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Time-based Spaced Continuous Descent Approaches in busy Terminal Manoeuvring Areas

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1. Introduction

Mitigation of aircraft noise for approaching aircraft is an area where considerable improvements are still possible through the introduction of noise abatement procedures, such as the Continuous Descent Approach (CDA) (Erkelens, 2000). One of the main issues when implementing CDAs is their negative effect on runway throughput, especially during busy operations in daytime. A reduction in landing time intervals might be achieved through precise inter arrival spacing. The combination of aircraft performing the CDA controlled by precise spacing algorithms is seen as one of the solutions to safely increase runway throughput, reduce delay times for arriving aircraft, and reducing fuel burn, emissions and noise impact (De Gaay Fortman et al., 2007; De Leege et al., 2009; De Prins et al., 2007).
The main algorithms used in these researches are all based on the Flap/Gear Scheduler (*FGS*) developed by Koeslag (2001) and improved by In 't Veld et al. (2009). The *FGS* is evaluated in these researches to investigate the effects of different flight path angles, different types of aircraft, different aircraft weight configurations and different wind conditions on *FGS* performance. The *FGS* is also combined with time and distance based spacing algorithms to ensure proper spacing between aircraft in arrival streams.
There are more spacing algorithms developed to control the Time-based Spaced CDA (TSCDA), such as the Thrust Controller (*TC*) by De Muynck et al. (2008) and the Speed Constraint Deviation controller (*SCD*), both developed at the National Aerospace Laboratory (NLR). The performances of these three controllers are evaluated in this chapter. Fast-time Monte Carlo Simulations (MCS) are performed using a realistic simulation environment and a realistic scenario. The effects of different wind conditions, aircraft weight configuration, arrival stream setup and the position of the aircraft in the arrival stream on the performance of the controllers are also evaluated.
In Section 2 the definition of the TSCDA is elaborated by discussing the goals of this concept and by giving the description of the approach used in this research. In Section 3 the working principles of the controllers are discussed. The results of the initial simulations performed to prove the working principles and to investigate the performance of the controllers in nominal conditions are also evaluated here. The experiment is described in Section 4, by discussing the independent variables and the simulation disturbances. The hypotheses of this research are

also given. The results of the MCS are listed in Section 5. The hypotheses are compared with the results and discussed in Section 6. The chapter ends with conclusions and recommendations.

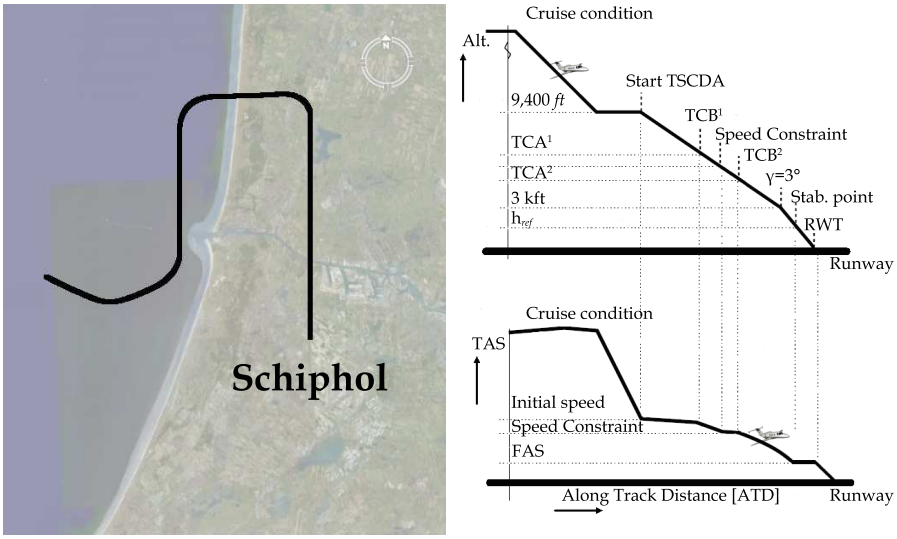
2. Time-based Spaced Continuous Descent Approaches

2.1 Requirements

To perform the evaluation of the controllers thoroughly, first the main requirements for the controllers are elaborated. The origins of these requirements follow from the main purposes of the TSCDA controllers, reduce fuel, reduce noise and maintain the throughput at the Runway Threshold (RWT):

- The algorithms should strive for a minimisation of noise and emissions produced by approaching aircraft in the Terminal Manoeuvring Area (TMA). The amount of noise at ground level is mainly determined by the altitude, thrust setting and configuration of passing aircraft. Reducing noise can thus be achieved by delaying the descent as much as possible (steep and continuous descent), by choosing "idle" thrust-setting and maintaining the cleanest configuration as long as possible. The CDA developed by Koeslag (2001) is based on this criterion.
- The algorithm should strive for a maximum throughput at the runway threshold. Maximum throughput at the RWT can be achieved by reducing the variability of the time space between landing aircraft. The minimum separation criteria are defined by the wake-vortex criteria which are set by the weight class of the landing aircraft.
- To avoid the development of an expensive concept, an integration of the algorithm in today's or near future's Air Traffic Management (ATM) systems should be easily possible without major changes in those ATM systems. Therefore, the assumption that other systems must be adapted to make use of the new algorithms should be avoided as much as possible. An implication of this requirement is that the aircraft should perform their approaches, while knowing as little as possible about the other aircraft in the arriving stream.
- The algorithm must be easily accepted by all who are involved. Pilots and Air Traffic Control (ATC) must be willing to use this new technique. The consequence of this requirement is for example that the algorithms should work properly with speed limitations set by ATC to improve the predictability of the aircraft movements in the TMA.
- The maximum possible difference between the slowest and fastest CDA at a certain moment in the approach is indicated by the *control space*. The last requirement is that this control space for each aircraft in the arrival stream should be as high as possible. The control of each aircraft should then be independent on the behaviour of other aircraft in the arrival stream and thus the need of knowing information about the other aircraft should again be limited as much as possible.

To meet the requirements related to noise and emissions, aircraft should perform a CDA in the TMA. The other requirements demand a simple and efficient algorithm that ensures proper spacing between aircraft in the arrival stream, which can easily be implemented in today's aircraft and ATC systems.



(a) Lateral path (b) Vertical path and speed profile

Fig. 1. Schematic presentation of the flight path. Characteristics according to Table 1 are based on (Meijer, 2008, A-3). In this illustration only one speed constraint is active.

2.2 Approach description

The CDA procedure used in this research is based on the same procedure as used in the *OPTIMAL* project (De Muynck et al., 2008). The characteristics of the approach are given in Table 1 and the schematic presentation of the approach is given in Figure 1.

2.2.1 Start altitude

The start altitude of the CDA is in this research set at 9,400 ft. The largest part of the noise is produced by aircraft flying below 10,000 ft. Therefore this research focuses on the last part of the descent from cruise altitude. The airspace below 10,000 ft is very crowded and it is worth to invest possible spacing issues. Merging aircraft into an arrival stream is another issue in the descent between cruise altitude and 10,000 ft, it is considered outside the scope of this research however.

2.2.2 Reference altitude

The Reference Altitude (h_{ref}) is the point where aircraft must be stabilised, in this scenario it is set at 1,000 ft. Stabilised means that the aircraft speed is equal to the Final Approach Speed (FAS), and the aircraft is in landing configuration, i.e., flaps and slats at maximum angle and gear down.

3. Algorithms

The algorithms used in this research are elaborated, first stating the main principle of time-based spacing CDAs, yielding the TSCDA. Then the three controllers are elaborated by discussing the basic principles and showing results of some initial simulations. These initial

Start altitude	9,400 ft
Initial speed	240 kts IAS
h_{ref}	1,000 ft
Speed constraint	250 kts IAS for $h < 10{,}000$ ft 220 kts IAS for $h < 5{,}500$ ft 180 kts IAS for $h < 3{,}400$ ft 160 kts IAS for $h < 1.500$ ft
Vertical path	$\gamma = 2^\circ$ for $h > 3{,}000$ ft $\gamma = 3^\circ$ for $h < 3{,}000$ ft
Lateral path	according to path illustrated in Figure 1(a)
End of simulation	at the RWT which is 50 ft above the begin of the runway 18R Schiphol airport

Table 1. Scenario characteristics.

simulations are performed for one type of aircraft, the Airbus A330-200, using a high-fidelity model.

3.1 Main principle

3.1.1 Required Time of Arrival

The combination of TBS with the CDA is based on a dynamically calculated Required Time of Arrival (RTA). During the TSCDA the Estimated Time of Arrival (ETA) is calculated by the Flight Management System (FMS) using the Trajectory Predictor (TP). It is assumed that this ETA can be send to the following aircraft in the arrival stream using ADS-B. The following aircraft in the arrival stream uses this ETA to calculate its RTA. Using:

$$RTA = ETA_{lead} + T_{space}, \tag{1}$$

where T_{space} is the required spacing interval between aircraft pairs in the arrival stream at the RWT, assumed to be 120 s (*Website: Single European Sky ATM Research [SESAR]*, n.d.).

