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DOI
10.2514/6.2023-1827

Publication date
2023

Document Version
Final published version

Published in
AIAA SciTech Forum 2023

AIAA SciTech Forum
23-27 January 2023, National Harbor, MD & Online
AIAA SCITECH 2023 Forum
10.2514/6.2023-1827

Procedure and Interface Design for Continuous Descent Approaches Under End Time Constraints

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The Continuous Descent Approach (CDA) offers reduced aircraft noise emissions and fuel consumption, but the obstacle limiting it to reduced traffic density conditions, is the low predictability of the trajectory and Estimated Time of Arrival (ETA). The solution proposed by this research is to develop a pilot support interface to facilitate the execution of a fixed flight path angle CDA, where thrust is not limited to idle and a velocity profile can be tracked, which will lead to a selected ETA. Initially, the CDA trajectory was investigated through an aerodynamic model, while the solution space of the ETA and the calculation of the stepwise velocity profile were defined. Following the analysis of the pilot's role, a two-fold support interface was designed based on Ecological Interface Design (EID), with a Vertical Situation Display (VSD) playing a central role for planning and execution. The interface was tested in a MATLAB®/Simulink® setup and five pilots were recruited to execute simulations over different wind conditions. Their on-time performance was satisfactory, while they worked with the provided cues and suggested some interface changes to offer more flexibility. A more robust application of the proposed approach can lead to a wider adoption of the CDA, as a validated procedure.

Nomenclature

C_D	=	Coefficient of drag	P_a	=	Atmospheric pressure
C_L	=	Coefficient of lift	T	=	Thrust
D	=	Drag	V_{sound}	=	Velocity of sound
g	=	Acceleration due to gravity	V_α	=	True airspeed
H	=	Altitude	α	=	Angle of attack
L	=	Lift	γ	=	Flight path angle
m	=	Mass	ρ	=	Air density

I. Introduction

The common arrival procedure, currently in use, where an aircraft flies from Top of Descent (ToD) until the interception of Glideslope (G/S), includes step-down descents and level flight segments. This method, which relies on Air Traffic Control (ATC) commands, creates traffic flows with uniformly decelerating aircraft and facilitates aircraft sequencing [1]. Going beyond the established navigational aids and procedures, the research done in the Aerospace industry has enhanced aircraft's capabilities regarding navigation with the Global Positioning System (GPS) and the Flight Management System (FMS), and more complex procedures and trajectories can be executed [2].
A related concept, that is currently in use at many airports is the Continuous Descent Approach (CDA), whose main

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goal is to mitigate the noise footprint of air traffic. One of the first analyses of CDA took place at the Dutch National Aerospace Laboratory NLR [3], as a possible Noise Abatement Procedure (NAP) for Schiphol International Airport (AMS/EHAM). This approach trajectory is executed in the Terminal Maneuvering Area (TMA) at higher altitude than the conventional approach and the aircraft intercepts the G/S, without performing level flight segments. CDA is defined as [4]:

"Continuous Descent Approach is an aircraft operating technique in which an arriving aircraft descends from an optimal position with minimum thrust and avoids level flight to the extent permitted by the safe operation of the aircraft and compliance with published procedures and ATC instructions."

After the initial presentation of CDA, it has been proven that it reduces the noise level and fuel consumption along approach routes, using different research methods. This concept was tested in computer simulations using aircraft performance data [5–8] in European airports varying in traffic load. In addition, more realistic conditions were examined in actual flight tests [9–12] and sessions in flight simulators [1, 11, 13].

