Control Space Analysis of Three-Degree Decelerating Approaches at Amsterdam Airport Schiphol

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Amsterdam Schiphol Airport currently uses a Continuous Descent Approach during night time operations only, due to reduced runway capacity caused by unpredictable individual aircraft behavior. The Three-Degree Decelerating Approach (TDDA) has been developed to increase predictability and runway capacity by switching the separation task from Air Traffic Control to the pilot on board the aircraft. The research described in this paper identifies the factors that influence the control space of aircraft performing a TDDA in a real-life setting. Control space is defined as the difference between the maximum and minimum duration to perform the TDDA. Using different control strategies, a fast approach or slow approach can be flown. A fast-time simulation tool was built to perform simulations with different aircraft types, initial weights, wind speeds and directions. Preliminary simulations indicate that a flap scheduler is needed to optimize control space, and the flap scheduling algorithm was enhanced to find optimal flap schedules for all wind conditions. The results of these simulations show that the influence of wind direction depends on aircraft aerodynamic characteristics, which mainly depend on the drag characteristics of the aircraft and aircraft weight. Furthermore, the results can be used to determine whether a TDDA can be executed using different aircraft and under different wind conditions.

I. Introduction

For the period 2008-2030, EUROCONTROL estimates air traffic will grow at an average rate of 2.3% to 3.5% per year.1 This increase in air traffic movements will result in a growth of the amount of noise and exhaust emissions. Moreover, the residential communities surrounding major airports are more densely populated, due to the increase in demand for housing. This effect results in an increase of residents suffering from noise nuisance. Measures must be taken to accommodate the growth of air traffic without affecting living comfort for nearby communities.

Methods to reduce the noise produced by airborne aircraft start at the source of noise: the engines and airframe. Engine manufacturers have put intensive effort into lowering engine noise over the years and new technologies will reduce the engine noise emission even further. A different method to reduce the total noise are new Noise Abatement Procedures (NAPs) that are primarily designed to lower noise nuisance. This can be achieved by using a preferential runway system to reduce nuisance in residential communities,2 using fixed routes (RNAV/RNP) to avoid overflying of residential areas during approach, removing level flight segments during approach and finally, reducing the amount of thrust applied during approach. It is apparent that a lower thrust setting also results in lower fuel consumption and hence lower fuel costs.

Research in the area of Noise Abatement Procedures includes new procedures such as the Continuous Descent Approach (CDA) of which different implementations are operational at different airports (e.g., Schiphol Airport, Los Angeles Airport, Frankfurt Airport, London Heathrow),3,4 and the CDAs successor, the Advanced Continuous Descent Approach.3,5 Although actual flight tests5,6 have proven that these procedures are successful in reducing noise, actual implementation showed that runway capacity was reduced. Due to difficulties in predicting 4-D trajectories by Air Traffic Control, additional spacing is applied to aircraft performing a CDA. Unfortunately, increasing separation results in a reduction of
capacity. Besides a decrease of capacity, Air Traffic Control issues deviating instructions for separation because of the predictability issues; hence, making the execution of a noise reducing approach nearly impossible. Research has shown that by using the Three-Degree Decelerating Approach (TDDA), aircraft separation can be maintained to normal standards by switching the separation task from Air Traffic Control to the pilot executing the TDDA.\textsuperscript{6,7}

During a TDDA, illustrated in Fig. 1 using the speed and altitude vs. along track distance plots, the aircraft performs a continuous descent along the 3° descent-path, which is an extension of the normal 3° ILS glideslope. Conventional approaches intercept the 3° descent-path after a level flight at 2,000-3,000 ft, whereas a TDDA intercepts the descent-path at higher altitudes reducing the total length of level flight segments at low altitudes. Initial altitude and speed can be set to appropriate values best accommodating the TDDA at a particular airport and should ultimately be the aircraft’s top of descent and cruising speed for optimal performance. The TDDA procedure is completed when the aircraft has reached its final approach speed, \( V_{app} \), and is in a stabilized landing configuration at the reference altitude, \( h_{ref} \). The decelerating descent is achieved by applying idle thrust and allowing the aircraft to decelerate using the aircraft’s flaps and gear to generate more drag. Once the reference speed is reached, thrust is reapplied to follow the normal ILS procedure down to the runway threshold.

The performance of the TDDA is described by two measures: the noise goal and spacing goal, which can be expressed as a time goal or in-trail separation goal. The noise goal is defined as the altitude at which the final approach speed is reached. If this altitude is higher than the reference altitude, thrust needs to be reapplied earlier, which has an adverse effect on noise reduction. Then again, if the altitude at which the approach speed is reached is lower than the reference altitude, safety is compromised since the aircraft is not in a stable configuration at the reference altitude. The time goal is defines as the difference between the Actual Time of Arrival (ATA) and the Required Time of Arrival (RTA) and either negatively impacts capacity or separation if not met. The same holds for the separation goal. When separation is too large, capacity is reduced, while violating minimum separation could result in a dangerous situation. Which goals apply, depend on the type of self-spacing used.

When using a spacing goal, expressed as an in-trail distance from the leading aircraft, the algorithm uses ADS-B intent-data from the leading aircraft to estimate the leading aircraft’s trajectory. Using aircraft intent information, a trajectory of the leading aircraft is created, and the scheduling algorithm uses this trajectory to optimize the thrust cutback altitude (\( h_{tcb} \)) and flap schedule to meet the noise goal and in-trail separation goal.

Separation can also be achieved by using time-based spacing.\textsuperscript{7,9} Aircraft performing the TDDA are given a RTA to cross the runway threshold, to assure separation during the entire approach. It is the pilot’s task to arrive at the runway threshold at the RTA and reach the reference speed at the reference altitude so that both noise and time goals are met. Recently, SESAR, the European Air Traffic Man-
agement Research-program, started the development phase of the modernization and synchronization of the European Air Traffic Management system. SESAR anticipates on using time-based spacing until full performance-based operations can be fully implemented. Time-based spacing has advantages over distance-based spacing since time-based spacing can increase airport capacity significantly during strong headwind operations, and no information about the leading aircraft is necessary.

