# Three-Degree Decelerating Approaches in Arrival Streams

## Continuous Descent Approaches in High Traffic Density

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*Abstract*—**Self-spacing is a solution for the runway capacity reduction that is intertwined with the use of continuous descent approaches in the current air traffic management system to reduce aircraft noise. In case of self-spacing the separation task is transferred from the air traffic controller to the pilot. The Three-Degree Decelerating Approach (TDDA) can be executed in a distance- or time-based self-spacing environment while yielding a noise reduction. A fast-time simulation tool has been developed to simulate arrival streams of different aircraft types executing the TDDA in both self-spacing scenarios under actual wind conditions. The tool was used to quantify the performance differences between distance- and time-based self-spacing in terms of capacity, noise reduction, and loss of separation. In the time-based scenario no effects of preceding aircraft on trailing aircraft could be identified. However, an increase in separation with a negative effect on the airport capacity in order to assure safe separation was required. In the distance-based self-spacing scenario a slow-down effect was observed that led to a decrease in the noise reduction towards the end of the arrival stream. This was solved by altering the initial separation between aircraft in the arrival stream. In the distance-based self-spacing scenario no negative effect on the runway capacity or safety has been identified.**

***Index Terms* -- Continuous Descent Approach, capacity, self-spacing**

## I. Introduction

To accommodate the forecasted further growth of aviation without increasing the noise impact measures must be taken [1-3]. Promising procedures are Continuous Descent Approaches (CDAs) but are infeasible in the current air traffic management system because of the negative effect on the runway capacity. During the approach Air Traffic Control (ATC) issues speed, altitude, and heading instructions to keep aircraft safely separated. During a CDA ATC can no longer give instructions; otherwise the aircraft are not able to follow their optimum descent path. Moreover it is unknown what the descent paths of the aircraft will be. The aircraft performance, pilot control strategy, and wind condition significantly affect the descent path. [3][4] Therefore Air Traffic Control (ATC) introduces additional spacing between aircraft to assure that the separation minima are respected, though at the cost of runway capacity. The capacity reduction prevents the CDA from being introduced at a large scale at the major airports in the world to reduce the noise nuisance in the vicinity of the airport.

The Three-Degree Decelerating Approach (TDDA) is a CDA capable of realizing a significant noise reduction. The procedure lies within the boundaries of present approach procedure limitations and can be implemented in a short term [4-6]. Major difference with the current ATM system and the key to application of a CDA without a drop in the runway capacity is the use of self-spacing. The spacing task is transferred from the air traffic controller to the pilot. The maneuverability of an aircraft while executing a CDA is limited and largely driven by the aircraft performance, wind conditions, and the control strategy of the pilot. The aircraft performance information is readily available in the cockpit rather than on the ground. A pilot can plan and execute, with the help of onboard systems, a CDA to remain safely separated and exploit the noise reduction potential of the CDA [5][6]. Previous research focused on the design of the procedure, and the required systems [4-6]. This paper discusses the feasibility of implementing the TDDA at high


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traffic density airports in a distance- or time-based self-spacing environment. It also introduces intent-based trajectory predictions to prevent transient motions from occurring in an arrival stream of aircraft. As will be discussed later, the slinky effect can only occur when relying on distance-based self-spacing.

Section II addresses the TDDA procedure in a distance-based and time-based the self-spacing environment. Section III focuses on the intent-based trajectory prediction applied when using distance-based self-spacing. Use of the TDDA in arrival streams imposes constraints on the initial separation between aircraft; this issue is addressed in Section IV. The fast-time simulation tool used to simulate arrival streams of different aircraft executing the TDDA in both self-spacing scenarios under actual wind conditions is presented in Section V. The performance of the TDDA in a distance- or time-based self-spacing environment is presented in Section VI. Section VII contains the conclusion.

