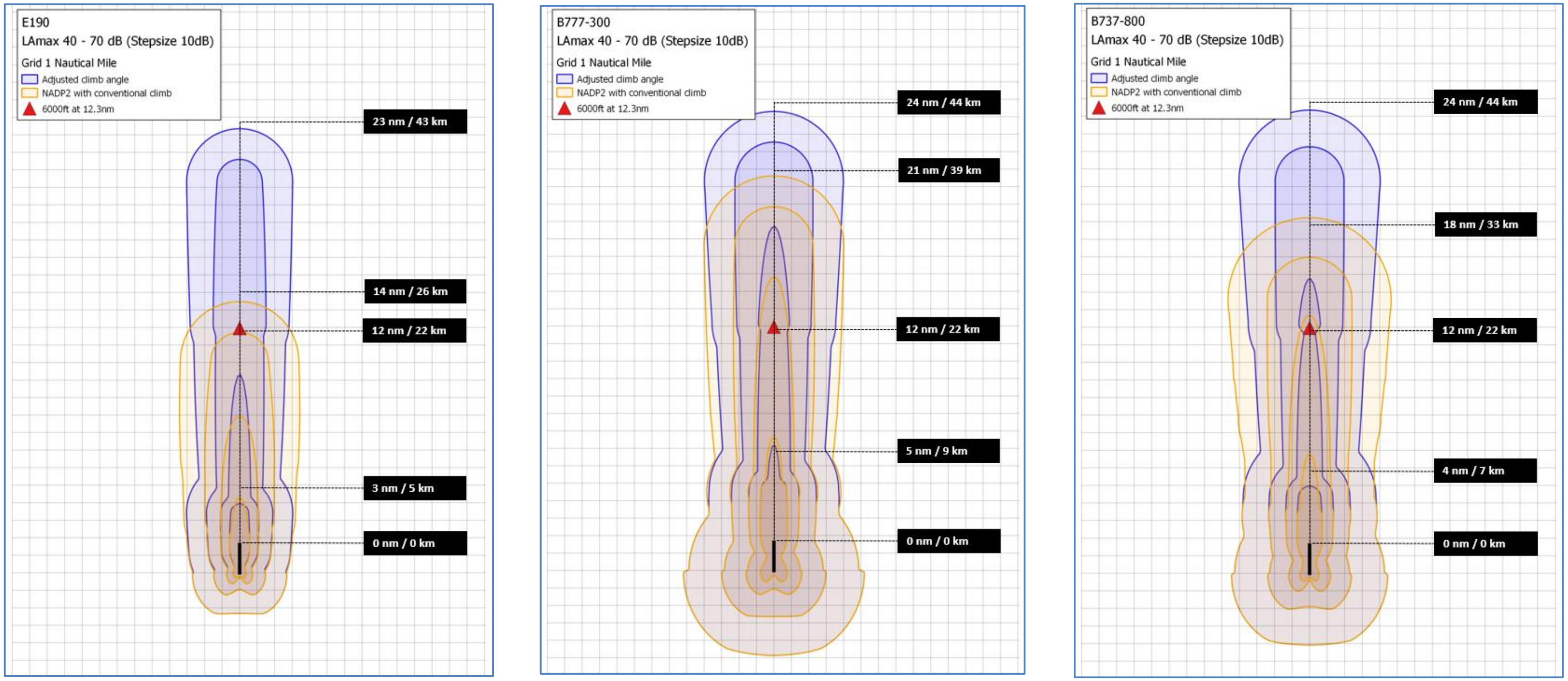

Figure 5: LAmax contours of different climb angles

4.2 Lden noise contours

For calculation of the Lden (Level Day-Evening-Night) noise contours a traffic composed of the three analysed aircraft types is used. Table 3 provides a summary of this traffic. The share of each aircraft type in the traffic is based on the share of comparable aircraft types (feeder, medium & long haul) in the Schiphol forecast of 2018 (GJ2018).

Table 3: Composition of Lden traffic

Lden traffic	
Aircraft movements	50.000
Share E190	25%
Share B737-800	60%
Share B777-300	15%

Figure 6 compares the Lden noise contours of the traffic with a conventional NADP2 departure and a departure with the fixed climb angle. The Lden contours combine the noise profiles of the different aircraft types and therefore shows similar differences as the LAmax contours in the previous paragraph.

As mentioned in the previous paragraph, the different aircraft reach the 2000ft level between 2 and 5 nm and then reduce power on the fixed 8% climb. The result of this reduction in engine power can be seen in Figure 6: the width of the 40dB(A) Lden noise contour reduces by about 1 nautical mile on both sides along the SID and the 50dB(A) Lden contour becomes about 3 nautical miles shorter. At the same time the fixed climb angle also causes the 40dB(A) Lden noise contour to become longer about 6 nautical miles longer since the aircraft fly at a lower altitude for a longer time.