The control space defines the range of possible RTAs that can be assigned to aircraft flying the TDDA. This range is limited by the minimum duration, or fastest approach possible, and the maximum duration, the slowest possible approach. This paper focuses on the control space of a single aircraft performing a TDDA. Separation is assumed to be assured by proper scheduling of RTAs, and consequently the separation goal is removed from the TDDA simulation. By identifying the minimum and maximum RTA for an aircraft at the Initial Approach Fix (IAF) the control space is determined.

A good understanding of how different factors influence TDAA performance is not available from previous research. These factors include aircraft characteristics (type, weight, etc.), routes (RNAV/RNP transitions) and wind conditions (speed and direction). Previous research focused on specific features of the TDDA, such as different methods for self-spacing and used straight routes for simulations. Most major airports have no published or predefined straight-in approaches mainly because curvilinear approaches make it possible to circumvent populated and restricted areas and to laterally separate departing and arriving traffic. Curvilinear approaches add lateral dynamics to the TDDA resulting in extra drag during turns. Moreover, due to variable aircraft heading, the longitudinal wind component an aircraft encounters is constantly changing, which in turn influences the performance of the aircraft’s descent.

The goal of this research is to gain a better understanding of the effects of aircraft characteristics on the performance of the TDDA and to distinguish between beneficial and adverse characteristics. This research therefore investigates the TDDA using curvilinear approaches to identify the effects of heading changes and turns in a realistic setting. Moreover, using a real-life setting, regulations apply which affect the execution of the TDDA. For instance, speed restrictions apply and runway availability differs per wind condition. This research uses the real-life setting of Amsterdam Airport Schiphol. Schiphol has a relatively small Terminal Maneuvering Area (TMA) in which departing and arriving traffic need to be properly managed. Currently, Schiphol has two runways available for noise abatement procedures which enables Schiphol to accommodate arriving aircraft during most wind conditions.

In Section II, this paper introduces control space in the context of the TDDA and elaborates on the factors influencing it. Section III describes the fast-time simulator tool used to determine the control space in different wind conditions, aircraft characteristics and routes. Preliminary simulations showed the impact wind has on deceleration profile and the flap scheduler needed to cope with accelerations under tailwind conditions. The use of variable mass in the simulation tool results in slight differences between forward and backward simulation runs; these differences are solved using forward scheduling. The new, enhanced flap scheduler is described in Section IV. The results of the simulations are presented and discussed in Section VI and Section VII. Finally, conclusions and recommendations are found in Section VIII and Section IX.

II. Control Space Analysis

When executing a TDDA, aircraft decelerate from their initial speed and altitude to their approach speed at 1,000 ft. The initial altitude is referred to as the top of descent of the TDDA. The aircraft achieves a decelerating descent by applying flaps and pulling gear down at certain velocities. The speed at which the gear is deployed is set to the same speed as the second flap setting before the landing flap setting. These flap settings can be set at any speed between the minimum flap speed, defined by $V_{\text{Flap}_{\text{min}}}$ and the maximum flap speed set by $V_{\text{FE}}$. By definition, these velocities are specified in indicated airspeed (IAS). A scheme, defining the speed at which a flap setting is deployed is named a flap schedule. The control space is determined by the TDDA with the shortest and longest duration. The fastest approach possible is obtained by extending all flaps at their maximum velocities (FlapMax) resulting in a fast and late deceleration, a low thrust cutback altitude and due to the extended period of the initial speed, also the shortest duration. The slowest approach is achieved through flap extension at their minimum velocities (FlapMin) resulting in a slow and early deceleration and longer duration. These schedules are referred to as ‘maximum flap schedule’ and ‘minimum flap schedule’, respectively. Fig. 2 shows the boundaries of the flap settings, minimum and maximum flap schedules, for the Boeing 737-800.

The dashed line in Fig. 2 represents the initial speed of the TDDA at Schiphol (250 KIAS). Scheduling above this speed has no effect on the deceleration profile and therefore does not further increase control space. The space between the minimum and maximum flap profile is referred to as the flap space. For
some conditions (aircraft type, weight, wind, etc.), the minimum flap schedule results in a deceleration profile that does not lead to the final approach speed at the reference altitude while following a $3^\circ$ descent path. In these cases, the minimum flap schedule needs to be adjusted (or tuned) to find a flap schedule with a deceleration profile that allows the aircraft to decelerate to the approach speed at the reference altitude and has a thrust cutback altitude close to the initial altitude of the TDDA. Flap schedule tuning is the process during which the flap schedule is adjusted to any value within the minimum and maximum speed ranges such that a specific goal is met. In the case of minimum flap schedule tuning, the goal is to find a minimum schedule that allows a descent just below the initial altitude.

Fig. 3 shows a speed vs. altitude profile of the Boeing 737-800 during an approach with the minimum and maximum flap schedules. The deceleration is started after passing the thrust cutback altitude which happens later for the maximum flap schedule due to the fast deployment of the remaining flaps and resulting fast deceleration. Because the maximum flap speed for the flaps 5 setting of the Boeing 737-800 is at 250 kts, the aircraft starts the initial descent to the thrust cutback altitude with this flap setting deployed.

II.A. Environmental Impact

From a noise abatement perspective, the profile with the highest thrust cutback altitude is favored. The thrust cutback altitude is not equal for different flap schedules as a result of different deceleration profiles.
The amount of thrust applied and, hence, fuel burned is thus different. By using the FAA’s Integrated Noise Model (INM), a qualitative assessment of the noise produced by aircraft flying the TDDA is performed, as shown in Fig. 4. Shown is the RIVER2A (starting at the circle and descending to the triangle) approach to runway 06, starting at 10,000 ft and intercepting the 3° descent path. The figures indicate the effect of the height of the thrust cutback altitude; the areas at a distance from the airport, the lighter areas are smaller for the slow (and low \(h_{tcb}\)) approach, while the noise load close to the flight path is also reduced. Moreover, the rapid deceleration of aircraft with a FlapMax-schedule results in higher speeds closer to the airport resulting in higher noise levels close to the runway.