## II. Three-Degree Decelerating Approach

### *A. Description of Procedure*

The TDDA is a straight-in approach along a fixed descent path with a -3° path angle as illustrated in Figure 1. [4-7]. The descent path coincides with the Instrument Landing System's (ILS) glide slope, except the aircraft intercepts the descent path at an altitude that lies well above the altitude the aircraft normally intercepts the ILS glide slope and starts with the final 3° descent. The aircraft descends with a constant IAS to a point where the engines are set to idle, this is point is referred to as the point of thrust cutback (TCB). Due to the aerodynamic drag the aircraft decelerates, during the deceleration the flaps and gear are extended. For safety reasons most operators require aircraft to be in a stabilized landing configuration before descending below 1000 ft. This is incorporated in the TDDA procedure by demanding the aircraft to be stabilized at the reference altitude, $h_{ref}$, which is located at 1000 ft. To accomplish this, the flap extension speeds are such that the final approach speed $V_{APP}$ is reached at $h_{ref}$ in a stabilized landing configuration. The flap extension speeds together form the flap schedule of the aircraft. Below $h_{ref}$ the aircraft maintains $V_{APP}$ by reapplying thrust and continues the approach until touchdown.

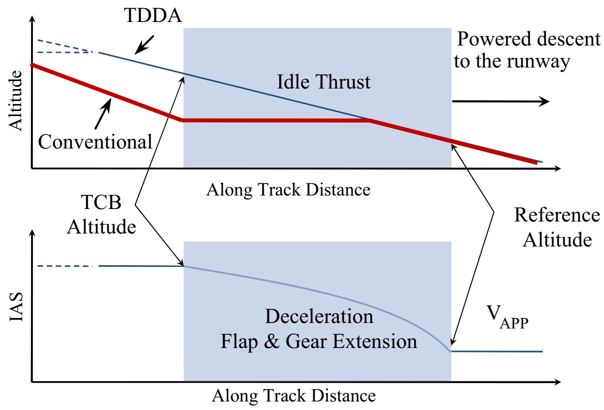


Figure 1. The TDDA Trajectory

The moment of thrust cutback and the flap schedule are the only controls the pilot has to reach $V_{APP}$ (noise goal) at the reference altitude. In addition the pilot has the responsibility to remain safely separated (separation goal) with the preceding aircraft or arrive at the commanded RTA (time goal). The applicable goals depend on the form of self-spacing that is used in the arrival stream.

Research showed that it is difficult for a pilot to determine the correct TCB altitude and a flap schedule [4][5]. Therefore the pilot is supported by a number of optimization and scheduling algorithms fed by wind and trajectory prediction algorithms to meet the noise goal, and separation or time goal [4-6]. Which optimization and scheduling algorithms are active depends on the part of the TDDA the aircraft is in. As soon as the aircraft intercepts the 3° descent path Thrust CutBack (TCB) altitude optimization starts for both the noise and separation/time goal. The algorithm determines the maximum TCB altitude using a binary search method.

When flying below the TCB altitude the Flap Scheduler Algorithm monitors whether the applicable goals will be met. The implemented flap scheduler is based on the scheduler originally described in [5]. If one of the goals is not met and scheduling is possible the flap scheduler updates the schedule. The updated schedule is determined using a binary search algorithm. Optimization of the noise goal is only performed if the time or separation goal is met. Below $h_{ref}$ no scheduling takes place.

### *B. Two Self-Spacing Scenarios*

Because of wake turbulence trailing aircraft must maintain a minimum separation with respect to the preceding aircraft. In the scenario proposed in this research the spacing task is transferred from the air traffic controller to the pilot to carry out CDAs without adverse affecting the runway capacity. Self-spacing can be either distance-based or time-based. Distance-based self-spacing using the relative state of the preceding aircraft might give rise to transient motions in the arrival stream (the slinky effect) resulting in separation violations [8]. Therefore time-based self-spacing was implemented in the TDDA [4]. Time-based spacing concepts proved best for in-trail self-spacing but are hard to implement into the current

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spatial working environment of pilots and controllers. Pilots indicated to prefer distance-based over time-based procedures [7].