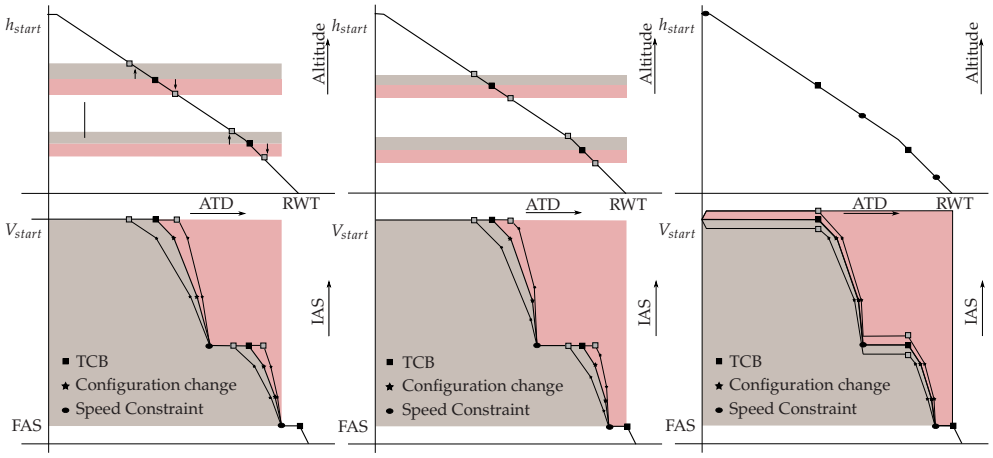
3.1.2 Trajectory predictor

The ETA is calculated by the TP of the FMS. In this research the NLR's Research FMS (RFMS) is used, see (Meijer, 2008, A-1-2). The TP uses the actual state of the aircraft, the flight plan stored in the RFMS and a simplified aircraft model to integrate the trajectory backwards from the end situation, which is zero altitude at the runway, to the actual state of the aircraft.
The output of the TP is the speed profile, altitude profile, the lateral profile, thrust profile and configuration profile. It is used for guidance purposes of the aircraft and also to control the aircraft performing the TSCDA. Using the speed, altitude and lateral profiles the ETA is calculated. This ETA is then corrected for the difference in actual position and predicted position of the aircraft. This means that the ETA is dependent on the calculation of the trajectory profiles and the actual state of the aircraft. So even if the TP is not triggered to calculate a new prediction, the ETA is updated during the approach.

3.1.3 Time-based spacing

Using the calculated RTA and the ETA calculated by the TP the spacing error (T_{err}) can be calculated:

$$T_{err} = RTA - ETA \tag{2}$$



(a) Thrust Controller (*TC*) (b) Flap/Gear Scheduler (*FGS*) (c) Speed Constraint Deviation controller (*SCD*)

Fig. 2. Schematic illustrations of the principles of the three TSCDA-controllers.

Every second during the approach T_{err} is calculated. If $|T_{err}| > 1.5$ s then the controllers are triggered to control the approach and the TP is triggered to calculate the profiles because the controllers changed the approach with respect to the speed, thrust and configuration profiles. The objective is to control the aircraft during the TSCDA so that T_{err} is zero at the RWT. Three different controllers have been evaluated: the *TC*, the *FGS* and the *SCD*, which are able to control the average airspeed during the TSCDA. If $T_{err} > 0$ then $RTA > ETA$ and the aircraft will arrive earlier than required at the RWT, the aircraft must fly the TSCDA at a lower average speed than the nominal situation. It must perform the TSCDA at a higher average speed in case $ETA > RTA$, see Figures 2(a), 2(b) and 2(c).

3.2 TSCDA controllers

3.2.1 Thrust Controller (*TC*)

3.2.1.1 Principle

The standard speed profile shown in Figure 1 indicates that the TSCDA can be divided in several parts. Due to the presence of speed constraints there are three parts where the aircraft decelerates to a new speed constraint and a fourth part where the aircraft decelerates to the Final Approach Speed (FAS). The noise reduction requirement demands idle thrust at these deceleration parts of the approach. These small differences in added thrust compared to idle thrust during the deceleration parts of the approach can have a negative effect on the produced noise and emissions. However, these differences in added thrust can be used to control the aircraft ETA, required to maintain the throughput at the RWT.

Now consider a nominal thrust setting of $N_{nominal} = N_{idle} + 10\%$ then $N_{min} = N_{nominal} - 10\% = N_{idle}$ and $N_{max} = N_{nominal} + 10\%$. The difference in the amount of thrust added can be used to control the average speed indirectly during deceleration and therefore can control the ETA and thus the spacing error T_{err}, see Figure 2(a). The *TC* uses the calculated T_{err} as input and it decides to increase or decrease the thrust for the decelerating parts of the TSCDA. This

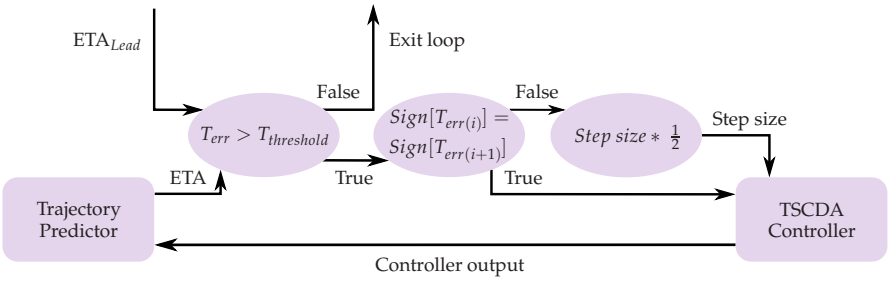


Fig. 3. Illustration of the main loop used by the TSCDA controllers. Stabilisation is derived using the reduction of the step size, each time the value of T_{err} crosses zero, where $T_{threshold}$ is set to 1.5 s.

Altitude [ft]	0	1,000	7,000	10,000	20,000	30,000	40,000	50,000
Speed [kts]	20	25	40	50	60	70	80	80
Direction [deg]	210	220	240	240	240	240	240	240

Table 2. Wind speeds, South West (SW) used in this research.

new thrust setting will be used by the TP to calculate the new speed profile for the rest of the TSCDA. This will be done until T_{err} <1 s or $N_{calc} = N_{min}$ or $N_{calc} = N_{max}$. This principle has been implemented in the RFMS and has been used in the *OPTIMAL* project (De Muynck et al., 2008), where it was investigated whether this method can be used to control the ETA while performing a TSCDA. An illustration of the main algorithm is given in Figure 3. This principle can only be used if the FMS is capable of giving any required N_1-command to control thrust instead of the normally used speed commands for this phase of flight. The NLR's RFMS in combination with NLR's *GRACE* based aircraft model is able to do that.

3.2.1.2 Initial simulations

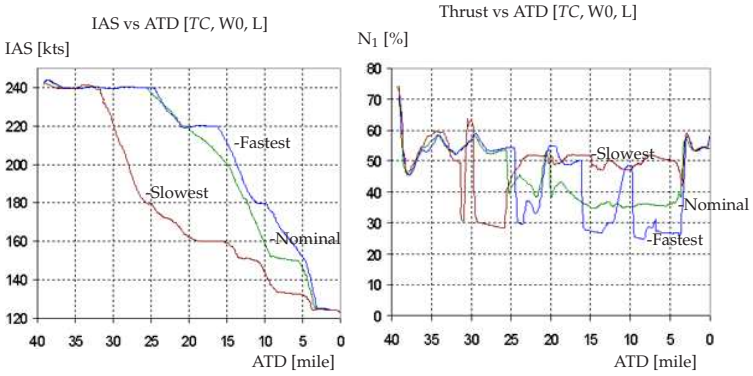
Initial simulations have been performed to prove the working of the controller. These simulations are performed using the simulation environment described in (Meijer, 2008, A). The scenario as described in Table 1 has been simulated in combination with two wind conditions and two different weight configurations of the Airbus A330-200, see Table 3. For these four conditions the controller has been triggered to perform the slowest, nominal and longest TSCDA possible. The results of the initial simulation (no wind and lightweight configuration) are given in Figures 4(a) and 4(b) and Table 4. With these results the working of the *TC* is proven. The difference between the speed profiles given in Figure 4(a), indicates that the *TC* enables a control space to slow down or speed up the TSCDA. The *TC* shows a better performance in slowing down the TSCDA than in speeding up the approach, Table 4. Figure 4(b)

parameter	research ID	mass · 1,000 kg
Light Weight (75% MLW)	LW	135.2
Heavy Weight (92% MLW)	HW	165.2

Table 3. Airbus A330-200 mass specification as percentage of the Maximum Landing Weight (MLW).

wind	mass	T_{nom}	T_{max}	$\Delta+$	T_{min}	$\Delta-$
Zero	HW	666.1	738.0	71.9	656.0	-10.1
SW	HW	671.1	760.9	96.9	664.0	-7.1
Zero	LW	697.1	801.1	104.0	671.9	-25.2
SW	LW	699.0	761.1	62.1	678.0	-21.0

Table 4. Method: *TC*, TSCDA duration in seconds.



(a) *TC* Speed profile (b) *TC* Output profile

Fig. 4. *TC*, one of the initial simulations of the basic scenario (zero Wind and LW).

shows an earlier Thrust Cutback (TCB) when performing a slow approach. The decelerating parts of the TSCDA are at a higher than nominal thrust setting, which results in a smaller deceleration possible and resulting in a lower average speed and therefore a longer duration of the approach. Table 4 shows the difference in TSCDA duration between heavyweight and lightweight aircraft. The FAS is lower for the LW configuration and this lower speed results in a lower average approach speed and thus in a longer duration of the TSCDA. A longer nominal duration of the TSCDA yields a larger control margin.