In addition, flap schedules also affect the amount of gaseous emissions emitted. Emissions can be divided into two segments: global emissions contributing to such things as global warming, and local emissions affecting the quality of life of near-airport residents. This research only focuses on the approach-phase of flight and therefore only local emissions are taken into consideration. Therefore, the entire descending trajectory, below 10,000 ft, is used in calculating the emissions. The Boeing Method 2-model (BM2) used to determine the emissions allows the quantification of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO\(_x\)). The BM2-model uses data from the ICAO Engine Emission Databank and corrects for off-test conditions, such as varying atmospheric conditions and thrust settings between the reference points of the data bank. Table 1 shows an overview of the total local emissions of a Boeing 737-800 flying a RIVER2A TDDA-approach. The effect of applying thrust for an elongated period of time is clearly visible in these numbers. An approach having the least amount of thrust applied is favorable, with regard to noise, fuel and gaseous emissions.

<table>
<thead>
<tr>
<th></th>
<th>Fast [lbs]</th>
<th>Slow [lbs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Burned</td>
<td>503.84</td>
<td>449.36</td>
</tr>
<tr>
<td>CO</td>
<td>1.4991</td>
<td>1.8810</td>
</tr>
<tr>
<td>HC</td>
<td>0.0893</td>
<td>0.1250</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>3.1701</td>
<td>2.4414</td>
</tr>
</tbody>
</table>

Table 1: Fuel and Gaseous Emissions for the Boeing 737-800 (CFM56-7B24 Engines) different flap schedules (RIVER2A).

II.B. Factors Influencing Control Space

Besides the conditions of the TDDA - such as flap schedule, initial and final conditions - environmental factors and aircraft characteristics affect control space. This subsection discusses these factors.

II.B.1. Wind Direction and Velocity

Assuming no vertical wind components or turbulence, wind is defined by two variables, speed and direction, which together determine the longitudinal and lateral wind component the aircraft encounters. It also influences the wind component used to determine the final approach speed and thus the reference
speed. Moreover, the minimum flap velocities depend on the wind component. Although the wind velocity can be equal, the approach speed the aircraft must reach during the TDDA and minimum flap schedule differ for each wind direction. The effect of wind direction is thus twofold.

When an aircraft approaches a runway along a fixed descent angle with a headwind component, the aircraft is able to decelerate faster relative to the ground, which lowers the thrust cutback altitude. This effect occurs because the kinematic glide-path angle, $\gamma_k$, is kept constant and therefore the aerodynamic glide-path angle, $\gamma_a$, is reduced, resulting in a stronger deceleration. The opposite holds true for a tailwind scenario; the aircraft decelerates slower, resulting in an early (high) thrust cutback altitude.

II.B.2. Aircraft Mass

Aircraft mass has a significant effect on the control space of aircraft; the lighter the aircraft, the larger the control space will be, since the minimum flap schedule is lower due to the dependence on stall speed. Moreover, less mass increases the total duration since $V_{app}$ is lower. Increasing aircraft mass decreases the thrust cutback altitude of the minimum flap schedule caused by the definition of the minimum flap speeds, which depends on aircraft stall speed, hence, higher minimum flap speeds. This effect only applies to the minimum flap schedule while the thrust cutback altitude of the maximum flap schedule increases due to the lower deceleration performance of heavier aircraft, resulting in a decreased control space.

II.B.3. Routes

The wind direction is not the only variable that affects the wind component; the heading of the aircraft itself is the other variable. If a particular route includes heading changes of more than 90°, the longitudinal wind component could change sign. For specific scenarios, it could therefore be advantageous to decelerate before or after a turn.

The turn itself also influences the performance of the TDDA. During turns, lift must be increased (see Eq. (1)) to account for the rotated lift vector. This increase in lift leads to an increase of drag due to the induced drag term used in aircraft aerodynamics.

III. Fast-Time TDDA Simulation Tool

To investigate the TDDA in several different conditions, a fast-time simulation tool was developed supporting different aircraft types, routes and environmental conditions. The basic components of the simulation tool are described in this section, while the newly implemented flap scheduler is discussed in Section IV, and

III.A. Aircraft Performance Modeling

To compute the aircraft trajectory, point-mass models are used. The equations of motion are derived using the balance of forces in Fig. 5.

![Figure 5: Forces acting on the aircraft.](image)

Assuming a small angle of attack and an in-line thrust vector the aerodynamic speed (true airspeed,
\[ V_a \) \) \) \) \) (sin \( \alpha \approx 0, \) \) \) \) \) \) \) \) \) \) \) \) \) \) \) \) \) \) cos \( \alpha_T \approx 1 \), \) \) \) \) \) \) \) \) \) \) \) \) \) \) \) the equations of motion in the aerodynamic reference frame, \( F_a \), are; \)
\[
\Sigma F_{xa} = T - D + mg \sin \gamma_a \\
\Sigma F_{ya} = L \sin \mu_a \\
\Sigma F_{za} = -L \cos \mu_a + mg \cos \gamma_a
\] \)
\)
To transform these equations to the kinematic reference frame, \( F_k \), use is made of kinematic relations to relate the equations of motion from the aerodynamic reference frame. These relations are derived using Fig. 6.

Using Eq. (1) and Eq. (2) the aerodynamic acceleration \( \ddot{x}_a \), is determined and integrated in time with a time step of 0.1 s to find the true airspeed \( V_a \), and kinematic speed. This yields the 4-D trajectories and predicted \( V_{app} \) at \( h_{ref} \). The segments above thrust cutback altitude and after \( h_{ref} \) use an instantaneous auto-throttle algorithm (see Section III.A.2) to determine the correct throttle setting for constant IAS, descending flight.

### III.A.1. Aircraft Model

The models used for the simulations are a reduced version of the flight models used by the Flight Dynamics Engine (FDE) of Microsoft Flight Simulator (MSFS) 2004 and FSX. The full models contain a simplified, dimensionless form of the classical equations of motion and are likely constructed using empirical data and data supplied by aircraft manufacturers. Since no official documentation about the implementation of these models is made available by Microsoft, the fidelity of the models is unknown. Yet, according to the flight simulator community, Microsoft adjusted the flight models in favor of user experience by exaggerating the thrust and drag forces. However, the research described in this paper focuses on the general effect of aircraft types and mass on the control space contrary to providing accurate and quantitative results for a specific type of aircraft. These models closely resemble the behavior of the real aircraft and are accurate enough to distinguish between small and large aircraft. For the purpose of this research, these models are considered suitable.