### C. *TDDA using Distance-based Self-Spacing*

In case of distance-based self-spacing it is the task of the pilot to assure that the separation minimum is never violated. Based on a prediction of the leading aircraft trajectory the own TDDA is planned such that the actual minimum separation lies close to the minimum allowable separation to achieve the highest airport capacity. Figure 2 shows the structure of the TDDA algorithm under distance-based self-spacing. The algorithm computes the separation between the aircraft based on trajectory predictions of the own and the preceding aircraft. The prediction of the own trajectory is also used to determine whether the noise goal will be met. If necessary an optimization of the TCB altitude or flap schedules takes place. TCB altitude optimization takes place when the aircraft is flying above the last computed TCB altitude. When the thust cutback has taken place and the aircraft has not reached the final approach speed, flap schedule optimization takes place.

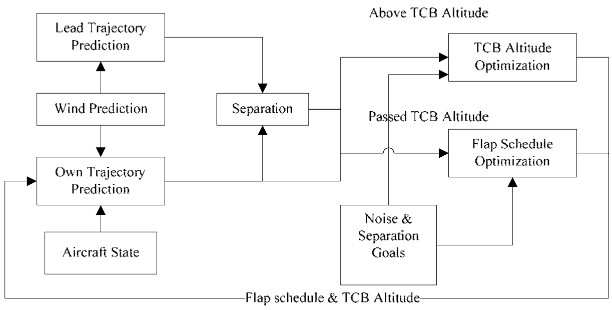


Figure 2. TDDA Algorithm for Distance-Based Self-Spacing

### D. *TDDA using Distance-based Self-Spacing*

Time-based self-spacing makes the on-board leading aircraft trajectory prediction superfluous, instead thereof each aircraft is supplied with an RTA. This does not imply that the separation minima do not have to be obeyed. Determination of RTAs that do not lead to separation violation will be addressed later. The task of the pilot is to arrive at the threshold at the RTA. The resulting TDDA should meet both the noise and time goal. The structure of the TDDA algorithm is identical to the structure under distance-based spacing. The RTA block replaces the lead prediction and separation blocks, see Figure 2.

## III. AIRCRAFT INTENT-BASED TRAJECORY PREDICTION

### A. *Using Aircraft Intent for Trajectory Prediction*

Distance-based self-separation requires a precise trajectory prediction of the preceding aircraft. An aircraft intent based prediction algorithm is proposed here. Aircraft intent is an unambiguous description of how the aircraft has to be operated within a given timeframe. The intent information is the input to a trajectory predictor [10].

Captured in the intent is the outcome of optimization of the trajectory by the TDDA algorithms on-board the leading aircraft. If an aircraft's descent profile is disturbed, for instance by a wind change or delayed pilot action, the TDDA algorithm optimizes the trajectory. The new trajectory is described in aircraft intent that is not in principal the same as the previous intent because of the optimization process. In predictions based on previous states no credit is given to the ongoing optimization process. This can cause unnecessary control actions from the trailing aircraft that can propagate through the arrival stream resulting in the slinky effect.

Ref. [11] shows that a trajectory prediction of the last constant speed segment of the TDDA is sufficient to determine the minimum separation. The change of the separation between two aircraft generally has closing characteristics. Based on the performance characteristics of a number of aircraft and the applicable separation minima it was concluded that the moment of minimum separation will take place when the leading aircraft is flying below the reference altitude.

### B. *Intent-Based Lead Aircraft Prediction*

Prediction of the last constant speed segment is sufficient to determine the minimum separation. This segment can be predicted independent of the other segments using the ETA, $V_{APP}$, and descent path angle as illustrated in Figure 3.