The procedure of CDA has been adapted to different forms, by modifying its parameters. For instance, the flight path angle of CDA was kept constant at $-3°$ (Three Degree Decelerating Approach) and the flap schedule, in combination with thrust cutback altitude (thrust set to idle), were subjected to optimization to reduce the noise footprint and maintain aircraft separation [11]. In addition, the effect of the flight path angle to noise footprint was considered in flight tests [9], namely for $-2°$, $-2.5°$, $-3°$, but the angle's impact did not result to be significant. The possibility of splitting the CDA into two different flight path angle segments was investigated with a constant flap schedule [14], provided an additional flexibility during planning of the approach and led to an acceptable time performance. In the case of having both flight path angle and flap velocities as free variables, it was proposed that the pilot can use the aircraft's total energy, which is converted to available control space, to define the decelerating strategy [15]. A modified $-3°$ CDA was also tested [15], which made the trajectory prediction easier, since the aircraft in this case intercepts the "extended" $-3°$ G/S, initially maintains its velocity and as it flies closer to the airport, it starts decelerating.

However, in the first stages of CDA development, it was noted [16] that the execution of this approach results in extending the planned landing interval from 1.8 minutes to 4 minutes, due to uncertainty concerning the Estimated Time of Arrival (ETA). Flight tests [9] likewise concluded that this procedure cannot be applied in peak traffic times, due to the lack of accurate trajectory prediction. The goal of this project is to propose a new agile approach to this problem, by modifying the initial concept of CDA, which has thrust as a free variable, in contrast with the aforementioned projects, and therefore be able to follow a velocity profile that leads to the desired ETA, thus the Required Time of Arrival (RTA).

The transition from a 3-D approach, hence the trajectory in space, to a 4-D concept, with the addition of time, has already been implemented [17], as the Advanced Continuous Descent Approach (ACDA). A research project [5], which applied the ACDA concept, added some flexibility to approach parameters, such as the flight path angle and thrust setting. However, this trajectory is fully executed by the FMS, which leaves the pilots without maintaining an appropriate situation awareness and it can be difficult for them to intervene, if needed [18].

Therefore, the other dimension of this project comes into place, namely engaging the pilot into this procedure. The concept of this approach concerns controlling the aircraft's trajectory from the Initial Approach Fix (IAF) to the Final Approach Fix (FAF) at the landing runway's threshold. The pilot can define the deceleration and descent trajectory, starting from choosing CDA's flight path angle. During this execution, the pilot remains on a supervisory role and interacts with the aircraft through automation, the autopilot. The information, such as the future trajectory, ETA limits and the commands to be followed to achieve this goal, can be either presented as cues in an existing display, like the Primary Flight Display (PFD) [1, 11, 12], or a new interface can be designed for this purpose [10, 14, 15, 19].

The design of this pilot support interface is based on previous work that took place for the CDA explicitly [14, 19] or, in general, for 4-D trajectories [20] and flight envelope visualization [21]. All these projects had, as a common framework the Ecological Interface Design (EID) [22, 23], which guides the design process towards supporting human cognition, in terms of depicting abstract properties and constraints of a system in an easily perceptible way for the pilot.

This article continues with Section II, starting with analysing previous work that has been executed on the concept of CDA that leads to defining the parameters of this approach. Then, the development of this project breaks down in its two main components, trajectory calculation and interface design. After finalizing the development of these aspects, the experimental procedure is described in Section IV, its results and implications are analyzed in Section V and finally Section VI concludes the findings of the project and poses future suggestions.

II. Background

Having shaped the outline of the taken approach, hence to modify the initial definition of CDA and be flexible in terms of thrust, in pursuing of achieving a desired ETA, the next step is to define the remaining parameters. At first, the flight path angle γ of CDA has been considered to be constant [9, 11, 13, 19], but also a free variable [15], but the latter is not adopted, since it may complicate more the task of separation by ATC. An example of this type of trajectory is presented in Figure 1. At $2,000$ ft [14], the interception of G/S can be noted, where the flight path angle changes from $-2°$ to $-3°$. A range for a CDA flight path angle is proposed to be from $-2°$ to $-3°$ [9], and in general higher angles are preferred, for less noise emissions, as long as the aircraft can decelerate without deploying the speedbrakes. Therefore,