For simplification, the simulation uses a reduced form (point-mass model) of the original MSFS models. The aerodynamic model is based on the following equations:

\[
C_L = C_{Lo} + C_{La} \cdot \alpha + \Delta C_{L_{flap}} \\
C_D = C_{Do} + C_{Da} \cdot \alpha + \Delta C_{D_{flap}} + \Delta C_{D_{gear}}
\] \)

### III.A.2. Engine model

All the aircraft used in the simulations have turbine engines installed. The parameters of the turbine engines are collected from the FDE of MSFS. These parameters consist of look-up tables indexed by the
throttle setting of the engine and use the Inverse Airpressure Ratio (IAP), $\frac{p_{\text{new}}}{p_{\text{vs}}}$, to determine the net thrust, $F_n$, and fuel-flow, $\dot{m}_f$. Fig. 7 shows a schematic overview of the turbine engine model.

The fuel-flow is used to determine the amount of fuel burned to simulate the decrease in aircraft weight and determine the gaseous emissions.

During the TDDA, the initial descent to the thrust cutback altitude is flown with a constant IAS hence, with thrust applied. To determine the mass reduction during the constant IAS segment, the fuel flow is needed, which depends on the throttle setting required to fly at a constant IAS. This is done using an auto-throttle algorithm which uses a method similar to Newton-Raphson’s method to rapidly find the required throttle setting. Using this calculated setting, the thrust and fuel flow are determined and applied in the equations of motion to determine the aircraft’s updated state vector.

III.A.3. Turns

Schiphol designed its night procedures to avoid densely populated residential areas. Currently, turns in these procedures are specified as turns between two straight track segments and actual dimension relies on aircraft characteristics and weather conditions. Due to these differences, dispersion between different flight-tracks occurs. For noise abatement reasons, it is advantageous to have fixed tracks located over non-residential areas so that all aircraft fly the same track in all conditions. With the introduction of new RNP procedures, this has become possible using radius to fix legs (RF). A radius to fix turn is defined as a constant radius turn between two fixes, begin and end point, around a center point. The inbound and outbound legs of the turn are defined tangent to the arc segment.

The RF procedure was developed over 15 years ago, but implementation of RF legs in NAPs has not been done before. The current design criteria - mainly for terrain avoidance - for RF legs make the procedure unusable for noise abatement procedures. To allow full use of RF legs in NAPs, these criteria must be updated by ICAO. At Schiphol, a trial project was conducted to investigate the noise benefits of radius to fix turns in departure procedures. In this project, the ‘Spijkerboor 1S’ departure from runway 24 was modified to include a radius to fix leg between the cities of Hoofddorp and Nieuw Vennep and the fleet of a major airline was modified to fly the new departure route. The aim was to increase navigation performance during the initial climb-out of this departure. Analysis showed that aircraft were able to fly a much more accurate flight track resulting in less dispersion in flight tracks compared to the conventional departure procedure. Flights typically remain within 100 meters of the departure centerline and were more robust in adverse weather conditions. Due to this result, the project workgroup recommends reduced restrictions for the use of radius to fix legs in approach procedures.

Implementing radius to fix turns in these procedures is expected to decrease track dispersion as happened in the project discussed above. In order to simulate these turns in the TDDA, the radius to fix description was used to define the turns in the simulation.

III.A.4. $V_{ref}$ calculation

The reference speed, $V_{ref}$, of the TDDA is defined as the approach speed, $V_{app}$. Airliners have different regulations to determine the approach speed, but they all contain a wind dependent term:

$$V_{app} = 1.3 \cdot V_{stall} + \text{wind additives}$$ (4)
The calculation of these wind additives are aircraft and airline specific and therefore a general expression is used to determine the wind additives for the aircraft during simulation runs:

\[
V_{\text{app}} = 1.3 \cdot V_{\text{stall}} + \begin{cases} 
5 & \text{if } \frac{V_{\text{long}}}{2} \leq 5 \\
\frac{V_{\text{long}}}{2} & \text{if } 5 < \frac{V_{\text{long}}}{2} < 20 \\
20 & \text{if } \frac{V_{\text{long}}}{2} \geq 20 
\end{cases}
\]  

(5)

The term \(V_{\text{long}}\) is the longitudinal component of the wind which the aircraft encounters at final approach. This component is also used to determine the minimum flap schedule (see Section IV.A).

III.B. Wind Model

Using a deterministic wind model, the effects of wind on the performance of the TDDA were investigated, and ensured that wind velocity and direction are exactly known at each point of the trajectory. The wind model generates wind profiles that are time-invariant, rotating and logarithmic with altitude. Wind velocity increases logarithmically up to the free wind altitude after which the velocity remains constant. During the same altitude range, the direction of the wind field rotates and remains constant when the free wind altitude is reached. Wind prediction during backward calculation was taken identical to the actual wind during forward simulation. Fig. 8 illustrates a typical, rotating, wind-profile.

![Logarithmic wind model for geostrophic wind of 330/20 (Geodetic reference frame).](image)

III.C. Direction of Simulation

The previously introduced simulation tool can simulate trajectories in two directions - forward and backward. The simulation starts at the top of descent and simulates downward until the reference speed is reached close to the reference height. The tool can also start at the reference speed and the reference height and calculate backward until the top of descent is reached. Switching between both methods is easily done by changing the initial and final constraints and changing the signs in the equations of motion (Eq. (1)) in case of backward simulation. The thrust cutback altitude is determined using a backward simulation, starting at the reference altitude and reference speed; the simulation runs to find the altitude at which the initial TDDA speed is reached. The simulation continues with a forward simulation from the IAF to the reference altitude. Due to changes in aircraft mass and direction of simulation, small differences between the two runs occur for which a forward flap scheduling algorithm was implemented to reduce these differences and reach the noise goal (see Section IV.C).

IV. Enhanced Flap Scheduler

In certain cases, the initial flap schedule is inadequate in decelerating the aircraft to the approach speed at 1,000 ft. This can either happen when the maximum thrust cutback altitude is above the top
of descent or when the aircraft accelerates during the idle-thrust descent due to a strong tailwind. This section elaborates on the influence of wind on the flap scheduler and provides an overview of the new algorithm.