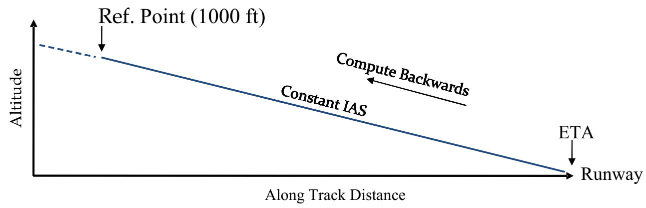


Figure 3. Intent-Based Trajectory Prediction

The speed and flight path angle are kept constant during the last stage of the final approach. No states of the preceding aircraft are used to predict the leading aircraft trajectory, only aircraft intent information is needed. The predictor starts at the runway threshold where the aircraft is at the ETA with speed $V_{APP}$ and computes the trajectory up to the reference altitude. No knowledge about the aerodynamic performance is required, because the airspeed and path angle remain constant. The prevailing wind is the only unknown and is estimated using a wind predictor as described in [11].

## IV. TDDAS IN ARRIVAL STREAMS

An arrival stream of aircraft consists of one leading aircraft and a number of trailing aircraft. The aircraft in the stream may vary in type and weight and have different deceleration profiles. The aircraft in the stream can be separated by time- or distance-based self-spacing. The leading aircraft is always supplied with an RTA and optimizes its TCB altitude and flap schedule to arrive at the RTA and meet the noise goal. The trailing aircraft, depending on the self-spacing concept, tries to

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meet their separation or time goal and the noise goal. The control space of the TDDA is limited, only if the separation or time goal falls within the control space a TDDA exploiting the noise reduction potential without a capacity loss is possible.

*A. TDDA Control Space Impacting Factors*

The TDDA control space boundaries are a function of the aircraft type, weight and prevailing wind conditions. The boundaries are set by the TDDA with the shortest and longest duration. To get the shortest duration all flaps are extended at their maximum speed yielding a fast but late deceleration and the lowest possible TCB altitude. The longest duration is achieved by extending flaps at their minimum speed resulting in a slow and early deceleration and the highest possible TCB altitude. Aircraft weight lowers the TCB altitude, shortens the time-to-fly, and reduces the control space. A headwind increases the duration of the TDDA and lowers the TCB altitudes, but also makes the control space smaller. The opposite occurs in case of a tailwind. The variance in TCB altitude and time-to-fly for each type and weight combination reflect the uncertainty in the descent profile of each aircraft ATC has to deal with causing the increase in separation. The impact of the wind conditions justifies the need of a wind predictor.

*B. Initial Separation Constraints*

To fly a TDDA that does not reduce runway capacity and meets the noise goal, the separation or time goal should fall in the control space. This imposes constraints on the initial separation with respect to the preceding aircraft or entry time. The constraints follow from the control space and leading aircraft trajectory (prediction) and type, and RTA if applicable.

*C. Initial Separation - Distance-Based Self-Spacing*

The initial separation under distance-based self-spacing is determined as shown in Figure 4. The separation goal implies that the minimum separation should equal the minimum safe separation. The separation goal is visualized by offsetting the lead's trajectory prediction over the required separation away

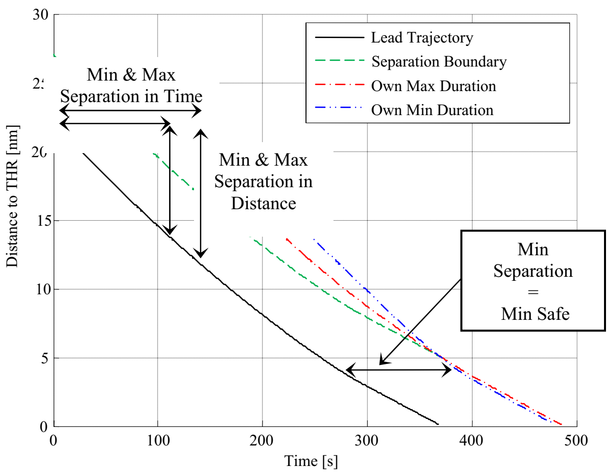


Figure 4. Min and Max Initial Separation for Distance Based Spacing

from the runway (separation boundary). The minimum allowable distance to the threshold when the lead aircraft is still flying is indicated by the separation boundary. By positioning the control space boundaries such that the minimum separation equals the minimum safe separation the minimum and maximum initial separation expressed in time or distance are determined.