3.2.2 Flap/Gear scheduler (*FGS*)

3.2.2.1 Principle

In the *FGS* (In 't Veld et al., 2009; Koeslag, 2001) the basic principle of controlling the ETA is based on optimising the moments of drag increase. Increasing the drag by selecting a next flap position or by deployment of the gear and holding the thrust constant at idle level decreases the speed of the aircraft. As for the other methods, this method uses the T_{err} as input. It calculates the next configuration speed till $T_{err} < 1s$ or $V_{config(i)} = V_{min(i)}$ or $V_{config(i)} = V_{max(i)}$. $V_{min(i)}$ and $V_{max(i)}$ according to Table 5.

3.2.2.2 Initial simulations

The same simulations have been performed with the *FGS* as those performed with the *TC* controller. Looking at the distances between the nominal, fast and slow graphs displayed in Figure 5(a) there is a small margin between the lines, this means a little control margin to control the duration of the TSCDA. This can also be seen in Table 6. Only a few seconds

	Condition:	FULL	3	GEAR	2	1	0
HW	$V_{FlapNom}$	152.2	167.0	167.0	174.4	209.3	-
	$V_{FlapMin}$	136.0	149.0	155.0	158.0	195.0	-
	$V_{FlapMax}$	179.0	185.0	195.0	204.0	235.0	-
LW	$V_{FlapNom}$	138.0	145.0	150.0	177.0	195.0	-
	$V_{FlapMin}$	130.0	140.0	150.0	160.0	170.0	-
	$V_{FlapMax}$	177.0	185.0	190.0	200.0	230.0	-

Table 5. Configuration speeds of the Airbus A330-200 [kts IAS], for HW and LW weight configurations.

wind	mass	T_{nom}	T_{max}	$\Delta+$	T_{min}	$\Delta-$
Zero	HW	657.0	658.2	1.2	655.0	-2.0
SW	HW	666.0	668.0	2.0	661.2	-4.8
Zero	LW	676.0	685.1	9.1	668.0	-8.0
SW	LW	682.1	694.0	11.9	674.0	-8.1

Table 6. Method: *FGS*, TSCDA duration in seconds.

of control margin is available. The lightweight configuration has a positive influence on the control margin, however it is still not the result which was expected by earlier researches (De Gaay Fortman et al., 2007; De Leege et al., 2009). The cause for this might be that the performance of the *FGS* is highly dependent on the type of aircraft used. The Airbus A330-200 used in this research is not the best type to show the working principle of the *FGS*. Figure 5(a) shows clearly the differences in TCB Altitude (TCA) resulting from the presence of speed constraints in the scenario. An earlier TCB in the slow case and a relative late TCB for the fast TSCDA. The controller output, the IAS at which a next configuration must be selected is given in Figure 5(b). Selecting the next configuration at a higher IAS results in a relative faster deceleration, so the moment of selecting idle thrust can be delayed and thus a longer period of the TSCDA the aircraft can fly at higher speed resulting in a higher average approach speed.

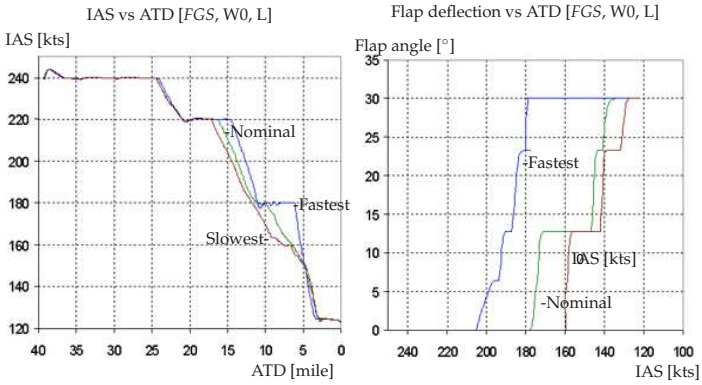
3.2.3 Speed Constraint Deviation controller (*SCD*)

3.2.3.1 Principle

The presence of speed constraints in the TSCDA procedure makes another principle of controlling possible, the *SCD*. The procedural speed constraints (see Table 1) introduce parts of the TSCDA where the aircraft is flying at constant IAS. A deviation of the speed constraint affects the average approach speed and thus the ETA, see Figure 2(c). The input is again the T_{err}. The output is a speed command for the autopilot. This $V_{command} = V_{constraint(i)} \pm V_{offset}$, where $V_{offset_{Max}}$ is 10 kts. This value is chosen to prove the working of this method. Implementing this controller in the FMS is done by integrating the controller in the speed controller of the autopilot. The working of the main algorithm, which is the same as used by the *TC* is illustrated in Figure 3.

3.2.3.2 Initial simulations

The principle illustrated in Figure 2(c) is shown in Figure 6(a). In contrast to the other methods there is no difference in the TCA. The control margin is only dependent on the selection of a higher or lower IAS compared to the original speed constraint. The output of the controller, Figure 6(b) shows that the commanded speed is according to the theory. Due to practical



(a) *FGS* Speed profile (b) *FGS* Output profile

Fig. 5. *FGS*, initial simulations of the basic scenario (zero Wind and LW).

wind	mass	T_{nom}	T_{max}	$\Delta+$	T_{min}	$\Delta-$
Zero	HW	657.2	687.1	29.9	640.2	-17.0
SW	HW	666.1	696.0	29.9	634.0	-32.1
Zero	LW	676.1	698.1	22.0	656.0	-20.1
SW	LW	682.0	703.1	21.1	657.0	-25.0

Table 7. Method: *SCD*, TSCDA duration in seconds.

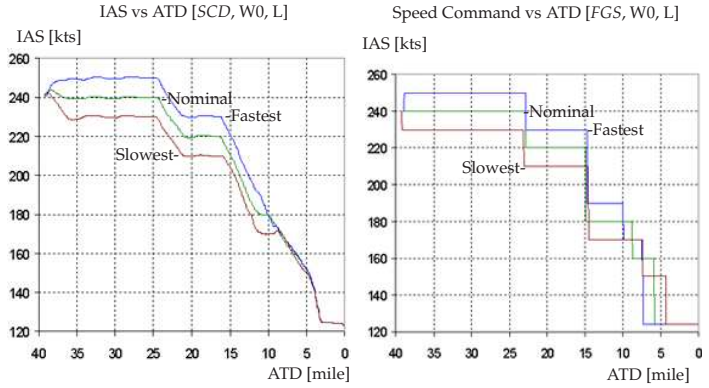
reasons the last speed constraint of 160 kts at 1,500 ft is not used to control the ETA in this research, so the *SCD* is inactive at that specific speed constraint. The commanded speed is then equal for the three conditions. This affects the control margin gained by the deviation at the speed constraint of 180 kts. In fact, the control margin gained by a specific speed constraint would be higher if that speed constraint is followed by another.

3.3 Controller performance

A comparison in TSCDA-duration, Tables 4, 6 and 7, and illustrated also in Figure 7, shows quite some difference in control margin between the three controllers. Also the influence of wind and mass on the performance of each controller is different. Even in these initial simulations without disturbances the differences between the performance are significant and therefore it is worth to investigate and evaluate the controllers performance more thoroughly.

4. Monte Carlo Simulation Experiment

The main question in this research is which of the three controllers shows the best performance in controlling the TSCDA. Considering the main purpose of the TSCDA: *reduce fuel use*, *reduce noise impact* while maintaining the *throughput at the RWT*, the performances of the controllers must be measured in performance metrics set by the objectives. It is not possible to answer the main question using the results of the initial simulations given in Section 2 only. It is necessary to perform Monte Carlo Simulations (MCS) to evaluate the controllers in a realistic test environment.



(a) *SCD* Speed profile (b) *SCD* Output profile

Fig. 6. *SCD*, initial simulations of the basic scenario (zero Wind and LW).

4.1 Monte Carlo Simulations

The MCS has three independent variables: the *type of controller*, the *wind condition* and the *setup of the arrival stream in terms of different aircraft mass*. The influence of these variables on the performance of the three different controllers must be derived from the results of the simulations. Besides those independent variables the simulations are performed in a realistic environment. The same scenario as used in the initial simulations of Section 2 has been used for the MCS. Two disturbances, a *Pilot Delay* at every change of configuration and an *Initial Spacing Error* are modelled in the simulation environment to improve the level of realism of this set of simulations. A combination of NLR's research simulators; *TMX*, *PC-Host* and *RFMS* is used as the simulation platform for the MCS (Meijer, 2008, A-1,3).

4.1.1 Independent variables

4.1.1.1 Controller

The three controllers; *TC*, *FGS* and *SCD*.

4.1.1.2 Wind condition

The influence of the wind will be evaluated by performing simulations without wind and with a South-Western wind, see Table 2 (as used in the *OPTIMAL* project (De Muynck et al., 2008)). During the TSCDA following the lateral path given in Figure 1(a) the controllers have to deal with cross wind, tailwind and a headwind with a strong cross component during final phase of the approach. This South-Western wind is also the most common wind direction in the TMA of Schiphol Airport.

4.1.1.3 Aircraft mass

The simulations used to evaluate the effect of a mass on the performance of the TSCDA controllers is combined with the simulations to evaluate the influence of the position of the aircraft in the arrival stream. In this research two different weight conditions are used. Lightweight LW and Heavyweight HW defined in Table 3. The difference in mass should be large enough to show possible effects.