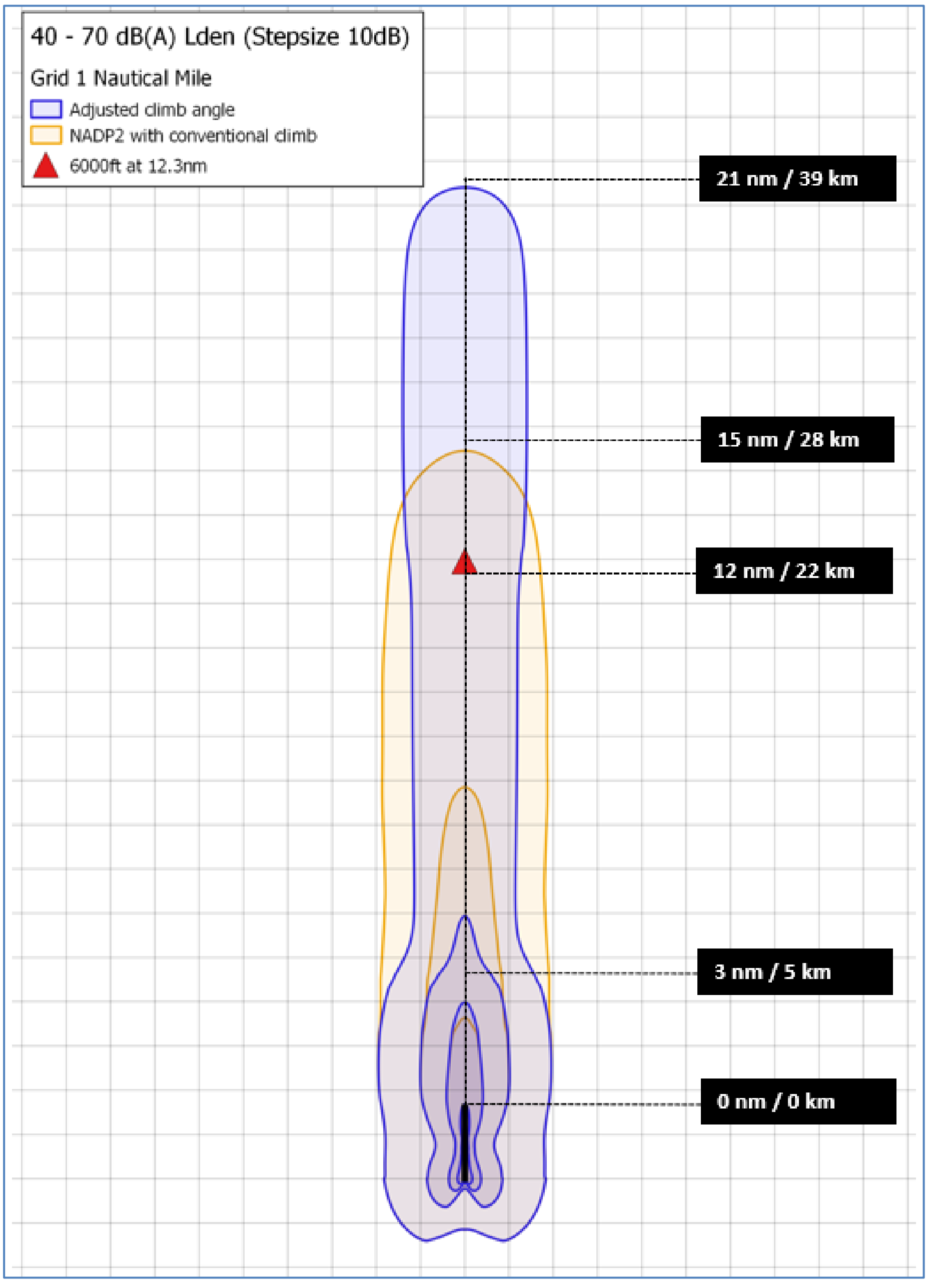

Figure 6: Comparison of Lden contours

5 Recommendations

The scope of this research was the exploration of possibilities and possible effects of both the lateral and vertical design choices in designing new SIDs. Since the scope was that of an exploration, several aspects are recommended for further research:

- Since ADS-B data was randomly drawn from the ADS-B server the analysed flights provide a good overview of average operations and flight performance. This means the proposed fixed climb angle of 8% is realistic for average operations. However, a more detailed analysis will be needed to ensure that the proposed angle can be achieved by 95% of the flights. One of the specific subjects in this analysis would be days with particularly hot weather in which aircraft climb performance will be reduced.
- The noise impact of the design climb angle has been analysed using three aircraft types which represent the current fleet at Schiphol. Additional analysis should focus on a wider range of aircraft types to provide further insights into the noise impact.