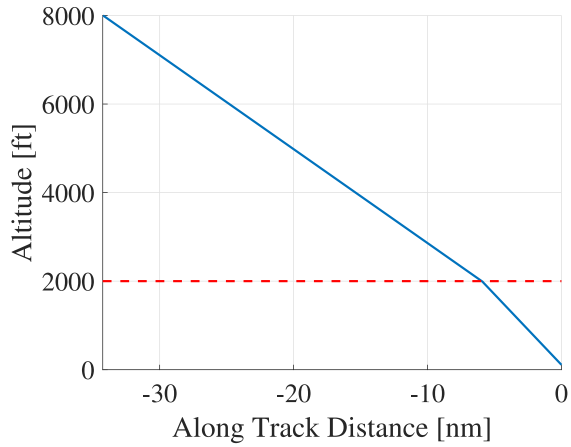


Fig. 1 Overview of a CDA trajectory

with a constant flight path angle, the last parameter, the flap schedule, which has been subjected to modification and optimization [11, 15], remains fixed, since it is preferred to keep flap deployment velocities at a narrow range to prevent an increase in pilot workload [24]. In addition, when flaps are extended close to their corresponding maximum operating velocities, it can lead to extensive wear. The primary analysis, that is needed for this project, is calculating the aircraft's trajectory from the IAF to the FAF and, consequently, the ETA. The other perspective, that is needed, is the application of trajectory calculation methods into the final interface design.

A. Trajectory calculation

The trajectory calculation follows the logic of an aerodynamic model, considered as a point mass, whose trajectory is calculated in 2-D (longitudinal and vertical axes) [1, 11], assuming that the effect of the lateral axis does not impact the ETA. The aircraft type that is used to calculate its trajectory for this approach is a Cessna Citation I, which is the basis of Delft University Aircraft Simulation Model and Analysis Tool (DASMAT). DASMAT's main goal is to assist flight dynamics and control research and it contains the aerodynamic and propulsion characteristics of Cessna Citation I. The basic specifications of this aircraft are mentioned in Table 1.

Table 1 Cessna Citation I specifications

Model Specification	**Value**
Length	13.26 m
Wingspan	14.33 m
Wing Area	24.99 m^2
Empty Weight	3,338 kg
Maximum Takeoff Weight	5,375 kg
Maximum Mach number	0.705
Range	2,460 km

The computational model consists of twelve nonlinear equations of motion, assuming a rigid aircraft with constant mass and a flat non-rotating earth. In addition, it incorporates an atmospheric model and optional capabilities, such as wind and turbulence, and it has already provided a platform to perform similar studies [1, 11, 15]. This simulation tool operates in Simulink®/MATLAB® and can perform both offline and online simulations.
Since DASMAT is a nonlinear model in Simulink®, it is not favorable to use it in performing multiple trajectory calculations needed in a real time application. However, this ability is crucial for a pilot support interface, which is based on future trajectory calculations. Therefore, a point mass model was implemented to structure these calculations [11] and DASMAT was used firstly, as a validation of this model, and then in the subsequent experiment setup. The formulation of this model includes also a wind velocity vector on the longitudinal axis, hence for nonzero wind conditions a deviation between the kinematic flight path angle γ_k and the aerodynamic flight path angle γ_α ($\Delta\gamma = \gamma_k - \gamma_\alpha$) is created.
In Figure 2, the forces acting on the aircraft (Thrust T, Drag D, Lift L, Weight mg), along with the angles and velocities, are depicted, so the equations of motion can be established afterwards. The True Airspeed (TAS) V_α added to wind

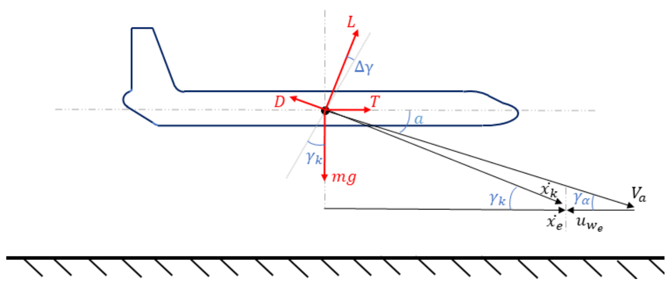


Fig. 2 Force diagram and related velocities/angles

velocity u_{w_e} composes the groundspeed $\dot{x_e}$, which is defined in the North-East-Down reference frame F_e. γ_k is the desired flight path angle of the aircraft during CDA and G/S, while γ_α can be derived from the velocities:

$$\gamma_\alpha = \arccos\left(\frac{\dot{x_e} - u_{w_e}}{V_\alpha}\right) \tag{1}$$