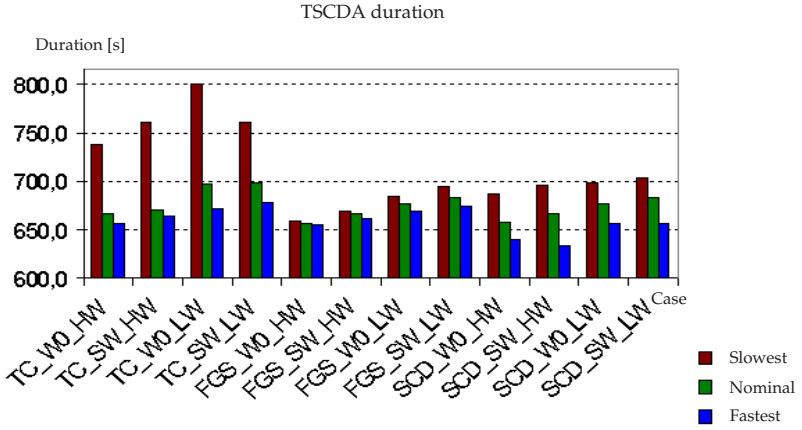


Fig. 7. TSCDA duration of all initial simulations.

stream	lead	pos. 2	pos. 3	pos. 4	trail
1, Full HW	HW	HW	HW	HW	HW
2, Full LW	LW	LW	LW	LW	LW
3, Mixed HW	HW	LW	HW	HW	HW
4, Mixed LW	LW	HW	LW	LW	LW

Table 8. The four types of arrival streams.

4.1.1.4 Arrival stream setup

The arrival streams consist of five aircraft, all the same Airbus A330-200 type. There are four different types of arrival streams, see Table 8. The mixed streams, three and four are used to evaluate the disturbance of a different deceleration profile induced by the different masses of aircraft in these streams. The first aircraft in the arrival stream performing the TSCDA according to the nominal speed profile, without the presence of a RTA at the RWT.

4.1.2 Simulation matrix

The combination of three different controllers, two types of wind and four types of arrival streams forms a set of 24 basic conditions for the MCS, see Figure 8. To test significance at a meaningful level, each basic condition has been simulated 50 times. Each simulation of a basic condition uses another set of disturbances, discussed below.

4.1.3 Disturbances

Two types of disturbances are used to make the simulations more realistic and to test the performance of the controllers in a more realistic environment. These two types are the modelled Pilot Delay on configuration changes. The second type of disturbance is the Initial Spacing Error. It is assumed that aircraft are properly merged but not perfectly spaced at the beginning of the approach. The induced time error at the begin of the TSCDA must be reduced to zero at the RWT.

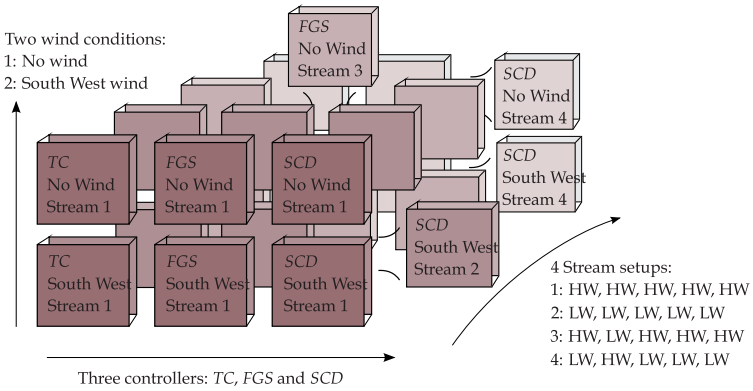
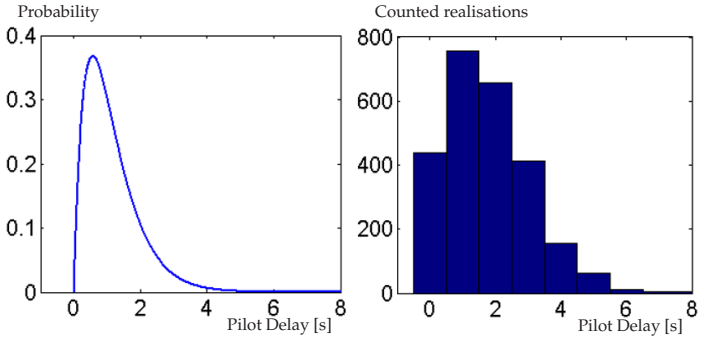


Fig. 8. Simulation matrix, 24 basic conditions.



(a) Poisson Distribution (b) Histogram of the generated data

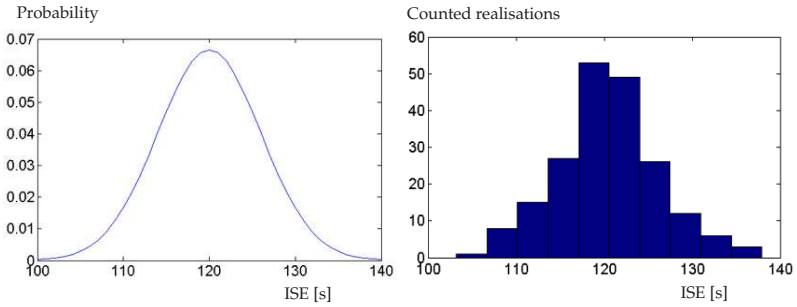
Fig. 9. Pilot Response Delay Model, Poisson distribution, mean = 1.75 s.

4.1.3.1 Pilot Response Delay Model

Configuration changes are the only pilot actions during the TSCDA. Thrust adjustment, vertical and lateral guidance are the other actions, which are performed by the autopilot. The delay between next configuration cues given by the FMS and the response of the pilot to these cues is modelled by the *Pilot Response Delay Model [PRDM]*. The delays are based on a Poisson distribution (De Prins et al., 2007). Each basic condition is simulated 50 times in this research. To get significant data from these runs, the data used by the disturbance models must be chosen carefully. A realisation of the Poisson distribution has been chosen for which the histogram of the generated data shows an equal distribution as compared with the theoretical distribution, see Figure 9.

4.1.3.2 Initial Spacing Error

To trigger the TSCDA-controllers, an Initial Spacing Error (ISE) has been modelled in the simulation environment. At the start point of the TSCDA, it is expected that the aircraft are properly merged in the arrival streams. However, the time space between aircraft at the start of



(a) Normal Distribution (b) Histogram of the generated data

Fig. 10. Overview of the Initial Spacing Errors in seconds, generated by a normal distribution with mean equal to 120 s and σ = 6 s.

the TSCDA is not expected to be equal to the required time space of 120 s at the RWT. The ISE is different between all aircraft in each of the 50 different arrival streams. The ISE sets are generated according to a normal distribution. The mean is chosen as the required time space between aircraft at the RWT and is equal to 120 s. The value for the standard deviation σ has been chosen so that the three controllers are tested to their limit derived in the initial simulations and set to σ = 6 s. To be sure that the generated data are according to the required normal distribution, the generated data has been evaluated by comparing the histogram of the generated data with the theoretical normal distribution, see Figure 10.

4.2 Hypotheses

From the definitions of the MCS described in the previous subsections, the following can be expected. The statements are related to the objectives for which the controllers are developed. The parameters which are derived from the MCS to evaluate these hypotheses are elaborated below.

4.2.1 Fuel use

The thrust is set to minimum when the TSCDA is controlled by the *FGS*. The other controllers use a higher thrust-setting and therefore it is hypothesised that the fuel use is minimum when using the *FGS*.

4.2.2 Noise reduction

Avoiding high thrust at low altitudes is the main method to reduce the noise impact on the ground. The most common reason to add thrust at low altitude is when the FAS is reached at a higher altitude than the reference altitude. A better controlled TSCDA reduces therefore the noise impact at ground level. It is hypothesised that there is a relation between the control margin and the accuracy of the controllers, see Figure 7, and therefore it is hypothesised that the *SCD* shows the best performance with respect to the accuracy. Since it is assumed that a better controlled TSCDA reduces the noise impact, it is hypothesised that the *SCD* shows the best performance with respect to noise reduction.

4.2.3 Spacing at RWT

Looking at the results given in Section 3.3, the control margin in a scenario without disturbances is the highest when using the *SCD* controller. However, the controller principle of the *SCD* is based on the presence of speed constraints. The lowest active speed constraint in this research is 180 kts if $h < 3{,}400$ ft. No active control is possible below this altitude, but below this altitude one kind of the disturbances are the pilot delay errors, which are activated during configuration changes. The *SCD* is not capable to control the TSCDA to compensate for those induced errors. The *FGS* and the *TC* are controllers which can compensate for errors induced during the last part of the TSCDA. It is hypothesised that the large control margin of the *SCD* affects the spacing at the RWT more than the reduced accuracy induced by the pilot delay errors effects the spacing at the RWT. Therefore it is hypothesised that the *SCD* will be the best controller to use to get the best time-based spacing between pairs of aircraft at the RWT.

4.2.4 Error accumulation in the arrival stream

Better controller performance will decrease the time-based spacing error between aircraft at the RWT. Better timing at the RWT of the leading aircraft will have a positive effect on the timing of the other aircraft in the arrival stream. Therefore it is hypothesised that a better control performance of a controller increases the performance of the other aircraft in the arrival stream.