IV.A. Minimum Flap Schedule and Aerodynamic Path Angle

The minimum flap schedule is defined by the approach speed for each specific flap setting:

\[ V_{\text{flap}_{\text{min}}} = 1.3 \cdot V_{\text{stall}_{\text{flap}}} + \text{wind additives} \]  

These wind additives are calculated using the same rules used to calculate the final approach speed (see Eq. (5)). A graphical representation of the minimum and maximum flap schedules for the Boeing 737-800 is given in Fig. 2. Selecting flaps at their minimum speeds results in a relatively low drag approach and hence the slowest deceleration possible, but also makes the aircraft more prone to acceleration due to wind. During the TDDA, the kinematic flight-path angle, \( \gamma_k \), is fixed at 3°. When the aircraft experiences a tailwind, the aerodynamic flight-path angle, \( \gamma_a \), increases (see Fig. 9). When \( \gamma_a \) increases, the component of the aircraft weight vector along the aerodynamic flight path increases and the acceleration of the aircraft increases accordingly (see Eq. (1)). Eventually, this can result in acceleration of the aircraft which is not allowed in this decelerating approach. Due to this behavior, a flap schedule that results in the aircraft accelerating during descent, is rejected and the flap scheduler is used to tune a new flap schedule (without accelerations). On the other hand, the opposite scenario, a headwind, is not a problem. Due to the acting headwind, \( \gamma_a \) is decreased resulting in a less steep descent allowing the aircraft to decelerate even faster. The faster deceleration results in a lower thrust cutback altitude.

The aerodynamic path angle at which the aircraft starts to accelerate depends on the aerodynamic performance of the aircraft and is inversely related to \( \frac{C_L}{C_D} \). Aircraft with a good gliding performance, or high \( \frac{C_L}{C_D} \), have a relatively small glide angle and hence a small range of descent angles that result in deceleration during the descent.

\[ \frac{C_L}{C_D} \]

Figure 9: Influence of wind on the aerodynamic path angle.

IV.B. Algorithm

When the flap scheduler is initiated, it checks whether the flap schedule requires adjustments to account for IAS accelerations or to lower the thrust cutback altitude to below the top of descent. When accelerations occur during the TDDA, the flap scheduler identifies the delayed flap setting (the aircraft requires more drag at a specific location of the trajectory), and the speed at which that flap setting is selected is incremented. This process repeats until a flap schedule is found that does not accelerate during any parts of the TDDA trajectory. When the thrust cutback altitude of the new flap schedule exceeds the top of descent as well, the second step of the flap scheduler is initiated to optimize the minimum flap schedule so that a thrust cutback altitude just below the top of descent is obtained.

The second step of the flap scheduler uses a binary search algorithm to tune each flap position to find a flap schedule with a thrust cutback altitude close to (but not exceeding) the top of descent. This new flap schedule is within the theoretical flap space of the aircraft and, therefore, no unique solution exists. To find a new minimum schedule, the flap scheduler could start by tuning the first flap (smallest deflection) or with last flap (largest deflection) first. Either method can be used but both methods lead to different results. The first method yields a low thrust cutback altitude but a slow deceleration, hence a longer duration. The other method yields the opposite: a high thrust cutback altitude and fast deceleration yielding a shorter duration. Since a long duration is favorable for the control space, the flap schedule algorithm starts tuning the first flap setting and cycles to the next flap setting if the influence of the current flap setting is at its maximum allowed speed. The search algorithm searches for the flap retraction speed that allows a thrust cutback altitude just below the top of descent. This search algorithm is run for all flap settings until no more variations are possible and selects the minimal schedule resulting in the thrust cutback altitude closest to the top of descent. This to assure a global optimum is
found instead of a local optimum. The drawback of this approach is that it requires more iterations to find a solution compared to other methods which define a safe value around the top of descent.

In theory, the flap scheduler can find schedules consisting of non-integer speed values as long as these values fall within the limits set by the minimum and maximum flap schedules. In reality, pilots are not able to differentiate real airspeed values in their cockpits and most digital displays show integer values only. Hence, the flap scheduler is set such that only integer values of the airspeed are considered. This approach also decreases algorithm run-time since using integer values only reduces the total set of possible schedules greatly. The downside of this approach is that the exact optimal schedule is not necessarily found.

Some of the routes used in this paper contain a heading change of 180° or more. This could result in the aircraft encountering a tailwind component during initial descent - from the reference altitude to the thrust cutback altitude - and a headwind component below the thrust cutback altitude. The flap scheduler checks if the IAS decreases during the initial (constant speed) descent to the thrust cutback altitude and adjusts the flap schedule to increase drag, if required, starting with the smallest flap setting. When even the maximum flap schedule does not yield a possible approach, the initial speed of the TDDA is lowered in steps of 10 kts until a possible approach is found.

IV.C. Forward Scheduling

During the backwards run, an initial estimate of the aircraft’s mass at the reference altitude is used to determine the thrust cutback altitude. When making the initial mass estimate, the wind field is not taken into account, causing deviations between aircraft mass in predicted and actual trajectories. To account for these deviations, a forward scheduling algorithm is run every 10 s. to allow the aircraft to match the predicted trajectory. When the aircraft is still above the thrust cutback altitude, the algorithm optimizes the thrust cutback altitude and if the aircraft is in idle descent, the flap schedule is optimized to meet the noise goal. This algorithm is illustrated in Fig. 11.

V. Simulation Set-Up

Arrival procedures at Schiphol require aircraft to arrive at the IAF, at or above 10,000 ft and 250 kts (KIAS). At the top of descent, the aircraft starts its descent to the reference altitude. An overview of the characteristics of the TDDA in this research are summarized in Table 2.

The simulations are run for two, different, aircraft types, the Boeing 747-400 and Boeing 737-800. The Boeing 747-400 is the larger aircraft and has a nominal (no wind) maximum thrust cutback altitude that is located above the top of descent for this procedure and thus needs flap scheduling to optimize the
Table 2: Summary of the TDDA characteristics in this research.