*D. Initial Separation - Time-Based Self-Spacing*

The constraints in case of time-based spacing are determined in a similar way. The time of arrival of both control space boundaries is set equal to the RTA from where the entry time interval is determined, see Figure 5. For reference the separation boundary is drawn, the minimum separation between both aircraft cannot be violated.

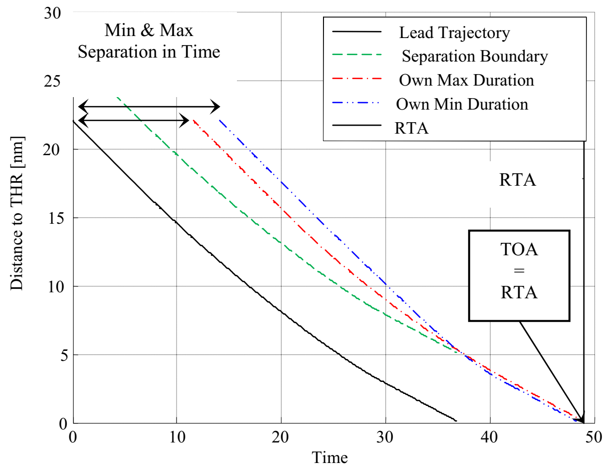


Figure 5. Min and Max Initial Separation for Time Based Spacing

The initial separation constraints are determined based on predictions of the own control space and lead trajectory that have an uncertainty or are subject to changes due to variable wind conditions. An initial separation located in the middle of the interval minimizes the risk that the separation or time goal drops out of the control space resulting in spacing gaps or failure to meet the noise goal. The TCB altitudes of the control space boundaries are the highest and lowest TCB altitude achievable. An initial separation close to the boundary leads to a relatively high or low TCB altitude.

*E. Initial Trajectory Optimization*

If the initial separation is well determined the control space is reduced by the preceding aircraft as shown in Figure 6. The own aircraft's trajectory should lie as close to the separation boundary as possible. The TCB optimization and flap scheduler search for trajectory with the maximum TCB altitude while still meeting all the goals.


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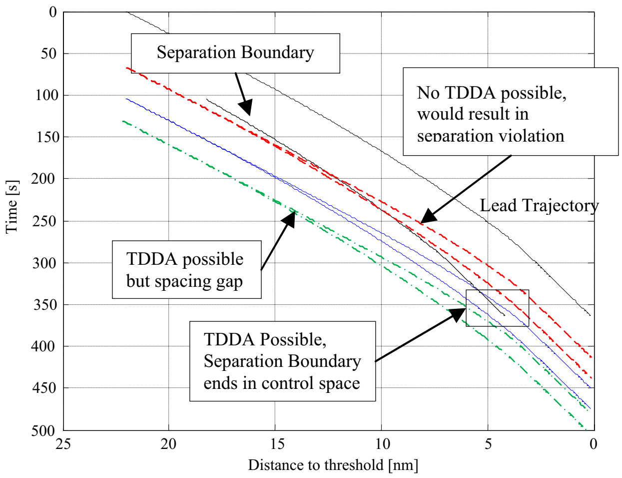


Figure 6. Effect of Leading Aircraft on Control Space

If the separation boundary crosses the lower control space boundary a TDDA that meets the noise goal is impossible without violation of the separation minima. If the separation boundary lies above the control space, execution of the TDDA leads to a spacing gap with an adverse effect on the airport capacity.

## V. Fast-Time TDDA Simulation Tool

The fast-time simulation tool simulates arrival streams of aircraft executing the TDDA in a distance- or time-based self-spacing environment under actual wind conditions. Implemented in the simulator is the TDDA with the optimization and scheduling algorithms depicted in Figure 2. For the aircraft trajectory computation and prediction use is made of point mass models approximating the following aircraft: Boeing 747-400, 777-300, 737-800, 737-400, and the Airbus 321. Randomness in the pilot response time is modeled using the Pilot Response Delay Model described in Ref. [12].