4.2.5 Wind effects

The SW wind in combination with the scenario used in this research results in a headwind during the final part of the approach. This headwind reduces the ground speed and therefore increases the flight time of this final part. This can have a positive effect on the control space of the controllers. The effect of a larger control space will be the smallest on the *SCD*, because the control space of the *SCD* is the largest of the three controllers. So the effect of wind on the performance of the controllers will be smallest in the *SCD* case. However the Trajectory Predictor of the RFMS predicts the wind by interpolating the wind given in Table 2. The actual wind will be different because the aircraft model uses another algorithm to compute the actual wind. This difference between predicted wind and actual wind is used as variance in the predicted wind. It is hypothesised that these prediction errors have a negative influence on the accuracy of the controllers and therefore the performance of the controllers.

4.2.6 Effect of varying aircraft mass

A lower aircraft mass will decrease the FAS. A lower FAS will increase the duration of the deceleration to this FAS. A longer flight time has a positive effect on the control margin of the *TC* and *FGS* controller and a negative effect on the control margin of the *SCD*. The influence of the longer flight time on the accuracy of the controllers is the smallest in case of the *SCD*, because the *SCD* has the largest control space and therefore the possible impact on the control space is relative small.

4.2.7 Effect of disturbance early in the arrival stream

The differences in flight times between HW and LW are relatively large compared to the control space of the controllers, see Tables 4, 6 and 7 and Figure 7. A different aircraft mass early in the stream means a large disturbance and it is expected that the controllers must work at their maximum performance. The spacing error at the RWT will be large for all second air-

craft in the arrival streams. It is expected that the effect of this disturbance on the *SCD* is the smallest of the three controllers.

4.3 Performance metrics

From the results of the MCS several performance metrics must be derived. These metrics are chosen so that the hypotheses can be evaluated and so that the main question in this research can be answered. Looking at the three main objectives for which the TSCDA is developed: *reduce fuel use during the approach*, *reduce noise impact at ground level in the TMA* and *maintain throughput at the RWT*, the main performance metrics are:

- The *fuel use* during the TSCDA. This parameter shows directly the capability of the controller to reduce fuel during the approach.
- The *spacing at the RWT*. This parameter indicates the accuracy of the controller and it also indicates the possible control margin of the controller. It therefore gives an indication if the *minimum time space between aircraft at the RWT* objective can be met. The ISE is distributed with σ = 6 s. This σ is also chosen to set the reference values of the spacing times at the RWT. The upper and lower bound of the spacing times are set by 120 s $\pm$ 6σ.
- The *stabilisation altitude h_{stab}, where V reaches the FAS*. If h_{stab} is above h_{ref} = 1,000 ft then thrust must be added earlier in the approach to maintain the speed, this will result in a higher noise impact. If the value of this performance metric is below 1,000 ft then safety issues occur, because the aircraft is not in a stabilised landing configuration below h_{ref}. A σ = 80 ft for h_{stab} is expected (De Leege et al., 2009). The upper and lower bound is set as 1,000 ft $\pm$ 3σ.
- The *controller efficiency* is also a factor to compute. The specific maximum controller output is recorded during the simulation. The actual controller output at h_{ref} is divided by the maximum controller output at h_{ref}. This computed value indicates that spacing errors at the RWT are the result of disturbances where the controllers can not compensate for.

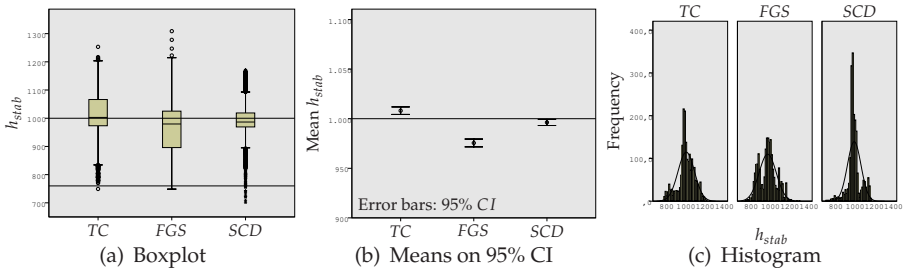
5. Results

5.1 Controllers compared

In this section the three controllers are evaluated by comparing the performance metrics derived from all the results of the simulations, these results are including the two wind conditions, four types of arrival streams and all the aircraft in the stream.

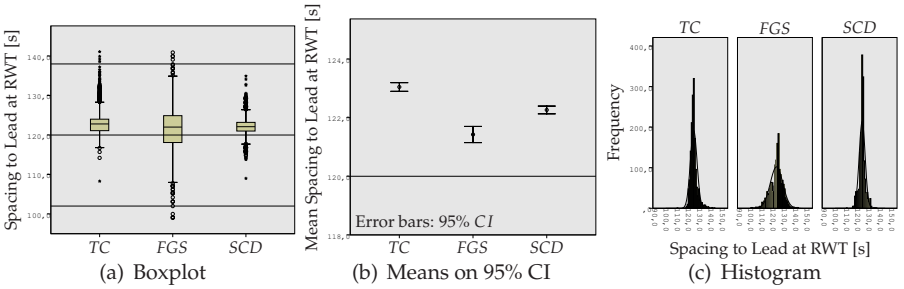
5.1.1 Stabilisation altitude

Figure 11 shows three diagrams which enable a visual comparison between the performance of the three controllers with respect to the performance metric: *the altitude where V reaches the FAS*, which is the stabilisation altitude (h_{stab}). The differences between the controllers are significant; *Analysis of Variance (ANOVA): F=78.876 , p <0.001*. The means, Figure 11(b), show the best performance of the *SCD* and the worst peformance of the *FGS*.
The *FGS* gives the most violations with respect to the lower bound of 760 ft. The distribution of h_{stab} in the *SCD* controlled case is the smallest of the three and the distribution in the *FGS* case is the largest. The three histograms, Figure 11(c), show distributions with two or three peaks. Further investigation of the influences of the other independent variables gives more insight in these distributions.



(a) Boxplot (b) Means on 95% CI (c) Histogram

Fig. 11. Altitude where V reaches the FAS (2,000 samples per controller).



(a) Boxplot (b) Means on 95% CI (c) Histogram

Fig. 12. Spacing to Lead at RWT [s] (1,600 samples per controller).

5.1.2 Spacing at RWT

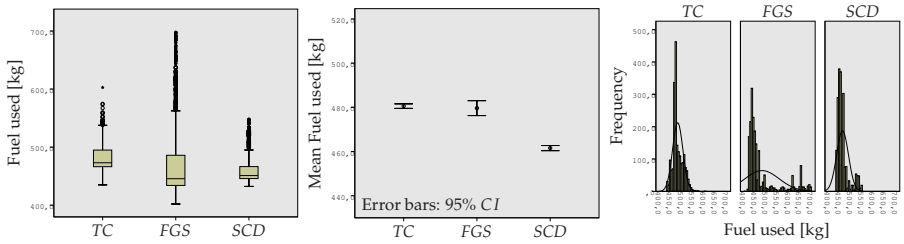
The differences between the controller performance with respect to the performance metric: spacing at the RWT as given in Figure 12 are significant; *ANOVA:* $F = 65.726$, $p < 0.001$. The means, Figure 12(b), show that the *FGS* controller performs best, the *TC* performs worst. The means of the three controllers lie all above the objective nominal value of 120 s. The *FGS* shows many violations on the lower limit set by 102 s. Using the *TC*, there are some violations on the upper limit only. The *SCD* gives no violations on the limits. The histograms in Figure 12(c) show all a normal distribution.

5.1.3 Fuel use

The performance metric 'fuel used' is shown in Figure 13. The differences between the controllers are partly significant *ANOVA: F=96.294 , p <0.001*. The *SCD* shows the lowest mean fuel use, on average 20 kg less fuel use per approach compared to the *TC* and *FGS*. The *FGS* gives a wide distribution compared to the other controllers and the *FGS* also gives the minimum and maximum values of the fuel use of all approaches. The *TC* and *SCD* show a more converged distribution than the *FGS*. The histograms of the *TC* and *FGS* results show a different distribution, although the means are equal.

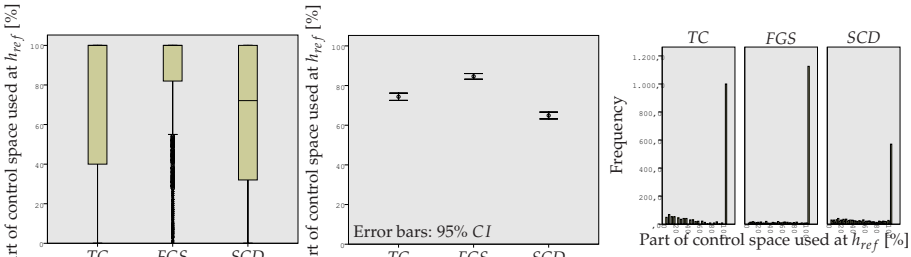
5.1.4 Controller efficiency

Figure 14 shows the performance metric 'controller efficiency' per controller. Although the histograms show no normal distributions, the ANOVA gives a clear result; the differences are



(a) Boxplot (b) Means on 95% CI (c) Histogram

Fig. 13. Fuel used during TSCDA [kg] (2,000 samples per controller).