<table>
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<tr>
<th>Characteristic</th>
<th>Value</th>
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<tr>
<td>Top of Descent</td>
<td>10,000 ft</td>
</tr>
<tr>
<td>Initial speed</td>
<td>250 kts</td>
</tr>
<tr>
<td>Reference altitude</td>
<td>1,000 ft</td>
</tr>
<tr>
<td>Reference speed</td>
<td>$V_{app}^a$</td>
</tr>
<tr>
<td>Minimum flap speed</td>
<td>$V_{flap_{min}}^b$</td>
</tr>
<tr>
<td>Maximum flap speed</td>
<td>$V_{FE}$</td>
</tr>
</tbody>
</table>

*a Calculation of the reference speed is discussed in Section III.A.4
*b Calculation of the minimum flap speed is discussed in Section IV.A

minimum flap schedule. To compare aircraft characteristics, the Boeing 737-800 is added for comparison. This medium-sized aircraft has a nominal thrust cutback altitude below 10,000 ft. For the remainder of this paper, the Boeing 747-400 and 737-800 are abbreviated 744 and 738 respectively.

Besides aircraft type, the influence of aircraft mass on the control space of the TDDA is investigated using three different aircraft weights: Operating Empty Weight (OEW), Maximum Landing Weight (MLW) and the mean of these two weights $OEW + MLW/2$.

This research uses the night transitions, currently in use for CDA operations during night hours at Schiphol Airport. Each route starts at one of the IAFs, ARTIP, RIVER or SUGOL, and avoids populated areas. For each runway, a merging point exists where these routes merge. This merging point is the start of the final approach segment during which the ILS-approach is intercepted. For runway 18R, these approaches are named NIRSI and NARIX, runway 06 has the SOKSI approach only.

The routes for runway 06 are named ARTIP2A, RIVER2A and SUGOL2A. Runway 18R uses the following names: ARTIP3B, RIVER3B, SUGOL3B and ARTIP2C. The latter route is the shortest route from ARTIP to runway 18R (see Fig. 12). The disadvantage of these routes is that many of these routes have a $\approx 180^\circ$ shift between their initial heading and final heading. This results in different wind component behavior between initial descent to thrust cutback altitude and final descent to the reference altitude.

Wind direction is varied using steps of $10^\circ$. The wind model parameters are set to a clockwise rotation and the wind velocity increases logarithmically with altitude. This results in approximately a double wind velocity at higher altitudes, see Fig. 8.

VI. Results

A baseline overview of the control spaces for these routes without wind is given in Table 3. Note that the 744 needs flap scheduling for all of these scenarios, this aircraft is too ‘clean’ to decelerate sufficiently during the TDDA. On the other hand, the 738 has a thrust cutback altitude below the top of descent
for all scenarios.

<table>
<thead>
<tr>
<th>Route</th>
<th>Boeing 737-800</th>
<th>Boeing 747-400</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARTIP2A</td>
<td>68 16</td>
<td>70 45</td>
</tr>
<tr>
<td>RIVER2A</td>
<td>69 17</td>
<td>69 47</td>
</tr>
<tr>
<td>SUGOL2A</td>
<td>68 16</td>
<td>70 47</td>
</tr>
<tr>
<td>ARTIP3B</td>
<td>68 16</td>
<td>73 44</td>
</tr>
<tr>
<td>RIVER3B</td>
<td>68 16</td>
<td>69 45</td>
</tr>
<tr>
<td>SUGOL3B</td>
<td>68 16</td>
<td>70 46</td>
</tr>
<tr>
<td>ARTIP2C</td>
<td>69 17</td>
<td>69 49</td>
</tr>
</tbody>
</table>

Table 3: Baseline control space properties.

The results in this chapter are displayed in a ‘wind dial’. Shown in the dial is the wind direction the wind is coming from at ground level. If a note indicates any acting wind, the wind velocity at ground level is given.

VI.A. Aircraft Type

Fig. 13 shows the control space diagram of both Boeing aircraft during the ARTIP2C transition for runway 18R (see Fig. 12).

![Control space diagram](image)

Figure 13: Control space diagram for ARTIP2C (runway 18R) transition and wind velocity: 4 kts.

Tailwind at final approach increases the control space of the 738, while a headwind reduces the control space resulting in the ellipse-shaped diagram. Flap scheduling is needed for the 744 for all wind directions of this scenario since the 744 cannot maintain a 3° descent path without accelerating in clean configuration and also has a top of descent higher than the initial altitude of the TDDA. The flap scheduler identifies the acceleration and applies an early flap setting which reduces the control space.

When the aircraft encounters a tailwind, the tendency to accelerate is even worse and the remaining flaps are selected earlier, decreasing the flap space and control space. Similar behavior of the two aircraft was observed for the other routes.

VI.B. Aircraft Mass

The effect of mass on control space is visible in Tables 3 and 4. Since the minimum flap schedule depends on the stall speed and hence aircraft mass, the flap space is larger for aircraft with less mass. Moreover, the larger aircraft type (744) has a smaller reduction in control space compared to the smaller aircraft (738). The percentage of OEW in MLW between the 744 and 738 are different and smaller for the 744 resulting in a smaller reduction in control space.

Table 4 shows another effect. Increasing aircraft mass affects the thrust cutback altitude differently for different schedules. Investigation of these trajectories shows that heavier aircraft decelerate slower than
Table 4: Control space properties (ARTIP2C transition - no wind).

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Weight</th>
<th>Total Duration [s]</th>
<th>TCB Altitude [ft]</th>
<th>Control Space</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fast</td>
<td>Slow</td>
<td>Fast</td>
</tr>
<tr>
<td>Boeing 737-800</td>
<td>OEW</td>
<td>557</td>
<td>626</td>
<td>2,449</td>
</tr>
<tr>
<td></td>
<td>MLW</td>
<td>556</td>
<td>573</td>
<td>3,140</td>
</tr>
<tr>
<td>Boeing 747-400</td>
<td>OEW</td>
<td>558</td>
<td>627</td>
<td>3,161</td>
</tr>
<tr>
<td></td>
<td>MLW</td>
<td>554</td>
<td>603</td>
<td>3,388</td>
</tr>
</tbody>
</table>

*a Minimum schedule did not suffice, flap scheduler tuned a new optimal minimum schedule

aircraft with less mass. This increases the thrust cutback altitude when the flap schedule is unchanged. Due to the increased mass, the final approach speed is also higher since the stall speed is increased. This increase is not high enough to cancel out the effect of the decreased deceleration. The effect of mass is thus more significant on its deceleration performance than on the final approach speed for similar flap schedule scenarios. This is the case for the maximum flap schedule which only depends on $V_{FE}$. When the flap schedule does depend on aircraft mass, which is always the case for the minimum flap schedule, the velocities in the flap schedule are increased due to the higher stall speeds for each flap setting, resulting in more drag at higher velocities and consequently a lower thrust cutback altitude.