## VI. Distance-Based vs. Time-Based Self-Spacing

Using the simulation tool 5000 arrival streams from eight aircraft in each self-spacing scenario have been generated. The aircraft type and weight were determined randomly. The following aircraft are present in the arrival streams: Boeing 747-400, 777-300, 737-800, 737-400, and the Airbus 321. Per type three different weights were assigned to the aircraft: the Operating Empty Weight (OEW), the Maximum Landing Weight (MLW), and the mean of the OEW and MLW. Weather observations have been used to create 54 time-varying wind profiles. To determine the initial separation interval a 0.2 nm buffer was added to the separation minima to account for uncertainties in the predictions and wind changes. The entry time into the arrival stream was set such that the aircraft were in the middle of their control space computed 10 minutes before the preceding aircraft starts his TDDA. The characteristics of the TDDA are summarized in Table 1.

TABLE I. TDDA Characteristics

| **Aspect** | **Value** |
|---|---|
| Top of Descent (TOD) | 7000 ft |
| Initial IAS | 230 kts |
| Reference Altitude ($h_{ref}$) | 1000 ft |
| Approach Speed ($V_{APP}$) | $1.3V_{stall}$ + 10 kts |
| Minimum Flap Speed | $1.3V_{stall}$ |
| Maximum Flap Speed | $V_{FE}$ |

The performance and feasibility of implementing the TDDA at a high traffic density airport in the two self-spacing scenarios was assessed using the formulated noise, separation, time goal, and the runway capacity.

### A. Noise Goal Performance

The noise goal is met if $V_{APP}$ is reached at $h_{ref}$. In case $V_{APP}$ is reached above $h_{ref}$, engine thrust needs to be reapplied above $h_{ref}$ resulting in more engine noise. From a safety point of view it is also not desired that the aircraft reaches $V_{APP}$ below $h_{ref}$. Figure 7 shows the average altitude where $V_{APP}$ was reached, hereafter referred to as $h_{V_{APP}}$, per position in the arrival stream. As expected for the time-based scenario no trend between the position of the aircraft and $h_{V_{APP}}$ could be identified (*R = 0.006, p = 0.287, Pearson 2-tailed*). On average $h_{V_{APP}}$ lies 20 ft above $h_{ref}$. When taking into account the 25 ft tolerance used during flap scheduling and TCB optimization it is concluded that on average the noise goal is met. For the distance-based scenario a positive correlation between $h_{V_{APP}}$ and the position in the stream can be identified (*R = 0.145, p < 0.001, Pearson 2-tailed*). The noise reduction deteriorates towards the end of the arrival stream.

Deterioration of the noise reduction is caused by accumulation of delays (slowdown effect) in the arrival stream. The TDDA is susceptible to time delays. If there is a delay in the arrival stream all trailing aircraft in the stream are affected by this delay. Aircraft further back in the arrival stream are confronted with longer delays than the aircraft in the beginning of the arrival stream, see Figure 8. To remain safely separated, aircraft increase the TCB altitude to the upper bound of their control space. If the aircraft still lose separation flap extension is advanced but this will result in failure to meet the noise goal. In case of a delayed arrival there is a significant correlation between $h_{ref}$ and the magnitude of