(a) Boxplot (b) Means on 95% CI (c) Histogram

Fig. 14. Part of control space used at h_{ref} [% of max. output] (1,600 samples per controller).

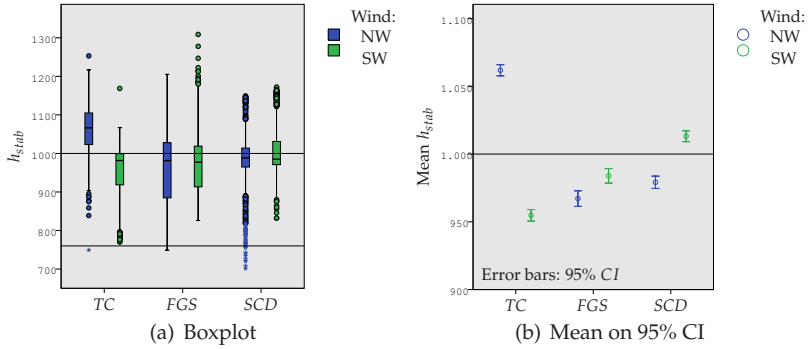
significant *ANOVA: F=135.528 , p <0.001*. Looking at the histograms, the *FGS* and the *TC* use their maximum control space most of the approaches, which is also indicated by the median which is equal to 100 for both cases. The mean of the *SCD* (65%) is low compared to the other means (*TC* 75% and *FGS* 85%).

5.2 Wind influence on controller performance

The wind influence on the performance of the three controllers is evaluated using the same performance metrics as used for the comparison of the three controllers for all the simulations. The results are split up by the controllers and by the wind conditions. Table 9 gives the results of the ANOVAs which are performed to evaluate the wind influence on the different controllers.

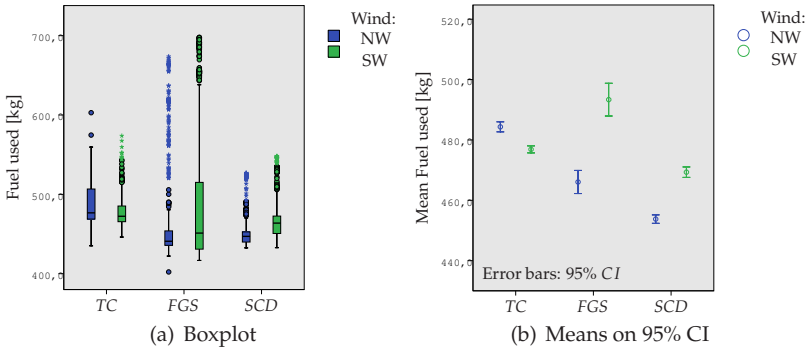
performance metric	general [F, p]	*TC* [F, p]	*FGS* [F, p]	*SCD* [F, p]
stabilisation altitude	151.2 , $\star\star$	1259 , $\star\star$	17.43 , $\star\star$	121.2 , $\star\star$
spacing at RWT	0.387 , 0.534	0.275 , 0.600	0.580 , 0.446	0.201 , 0.654
fuel use	138.3 , $\star\star$	52.60 , $\star\star$	64.82 , $\star\star$	189.0 , $\star\star$
control efficiency	2.920 , 0.088	4.349 , 0.037	2.510 , 0.113	0.388 , 0.533

Table 9. Overview of ANOVAs with respect to Wind influence; a significant difference occurs if p <0.05, and $\star\star$ indicates that $p < 0.001$.



(a) Boxplot (b) Mean on 95% CI

Fig. 15. Wind influence on h_{stab} (1,000 samples per controller per wind condition).



(a) Boxplot (b) Means on 95% CI

Fig. 16. Wind influence on fuel burn [kg] (1,000 samples per controller per wind condition).

5.2.1 Stabilisation altitude

There are significant differences between the stabilisation altitudes of the two wind conditions. The differences in wind influence on the different controllers are also significant, see Table 9. In all the three controller cases the wind influence has a positive effect on the means of h_{stab}. The absolute effect of wind on the means of the *TC* and *FGS* are opposite compared to the effect of wind on the *SCD*. The wind influence on the *SCD* is small as compared to the other controllers.

5.2.2 Spacing at RWT

There is no significant influence of the wind on the spacing performance at the RWT, Table 9. The spacing times out of limits appear in the wind case only.

5.2.3 Fuel use

Figure 16 and Table 9 show significant differences in fuel burn. The *TC* uses on average less fuel in the wind case, *FGS* and *SCD* use on average more fuel in case of wind. There is a wide distribution of fuel burn in the wind case in combination with the *FGS*.

performance metric	general [F, p]	TC [F, p]	FGS [F, p]	SCD [F, p]
stabilisation altitude	107.2 , $\star\star$	50.49 , $\star\star$	30.66 , $\star\star$	14.23 , $\star\star$
spacing at RWT	15.76 , $\star\star$	42.73 , $\star\star$	3.681 , 0.012	2.907 , 0.034
fuel use	163.0 , $\star\star$	18.86 , $\star\star$	70.19 , $\star\star$	52.79 , $\star\star$
control efficiency	21.33 , $\star\star$	14.75 , $\star\star$	13.50 , $\star\star$	15.97 , $\star\star$

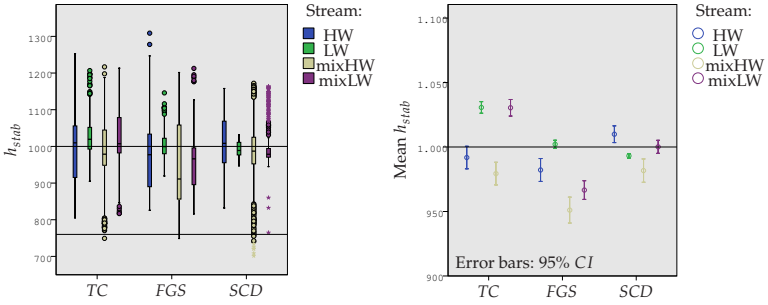
Table 10. ANOVAs with respect to stream setup and aircraft mass; a significant difference occurs if p <0.05, and $\star\star$ indicates that $p < 0.001$.

5.2.4 Controller efficiency

Table 9 indicates no significant differences in the controller efficiency when analysing the wind influence on all simulation results and the wind influence on the *FGS* and *SCD* controllers. The wind influence on the *TC* controller is significant. A SW wind has a negative effect on the control efficiency.

5.3 Effect of aircraft mass and stream setup

5.3.1 Stabilisation altitude



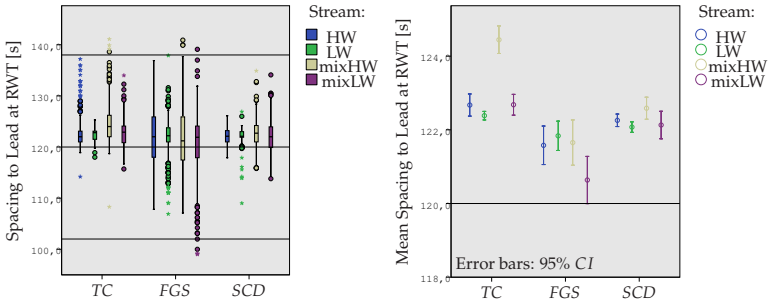
(a) Boxplot (b) Means on 95% CI

Fig. 17. Effects of aircraft mass and stream setup on h_{stab} (500 samples per controller/stream type).

Figure 17 and Table 10 show significant differences between the means of h_{stab}. The effect of the stream setup and aircraft mass is significantly different for each controller. This effect is smallest in the *SCD* case and largest in the *TC* case. The *Mixed HW* stream shows h_{stab} values below the lower limit only. The values of h_{stab} in case of mixed streams are wider distributed than the values of h_{stab} of the HW and LW streams and distribution of h_{stab} is wider for the HW stream compared to distribution of h_{stab} of the LW stream. The effect of a different stream setup is the smallest for the *SCD* controller.

5.3.2 Spacing at RWT

Figure 18 and Table 10 show significant differences between the spacing times at the RWT for all runs. Further analysing all data focused on the effect of the different streams gives no significant differences for spacing times. Table 10 shows significant different effects of the different streams in spacing times on the controllers specific. Spacing times below the lower limit only occur in the *mixedLW* stream.

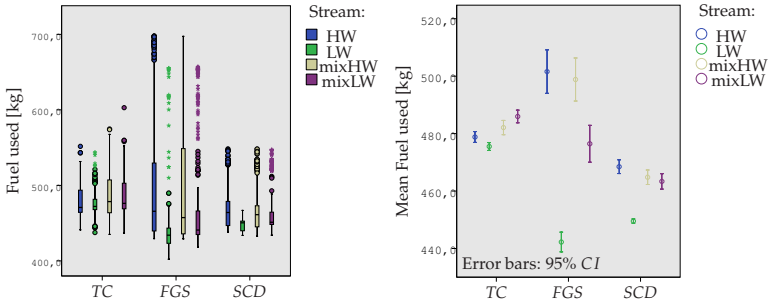


(a) Boxplot (b) Means on 95% CI

Fig. 18. Effects of aircraft mass and stream setup, spacing to Lead at RWT [s] (400 samples per controller/stream type).