![Figure 14](image-url)  
(a) Boeing 737-800  
(b) Boeing 747-400

Figure 14: Control Space diagram for ARTIP2C (runway 18R) transition with OEW and MLW aircraft mass and wind speed: 4 kts.

Another effect is visible from Fig. 14, the shapes of the control space diagrams for the different aircraft types and masses are different. For the 744, the thrust cutback altitudes of the minimum flap schedule for both mass conditions are both bound by the top of descent (10,000 ft.), reducing the control space even further during tailwind conditions. The difference between tailwind and headwind conditions becomes smaller when aircraft weight is increased. Moreover, maximum control space for the 744 at MLW does not occur when the aircraft encounters a full headwind during final approach, but when different longitudinal wind components are encountered throughout the entire approach. In case of the ARTIP2C approach, the control space is maximum at a wind direction of approximately 310°. In this scenario, the aircraft experiences a headwind during the initial descent which allows the aircraft to decelerate without applying early flaps, while during the final approach segment, the aircraft experiences a slight tailwind.

VI.C. Routes

The experienced longitudinal wind component, apart from the wind direction, depends on the aircraft heading. When the idle thrust segment falls within different route segments, the control space diagram is expected to be different. When no wind is applied (see Table 3), the control spaces are fairly similar when the 738 is flying the westerly routes which share the NIRS I approach. For the scenarios in Table 3,
the idle thrust segments start after passing NIRSI resulting in the same control spaces. The 744, with its larger control space and higher maximum thrust cutback altitude, does not have this effect since the idle thrust segments are initiated earlier along the route.

![Control Space diagrams for Boeing 747-400 @ MLW and wind speed: 4 kts.](image)

Figure 15: Control Space diagrams for Boeing 747-400 @ MLW and wind speed: 4 kts.

The effect of wind on aircraft performing the TDDA while flying these routes is visualized in the control space diagrams of all transitions for the 744 in Fig. 15 and for the 738 in Fig. 16. Even though a slight wind is applied, the 738 has similar control spaces for routes sharing the same final approach. The moderate wind field does not affect the 738 enough to extend the idle-thrust segment to a point before the final approaches.

When analyzing the routes for runway 06 and the 744, one notices the smaller control space for the RIVER2A transition in the wind direction range 180° to 260°. This route experiences a tailwind throughout the entire route, while the other routes experience a headwind initially, increasing the control space. Since the idle-thrust segment of the 744 do not share the same routes exactly, the control space...
diagrams for different routes are different. These differences become larger when the wind field is stronger.

VI.D. Wind Velocity

The effect of wind direction on control space has been treated during the discussion of the previous results, but the influence of wind velocity is treated separately in this section. The wind velocity determines the wind additives used when calculating the final approach speed and used in determining the minimum flap schedule.

Fig. 17 illustrates control space diagrams for the 738 for two transitions. The stronger the wind component encountered along the trajectory, the larger the effect on the control space. The RIVER2A transition, which most resembles a straight in approach, clearly illustrates the beneficial effect of tailwind on control space. Moreover, the increase in control space due to tailwinds is larger than the reduction of control space during headwinds. When a tailwind is excessively strong, the thrust cutback altitude of the minimum flap schedule exceeds the top of descent and adjustment of the minimum flap schedule is needed, reducing control space.

The 744 shows a different image (see Fig. 18). The two moderate wind conditions show that increasing the wind velocity decreases control space during tailwind conditions and increases control space during headwind conditions. During tailwind conditions the thrust cutback altitude of the maximum flap schedule (fast deceleration) increases and the thrust cutback altitude of the minimum flap schedule is still close to the top of descent, reducing the control space.

When the wind velocity is further increased, the shapes of the diagrams change significantly. The control space shape of the RIVER2A transition and wind velocity of 16 kts contains dents at certain wind directions. The dents at 300° are caused by the need for flap deployment during the initial segment of the SOKSI approach. The wind is almost fully aligned with the aircraft and accelerates the aircraft during this segment. Deploying flaps earlier, and therefore reducing flap space, cancels the acceleration but also reduces the control space. The locations and velocities at which these accelerations occur are different for each wind condition, resulting in these dents.

The ARTIP2C transition (see Fig. 18b) shows another interesting feature. The wind directions from 110° - 160° show a decrease in control space even though these directions result in a headwind during final approach. These wind directions also result in a tailwind during the initial descent in which the aircraft would accelerate if no extra drag devices were deployed. This early deployment of flaps increases the aircraft’s drag but reduces the flap space and hence control space. Instead of early flap deflection, aircraft spoilers (speed brakes or lift dumpers) could be used, but the use of spoilers is not favored by pilots and therefore not allowed during the TDAA. Moreover, spoilers increase the aircraft’s airframe noise reducing the noise relieving effect of the TDAA.
Fig. 18: Control space diagrams for the Boeing 747-400 for different wind velocities.

VII. Discussion

This paper focuses on the control space of the TDDA at Schiphol Airport. Current implementation of NAPs at Schiphol has reduced the airport’s capacity due to uncertainties in the approach profile.

The use of the CDA is therefore limited to night operations only, when capacity is lowest. The TDDA reduces these uncertainties by transferring the separation task from the Air Traffic Controller to the pilot. Previous research⁷ in the Netherlands, concluded that the TDDA can be implemented while maintaining the same operational capacity of conventional approaches while reducing the noise load around airports.

The results indicate that the control space is affected by many parameters. Aircraft with a high \( C_l \) decelerate slowly, resulting in the need for flap scheduling to optimize the thrust cutback altitude. The 744 is a good example of this behavior. The aircraft mass is another factor impacting control space. Aircraft mass negatively affected the control space for all aircraft investigated in this paper. This effect is smaller or larger, depending on the ratio between aircraft operating empty weight and total weight.