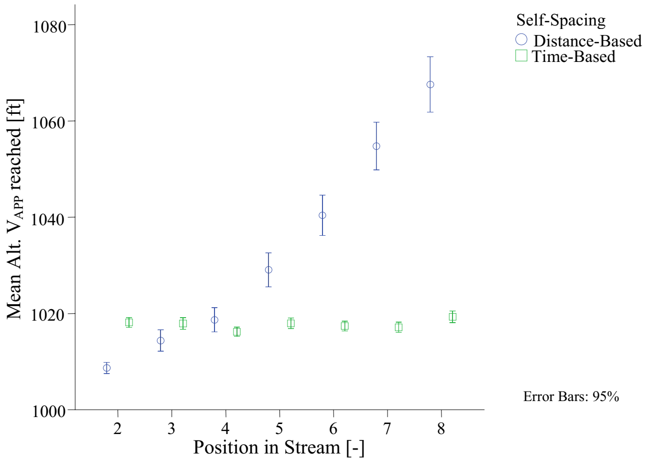


Figure 7. Altitude $V_{APP}$ reached


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the delay (*$R$ = 0.672, $p < 0.001$, Pearson 2-tailed*). Arrivals earlier than expected have no effect on the noise goal (*$R$ = 0.057, $p < 0.001$, Pearson 2-tailed*).

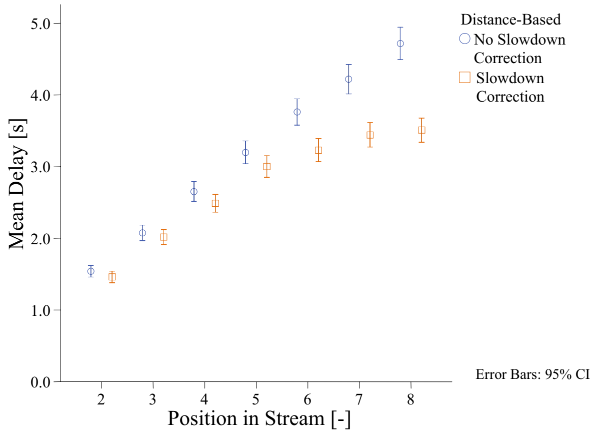


Figure 8. Slowdown effect in distance-based scenario

Deterioration of the noise reduction due to accumulating time delays was suppressed by increasing the initial separation between the aircraft in the end of the arrival stream. In the simulation this has been accomplished by increasing the separation buffer from 0.2 nm to 0.5 nm. In case of a delay the aircraft reduce the spacing to the allowed minimum and still reach $V_{APP}$ at $h_{ref}$. The increase in time delay flattens and a positive correlation between $h_{V_{APP}}$ and the position can no longer be identified (*$R$ = 0.040, $p < 0.001$, Pearson 2-tailed*).

## *B. Separation*

Under distance-based spacing a separation goal is formulated. The flap and TCB scheduling should be such that the minimum separation equals the minimum safe separation. Although there is no separation goal in the time-based scenario the minimum separation cannot be violated. Separation should be assured by adhering to the RTA. 99% of the aircraft arrive within 6.5 s of the RTA at the threshold. Table 2 lists the mean and median excess separation between aircraft and percentage of aircraft with a loss of separation with respect to the preceding aircraft. In case of time-based separation four times more separation violations occur. A part of the violations in both scenarios would obviously have led to a go-around. Go-arounds do occur during current approaches; London Gatwick reported go-around percentages varying between 0.29% and 0.47% [13]. The percentage achieved in the distance-based scenario falls in this range. To achieve the same result for time-based spacing, the only available measure is addition of separation on top of the minimal separation used for the computation of the RTAs. Based on the separation margin distribution, 0.5 nm additional separation was applied (+0.3 nm). The separation violation percentage dropped to 0.27%.

TABLE II. SEPARATION GOAL PERFORMANCE

| | **Descriptive** | | |
|---|---|---|---|
| **Self Spacing** | ***Mean*** | ***Median*** | ***Separation Loss*** |
| Time-Based | 0.47 nm | 0.22 nm | 1.42% |
| Distance-Based | 0.37 nm | 0.31 nm | 0.32% |

## *C. Runway Capacity*

In this section the realized runway capacity is evaluated. For the distance-based self-spacing use is made of the arrival stream initially described in Section VI with a correction for the slowdown effect. In the time-based scenario use is made of the same arrival stream as initially described with 0.5 nm additional spacing applied on top of the separation minima to compute the RTAs. The capacity figures are based on 5000 randomly created arrival streams per self-spacing scenario. The runway capacity is a function of the traffic mix, because the traffic mix (on average: 40% heavy, 60% large) is determined randomly, variation in the runway capacity can be expected, see Figure 9. Table 3 lists descriptive statistics.