The effects of the different streams on the spacing times is the smallest using the *SCD*. The mean of the spacing time in the *mixedLW* stream using the *TC* is large compared to the means of the other streams. The distribution of spacing times at the RWT is smallest for the LW stream for all controllers.

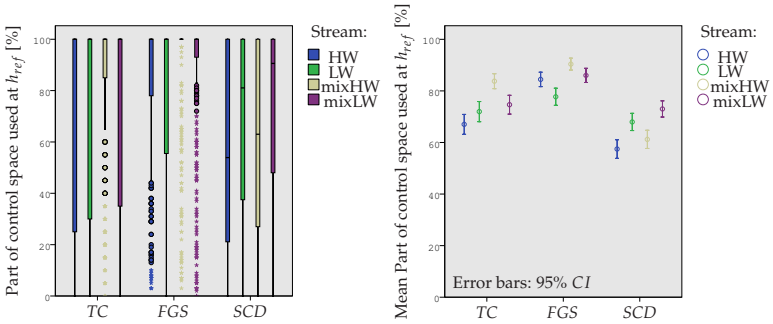
5.3.3 Fuel use



(a) Boxplot (b) Means on 95% CI

Fig. 19. Effect of aircraft mass and stream setup, fuel burn [kg] (500 samples per controller/stream type)

Figure 19 and Table 10 show significant differences in fuel burn between the arrival streams. The differences between the HW and *mixedHW* streams are not significant. Generally, LW aircraft consume less fuel. Figure 19(b) shows a large difference in fuel use of the LW stream in the *TC* and *SCD* cases. The effect of different arrival streams on the fuel use is the smallest for the *TC* and largest for the *FGS*.



(a) Boxplot (b) Mean on 95% CI

Fig. 20. Effect of aircraft mass and stream setup, part of control space used at h_{ref} [% of max. controller output] (400 samples per controller/stream type).

5.3.4 Controller efficiency

Figure 20 and Table 10 show different controller efficiencies for the different arrival streams. The differences between the HW and LW streams are not significant, the differences between the *mixedHW* and *mixedLW* streams are also not significant. The position of the means for each stream in Figure 20(b) show different patterns for each controller.

5.4 Effect of the position in arrival stream

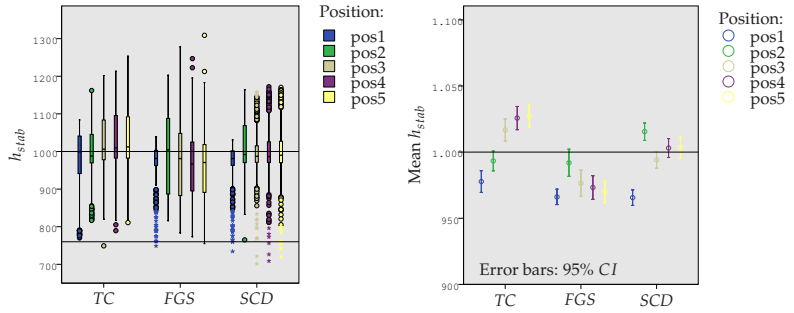
performance metric	general [F, p]	TC [F, p]	FGS [F, p]	SCD [F, p]
stabilisation altitude	61.31 , $\star\star$	26.76 , $\star\star$	4.883 , 0.001	29.59 , $\star\star$
spacing at RWT	26.23 , $\star\star$	37.51 , 0.600	0.513 , 0.673	28.38 , 0.654
fuel use	80.99 , $\star\star$	45.96 , $\star\star$	28.29 , $\star\star$	25.37 , $\star\star$
control efficiency	0.352 , 0.788	1.835 , 0.139	3.689 , 0.012	0.539 , 0.655

Table 11. Overview of ANOVAs with respect to the position in arrival stream; a significant difference occurs if p <0.05, and $\star\star$ indicates that $p < 0.001$.

5.4.1 Stabilisation altitude

Figure 21 and Table 11 give significant differences in the effect of the aircraft's position in the arrival stream with respect to h_{stab}. Further analysis shows that there are no significant differences between positions 2 to 5 in the stream. The influence of the position in the arrival stream on h_{stab} with respect to the three controllers is significant. The distribution of h_{stab} 'position 1' is largest compared to the other positions. The means of h_{stab} for 'position 2' are different compared to h_{stab} of the other positions.

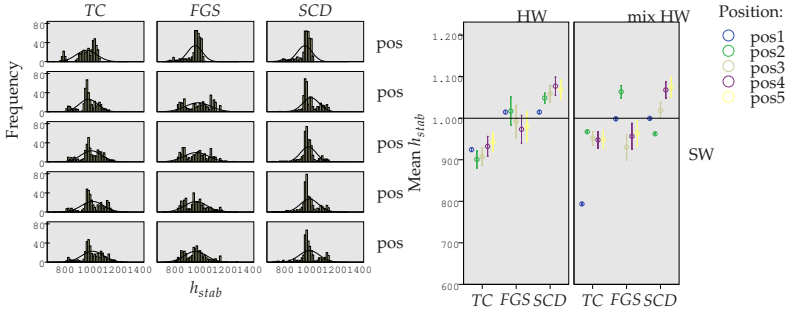
The pattern of the means for the *FGS* in Figure 21(b) shows a decrease in h_{stab}, the *TC* and *SCD* shows an increase in h_{stab}. The distribution of h_{stab} for 'position 1' controlled by the *TC* shows a peak at 800 ft, see Figure 22(a), this is further analysed. Figure 22(b) shows the relative low means h_{stab} of the *TC* runs for position 1. All simulations of the first aircraft in the arrival stream are loaded by disturbances, those aircraft should perform the approach according to the nominal profiles of the controllers. So it is expected that there are no large differences between h_{stab} of the first aircraft in the different streams if the aircraft mass is equal.



(a) Boxplot (b) Means on 95% CI

Fig. 21. Effect of the position in arrival stream on h_{stab} (400 samples per controller per position).

Figure 23 shows flight data of the second run of the HW and *mixedHW* streams controlled by the *TC* and with the SW wind condition. The data presented in this figure shows what happened during all the simulations in this specific case. Problems occurred in the flap deflection while descending from 1,850 ft to 1,700 ft. Output data of the Trajectory Predictor of the RFMS show normal behaviour for all the runs in this case, so the problem can be found in the aircraft model. More specific data of the flap deflection in the aircraft model is not available and therefore a further analysis of the problem which caused the wrong flap deflection in this specific case could not be performed.
The problem of the worse deceleration caused by problems in the flap deflection part of the aircraft model has no effect on the other aircraft in the arrival stream because there is no relation found between the spacing at the RWT and the stabilisation altitude and the input of the controllers is only the ETA of Lead in the arrival stream.



(a) Histograms

(b) Means on 95% CI, split up by type of stream, wind condition, position in arrival stream and controller, zoomed in on the HW and *mixedHW* streams

Fig. 22. Altitude where V reaches the FAS (400 samples per controller per position).

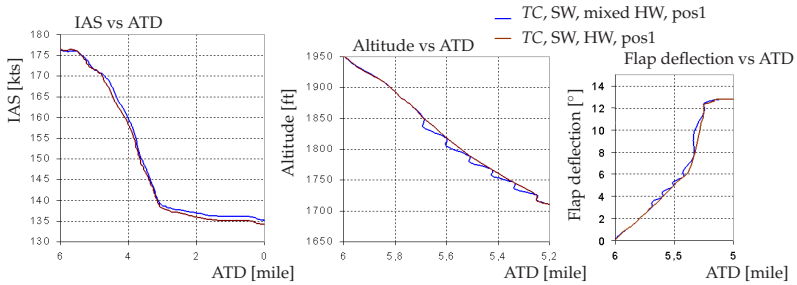


Fig. 23. Two particular approaches compared with respect to altitude, IAS and Flap deflection vs ATD. The data are derived from flight data of the first aircraft of the second stream.

5.4.2 Spacing at RWT

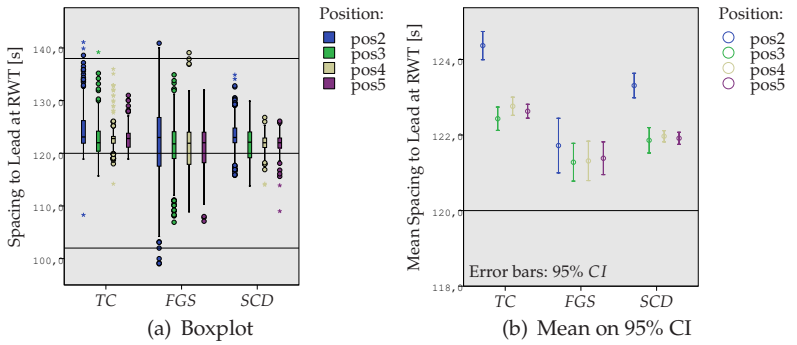
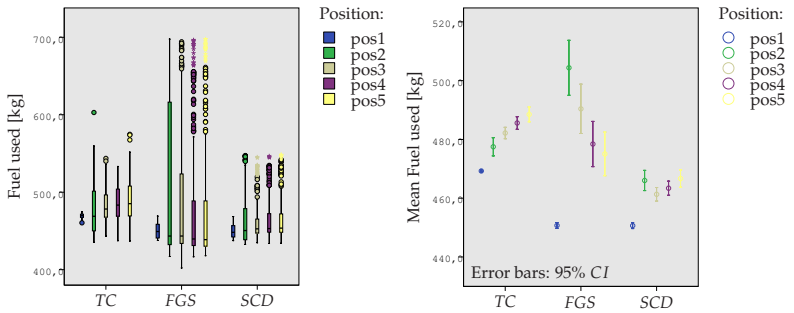


Fig. 24. Effect of the position in arrival stream, spacing to Lead at RWT [s] (400 samples per controller per wind condition).