A Data sample

This analysis is based on actual flight tracks for departing aircraft from Schiphol. For this analysis a set of 24138 flight tracks of departures from Schiphol 2018 and 2019 were randomly drawn from To70's ADS-B database. Several restrictions were included in the drawing process to ensure data quality:

- Only flights which conducted a continuous climb from 1000ft till flight level 130 were selected
- Only flights with stable datapoints (no sudden changes) were selected

Table 4 provides a comparison between the most common aircraft types in the Schiphol forecast of 2018 (GJ2018) with the data sample collected from the ADS-B database. The comparison shows that the E190 is underrepresented in the ADS-B data sample. With over 300 records there is still enough data to draw conclusions on the performance of the E190. The DH8D is also underrepresented in the dataset. With only 5 flights in the dataset this is the only frequently operated aircraft which cannot be considered in the analysis. Besides these specific aircraft type the data sample is overall comparable to the Schiphol forecast, therefore resembling the operation at Schiphol.

Table 4: comparison of Schiphol forecast and collected ADS-B data

AC type	GJ2018	ADS-B
B738	21.3%	26.8%
E190	13.4%	1.5%
A320	10.2%	10.3%
B737	8.4%	9.1%
E75L	7.1%	9.1%
A319	6.7%	6.0%
A321	3.4%	3.1%
B744	2.8%	2.4%
A333	2.7%	3.4%
B772	2.6%	2.2%
B77W	2.4%	3.0%
A332	1.9%	1.8%
B739	1.8%	3.0%
DH8D	1.8%	0.02%
F70	1.6%	0.1%
B789	1.3%	2.5%
B788	0.7%	0.5%
E145	0.7%	0.0%
B763	0.6%	1.2%
B733	0.6%	0.7%

A select number of old or General Aviation aircraft types were excluded from the analysis. Together they account for 1.6% of flights in the dataset. It is expected that these aircraft types won't create an operational problem when the speed restriction is introduced. X provides an overview of the excluded aircraft types. The flights in Table 5 are divided into two aircraft groups, based on the reason why they are excluded and why it is not a problem if they cannot reach the speed limit.

- General aviation aircraft: These are mostly business jets which visit Schiphol occasionally. They are primarily facilitated at RWY 04-22 (Oostbaan) and are therefore separated from the main aircraft departure sequence at Schiphol for which the 250 knots restriction would apply.
- Old aircraft: These are old aircraft which lack the performance to reach 250 knots at 4000ft. The number of movements carried out with these aircraft has been declining over the years to only a limited number of flights. It is expected that in the upcoming years these aircraft types will no longer carry out operations at Schiphol.

Table 5: Flights excluded from data sample

Type	Occurrences	Aircraft group
BE4W	1	General Aviation aircraft
LJ75	1	
GLF6	2	
C560	2	
BE40	1	
C750	1	
E35L	7	
E550	1	
DC93	1	
E55P	20	
GLF5	4	
CL35	19	
FA50	1	
SF24	2	
FA8X	3	
G280	1	
C68A	15	
GL5T	3	
E145	1	Old aircraft
A306	51	
YK40	1	
F100	105	
B462	1	
ATP	1	

B Capacity analysis method

The analysis of capacity consists of a simulated sequence of 1000 departures using speed profiles of the sample flights that departs at the maximum rate without violating longitudinal separation requirements until 15 nm from the runway. Through this method capacity is based on a realistic set of aircraft behaviour was combined with a large sample that eliminated the effects of the actual sequence.

B 1 Simulation procedure

The simulation procedure consists of 5 steps:

1. Create a random sequence of aircraft types based on the type distribution at Schiphol in 2018.
2. For each aircraft type: select a random flight profile for that type as recorded in our collection.
3. Place the speed profiles after each other based on the minimum departure time interval.
    - 60 seconds for heavy following heavy or medium and for medium following medium
    - 120 seconds for medium following heavy
4. Calculate the longitudinal separation over the entire profile and if insufficient, delay the trailing aircraft until sufficient separation is achieved over the entire profile.
5. The time between the first departure and the last departure indicates the average departure rate.

For the analysis of each speed restriction the random flight profile for a type has to comply to that speed restriction. This ensures that the restriction is applied while not further limiting variation in profiles.

B 2 Overestimating capacity

The baseline model in which no ATC buffer is applied achieves an average rate of 50 departures per hour. This is much higher than the maximum 40 departures in the declared capacity at Schiphol. This difference between modelled and declared capacity can be explained by:

- difference between (hourly) declared capacity which is an average rate. In reality, higher rates may be achieved but are unlikely to be sustained for a full hour.
- other factors that reduce the departure capacity
    - While avoided, consecutive departures on non ICAO-separated SIDs do occur requiring ATC buffer
    - Lack of runway availability due to crossing aircraft, inspections
- other factors that reduce achieved capacity
    - lack of demand at the runway
    - response time between clearance and start of take-off roll

These factors will also apply to a scenario with a single SID. Therefore, expected reduction in capacity is likely to be comparable in that scenario.