TABLE III. RUNWAY CAPACITY STATICTICS

| | **Descriptive [AC/H]** | | | | | |
|---|---|---|---|---|---|---|
| ***Self-Spacing*** | ***Mean*** | ***Median*** | ***Std.*** | ***Min*** | ***Max*** | ***Range*** |
| Time-Based | 35.7 | 35.3 | 3.3 | 26.7 | 49.7 | 23.0 |
| Distance-Based | 39.2 | 38.8 | 3.6 | 30.9 | 53.3 | 22.3 |

Time-based spacing results in a lower runway capacity than distance-based spacing. An ANOVA indicates that the difference is significant. *($F$ = 2560.04, $p < 0.001$).*

To compare the realized runway capacity with the theoretical maximum capacity a 'packing factor' is used:

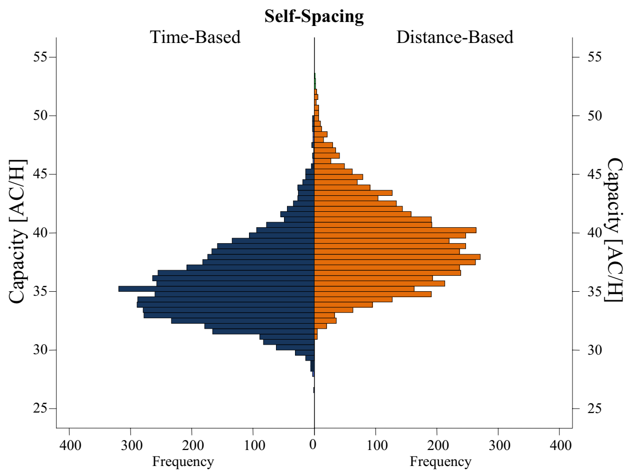


Figure 9. Runway Capacity

$$PF = \frac{\sum_{i=2}^{k} S_{allowed}}{\sum_{i=2}^{k} S_{actual}} \quad \forall S_{actual} \geq S_{allowed} \qquad (1)$$

where $k$ is the number the aircraft in the arrival stream, $S_{actual}$ is the actual separation minimum between two aircraft, and $S_{allowed}$ the minimum safe separation. Separation violations are not included in the *PF* calculation. If *PF* = *1* the runway capacity is equal to the theoretical maximum. As expected the PF for distance-based spacing is higher than for time-based spacing, 0.90 and 0.81 respectively. In case of time-based separation it is clear that there is a significant reduction in

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capacity. Distance-based self-spacing outperforms time-based spacing in terms capacity by more than three AC/H. Given the changing wind condition and pilot behavior and spacing capabilities of ATC the PF for the conventional approach will always be lower than one.

## VIII. Conclusion

The aim of this research was to assess the feasibility assessment of implementing the TDDA at a high traffic density airport in a distance- and time-based self-spacing scenario. A fast-time simulation tool was developed and used to quantify the performance differences between distance- and time-based self-spacing in terms of capacity, noise reduction, and loss of separation.

For the time-based scenario no effects of preceding aircraft on trailing aircraft could be identified. However, an increase in separation with a negative effect on the airport capacity to assure safe separation was required. In the distance-based self-spacing scenario a slow-down effect was observed leading to a decrease in the noise reduction towards the end of the arrival stream. The deteriorating noise reduction was solved by altering the initial separation between aircraft in the arrival stream.

After making the aforementioned adjustments, distance-based and time-based self-spacing perform comparable except for the capacity where the distance-based scenario has a three AC/H advantage. Capacity is one of the major factors restraining the use of NAPs and especially CDAs; in that respect distance-based self-spacing is the most promising option.

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