There are significant differences of the spacing times at the RWT between the positions in the arrival stream according to Table 11. This significant difference is not found for the positions 3, 4 and 5 in the arrival stream, however. Within the three controllers the differences in spacing times is not significant between the positions, according to Table 11. The only values out of the lower limit are in *Position 2* in the *FGS* case. The distribution of the spacing times at higher positions in the streams is smaller than the distribution of the spacing times of positions 1 and 2.

5.4.3 Fuel use

There are significant differences of fuel use between the positions in the arrival stream according to Table 11. This significant difference is not found for the positions 3, 4 and 5 in the arrival stream. Within the three controllers the differences in fuel use is significant between the positions, according to Table 11. Figure 25 shows the lowest fuel use at position 1. In the *TC* case, a higher position in the stream causes a higher fuel use. In the *FGS* case there is a lower fuel use at higher positions in the stream (after position 2). The *SCD* case shows the



(a) Boxplot (b) Means on 95% CI

Fig. 25. Effect of the position in arrival stream, fuel used during TSCDA [kg] (400 samples per controller per wind condition).

smallest effect of the different positions of the three controllers. The fuel use of position 2 is different compared to the other positions.

5.4.4 Controller efficiency

Table 11 shows no significant differences between the controller efficiencies between the positions in the arrival stream. Within the controller cases there are no significant differences between the efficiencies of the *TC* and *SCD*. The differences are in the *FGS*, i.e., at higher positions performance is better.

5.5 Interaction effects

Interaction effects of the independent variables on the performance metrics are investigated. These effects are in most of the cases significant. The significant effects can be summarised as follows; the stream setup amplifies the influence of the other independent variables on the performance metrics significantly in all cases. Different positions and different wind conditions show the same effect, however these effects are not significant.

6. Discussion

6.1 Fuel use

It was hypothesised that the *FGS* uses on average the lowest amount of fuel for the approach. The results of the simulations show that the *SCD* uses on average the lowest amount of fuel. The meaning of an, on average, 20 kg less fuel use per approach is quite significant. However looking at the extreme values, the approach with the minimum fuel use is controlled by the *FGS* as hypothesised. The results show a relation between the control performance of the *FGS* controller and a larger standard deviation of the fuel use and on average larger amount of fuel per approach.

A SW wind condition results in a higher fuel use for the *FGS* and *SCD*, but reduces the fuel use of the *TC*. This might be caused by the fact that the *TC* uses thrust adjustments to control the TSCDA and therefore directly affects the fuel use during the approach. This statement combined with the fact that the SW wind condition affects the ground speed, and therefore the ETA of the aircraft, results in the good performance of the *TC* in the SW condition.

LW aircraft uses less fuel than HW aircraft. The effect of a different aircraft mass on the fuel use is largest for the *FGS* and smallest for the *TC*. It was hypothesised that the *SCD* should have the smallest deviations caused by differences in aircraft mass and stream setup. For the fuel use this hypotheses is rejected, because the *TC* controller performs best. The first aircraft in the arrival stream uses the lowest amount of fuel, these aircraft perform the approach at nominal profiles, the controllers are inactive. The *FGS* shows the largest difference in fuel use per position, as hypothesized.

6.2 Noise reduction and safety aspects

The controllers have to perform the approach so that the stabilisation altitude h_{stab} equals the h_{ref} = 1,000 ft. Higher stabilisation means that the FAS is reached at a higher altitude which results in an earlier moment of adding thrust to maintain the speed. Lower stabilisation is not preferred because safety aspects require a minimum stabilisation altitude of 1,000 ft. Looking at all results it can be concluded that the *SCD* controls the TSCDA the best of the three controllers. The mean stabilisation altitude of the *SCD* is almost equal to 1,000 ft and the standard deviation is small compared to those of the other controllers. The histograms show more than one peak in the distributions of h_{stab}. These peaks are related to the effect of the different arrival streams on h_{stab}.

The wind influence on the performance of the *TC* is large compared to the other controllers, the *SCD* gives the smallest differences in h_{stab} between the two wind conditions. Is was hypothesised that the influence of wind on the controller's performance is smallest in the *SCD* case. Different aircraft mass contributes to large differences in h_{stab}. Again this effect is smallest on the *SCD*. LW aircraft perform the approach better than the HW aircraft with respect to h_{stab}. The results of the *FGS* indicates many problems in the mixed aircraft streams. The disturbance induced by the second aircraft has a large negative effect on the performance of the *FGS*. The stabilisation altitudes at each position in the arrival stream are quite different for each controller. The *TC* and *SCD* give higher h_{stab} for higher positions in the arrival stream. The results of the *FGS* case show not this pattern. The second position in the arrival streams shows the largest differences compared to the other positions. The extra initial spacing error caused by the different flight times between HW and LW aircraft affects the controllers' performance.

6.3 Spacing at RWT

The average spacing times of the *FGS* are closest to the objective of 120 s. However, there were many runs in the *FGS* case where the spacing at the RWT was outside the limits set by 102 s and 138 s. This means that although the mean spacing error is smallest, the variability is the largest. The *SCD* gives the narrowest distribution and is therefore the best controller with respect to the performance metric 'spacing at the RWT', as was hypothesised. The assumption that the negative effect of the presence of an ISE on the spacing at the RWT is larger than the effect of the presence of pilot delay errors on the spacing at the RWT, is also justified.

The controller efficiencies of the three controllers gives the same result, the *SCD* is best capable of controlling the aircraft with respect to the spacing at the RWT. The maximum output value of the *SCD* is $\pm$ 10 kts. This value was arbitrary chosen. The controller efficiencies of the *SCD* show that the TSCDA concept is even possible with a smaller maximum *SCD* output value.

Earlier researches on the *FGS* show a better performance of this controller with respect to the spacing at the RWT (De Leege et al., 2009). The bad performance of the *FGS* in this research is related to the type of aircraft used, the Airbus A330. The *FGS* of the A330 controls 4 dif-

ferent flap positions, the *FGS* of a B747 controls 6 flap positions which increases the control space. The scenario used in this research is more realistic than the scenarios used by previous researches, however.
The wind influences on the spacing times at the RTW are not significant.
There are differences in spacing performance between the different arrival streams. First the mean spacing time is closer to the objective for LW aircraft compared to HW aircraft. This effect is smallest for the *SCD* as hypothesised. A disturbance in the arrival stream as in the mixed weight aircraft streams has a negative influence on the performance of the controllers. LW aircraft perform better in combination with all controllers, this was also hypothesised. The duration of the deceleration is longer for LW aircraft, this increases the control margin of the controllers resulting in better spacing performance.
The *SCD* controller is not capable to compensate for errors induces by the PRDM. It was hypothesised that this could have a bad influence on the performance of the *SCD*. The results also show this influence, because the mean spacing error of 2.5 s in the *SCD* case is large, although the controller is not performing at its maximum capacity. However, the *SCD* still performs properly, because the mean spacing time of the *SCD* is situated between the mean spacing times of the *FGS* and the *TC* and the standard deviation of the *SCD* is smallest of the three controllers.
The mean of the spacing error derived from all results is +3 s. The spacing error is derived from the ETA, which is calculated using the TP of the RFMS. A positive standard spacing error indicates that the calculation of the ETA is not performed properly. The code of the TP of the RFMS shows that the backwards calculation of the speed and altitude profiles starts at 0 ft above the runway. The end of the simulation is the RWT which is situated 50 ft above the runway. This difference of 50 ft introduces a standard error in the calculation of the ETA which results in the slow approaches.

7. Conclusions

This research showed significant differences in the performance of three different controllers *TC*, *FGS* and *SCD* capable of performing the TSCDA in arrival streams. The fuel use, noise impact and spacing performance of the three controllers are compared, and the *SCD* shows the best performance. Wind influence, different aircraft mass, arrival stream setup and position in the arrival streams affects the performance of the controllers. These effects are smallest for the *SCD*. Compared to the *FGS* used in previous researches the *FGS* performs less accurate at controlling the TSCDA. The more realistic scenario, the high-fidelity simulation environment and the specific type of aircraft used in this research give new insight in the performance of the *FGS*. With respect to fuel use the performances of the *TC* and *FGS* are equal. The *TC* performs between the *SCD* and *FGS* with respect to spacing criteria.

8. Recommendations

It is recommended that more types of aircraft are simulated. The specific aircraft deceleration performance has a large influence on the performance on the TSCDA controllers. The interaction between aircraft in arrival streams built up from applying more than one type of aircraft is worth to evaluate.
Disturbances such as a reduced accuracy of the ADS-B model, turbulence during the approach and a reduced navigation performance should be implemented as well to get a more realistic simulation environment. The influence of larger ISE's should also be investigated.

It is further recommended that the results of this research are analysed using a noise footprint tool to compute the absolute noise impact. The results could give a different conclusion about the best controller performance, because other important parameters, such as the configuration change moments, can have a different effect on the noise impact. Similarly, it is recommended that metrics regarding emissions during the approach are included in future research efforts.

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