The effect of wind in general is considerable. While the wind velocity remains constant, the wind direction has a large impact on the control space, ranging from less than 10 s to a control space of more than 30 s (see Fig. 19b). Tailwinds during the TDDA positively contribute to the control space of aircraft with a maximum thrust cutback altitude below the top of descent. Once the thrust cutback altitude is higher than the top of descent, the flap scheduler is needed to find a flap schedule, resulting in smaller control space. Moreover, a tailwind increases the aircraft ground speed, resulting in a longer ground roll during landing. The latter argument is the reason why tailwind landings are only allowed up to a certain maximum (i.e., 7 kts at Schiphol). When a headwind is experienced, the thrust cutback lowers accordingly, resulting in a smaller control space.

Due to the curvilinear appearance of the night transitions of Schiphol, the wind components experienced by the aircraft depend on the wind direction and track heading. Many of the transitions share segments (final approach) resulting in similar control space diagrams when the idle-thrust segment falls within these final segments. On the other hand, the longitudinal wind component varies due to the rotating wind model and curvilinear routes. High \( \frac{C_D}{C_l} \) aircraft, with a slow deceleration profile, and using the minimum flap schedule, need flap scheduling to adjust the schedule such that a TDDA is possible that fits all the constraints. The minimum schedule depends on many parameters, so as aircraft charac-
characteristics, route and wind conditions. All these factors make it hard to predict the exact control space for these conditions. Besides the varying wind components, curvilinear routes affect the TDDA since turns are present. During turns, additional drag is introduced, which contributes to the deceleration of the aircraft and consequently lowers the thrust cutback altitude.

The control space allows calculation of possible RTAs for aircraft arrival scheduling. If the aircraft’s RTA, control space and position of the RTA within the control space are known, the time window to pass the IAF and meet the time goal can be calculated. Assuming that the RTAs are calculated for optimal airport capacity, ATC must ensure that aircraft pass the IAF within the time window in order not to sacrifice capacity. Since the time window is equal to the control space, the time window ranges from a mere 10 s to more than 100 s. If the time window is small, the possibility of aircraft not passing the IAF in the time window increases, which results in a loss of capacity.

VIII. Conclusions

A fast-time simulator was developed and used to investigate factors influencing the performance of aircraft executing a TDDA. Aircraft performance is highly dependent on aerodynamic characteristics and determines whether flap-scheduling is required to increase the deceleration performance of the aircraft. Moreover, inertia effects of increased aircraft mass lowers the deceleration profile of aircraft. Finally, environmental effects, such as wind (velocity and direction) and trajectory, affect control space since these parameters together determine the horizontal wind component encountered by the aircraft and affect the kinematic glide-angle of the aircraft. In tailwind conditions, control space might be optimal, but the TDDA is still of limited use due to airport restrictions during tailwind landings. For headwind conditions, the TDDA is almost always possible but with limited control space and a decrease of airport capacity due to wake turbulence separation at final approach. New research must investigate options to increase performance and acceptability of NAPs.

IX. Recommendations

To increase control space and time window, an interesting option is to modify the TDDA to include an initial descent segment of 2° to increase the deceleration performance during this segment. Unfortunately, this change will cause aircraft to descend at an earlier location along track, resulting in a decrease of height over ground and thus more noise nuisance for residents further away from the airport. The location at which the descent is changed from 2° to 3° could be fixed or used as an extra control variable during the Modified-TDDA. The latter case is interesting since this could reduce the minimum flap schedule in scenarios where the wind component changes direction, and hence increases control space.
Current implementation of the TDDA prescribes that both the minimum and maximum schedules use the same initial speed and altitude at the top of descent of the TDDA. By removing this requirement, the minimum flap schedule approach could be initiated with a lower speed so that flap scheduling is not needed during the descent from the top of descent to the reference altitude. The principle behind this adjustment is that airspeed is reduced during the level segment between the IAF and top of descent.

Aircraft with a thrust cutback altitude range below the top of descent of the TDDA could increase control space by removing the idle-thrust restriction. The deceleration performance of these aircraft can be increased by applying limited thrust to a few percentages above idle-thrust. The rationale is that lowering the deceleration profile of the minimum flap schedule increases the duration of the procedure and hence control space. The disadvantage of adjusting the amount of thrust applied is an increased aircraft noise emission and fuel burn.

To use the advantages of aircraft with large control spaces and a high maximum thrust cutback altitude, approach routes should be redesigned to initiate the TDDA at a variable initial speed and altitude. A possible option is start the TDDA at a higher altitude for the 744 while the 738 starts at a higher speed but same altitude. Moreover, some of the routes used in this paper start relatively far away from the runway threshold (ARTIP2A, RIVER3B, ARTIP3B). If these routes could initiate the TDDA at a higher altitude and/or speed, more control space could be generated. The effects on aircraft separation of this amendment and the deceleration performance of aircraft at higher altitudes must be investigated.

Finally, another option arises by removing the fixed 3° descent path restriction and variable flap schedule. An approach procedure can be seen as a controlled loss of aircraft energy; at the initial top of descent, the aircraft is ‘high and fast’; hence, it has a high total energy (consisting of potential and kinetic energy) while the reference point is ‘low and slow’. Losing energy is only possible through work of drag forces. Interchanging the restrictions; fixing the flap schedule and varying the descent angle results in a different approach path. The reference velocity and height, initial velocity and height remain equal but the vertical path in between will be different for different types of aircraft. Control space is the result of different vertical paths resulting in different deceleration profiles. The vertical path will be divided into multiple segments of constant descent angle allowing deceleration or constant speed flight. The planning of the vertical trajectory depends on the total energy state and energy rate efficiency. After planning, the intended path is flown and to account for errors (caused by wind or guidance errors), the segments can be ‘scheduled’ by adjusting the descent angles to meet RTAs or time intervals from a leading aircraft. Calculation of the vertical (energy) trajectory is a new research topic, currently under investigation. Preliminary results show decreased fuel use and lower noise emissions compared to conventional approaches.

References