The TAS is calculated as:

$$V_\alpha = \sqrt{(\dot{x_e} - u_{w_e})^2 + (\dot{x_e} tan(\gamma_k))^2} \tag{2}$$

By making a small angle approximation for the angle of attack α, the equations of motion on the longitudinal and vertical axes of the kinematic frame of reference F_k are:

$$Lcos(\Delta\gamma) - mgcos(\gamma_k) + Tsin(\Delta\gamma) - Dsin(\Delta\gamma) = 0 \tag{3}$$

$$-Lsin(\Delta\gamma) + mgsin(\gamma_k) + Tcos(\Delta\gamma) - Dcos(\Delta\gamma) = m\ddot{x_k} \tag{4}$$

For the vertical axis, the components multiplied with $sin(\Delta\gamma)$ can be omitted, so L is easily derived and its coefficient C_L is calculated. Then, on the longitudinal axis, the coefficient of drag C_D is estimated by a second order polynomial, as a function of C_L, whose coefficients depend on the value of C_L and the aircraft configuration [11]. The last component to define in the Equation 4, so it can be solved, is either the value of T or the acceleration $\ddot{x_k}$. In the previous applications of this trajectory calculation [1, 11], only idle thrust was used as input and in this project it is approximated as a percentage of the maximum thrust, which is defined as a function of Mach number and atmospheric pressure. However, the main difference of this project is to create the capability to follow a velocity profile. Therefore, if a velocity profile is imposed, the value of $\dot{x_k}$ is known for the next time step, so $\ddot{x_k}$ can be calculated and used as input to the Equation 4. If the output of this equation, T, is less than the corresponding idle thrust, then the input to the equation switches back to thrust for that particular time step. All of these components, that lead to the general trajectory calculation algorithm, are arranged in a flowchart in Figure 3.
The planning of a CDA, from the IAF in the TMA (H_{IAF}, IAS_{IAF}) up to the FAF close to the landing runway (H_{FAF}, IAS_{FAF}), is based on this general algorithm, and having set the flap/gear schedule, aircraft's mass and wind velocity, three different calculation applications were developed to accommodate its needs. The first application of this algorithm, calculates the maximum ETA from the IAF to the FAF for a given γ_{CDA}. In detail, starting at the IAF, the input to the algorithm is idle thrust, which is kept at that level until the aircraft decelerates to IAS_{FAF}. Then, the input to the

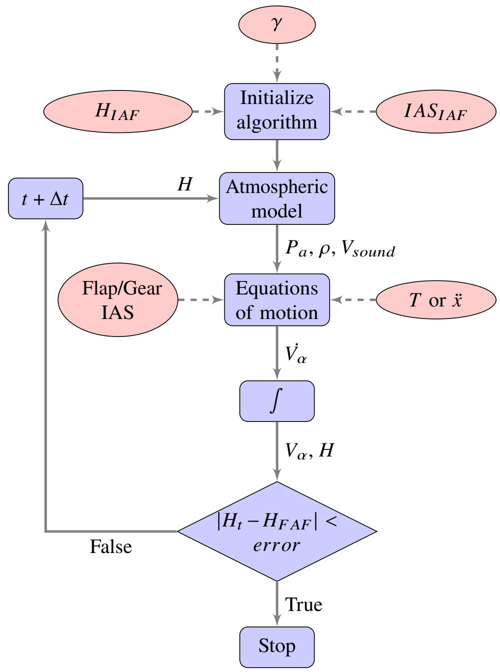


Fig. 3 Trajectory algorithm flowchart

algorithm changes to $\ddot{x}$ and the appropriate value for thrust to maintain the IAS_{FAF} is calculated until the aircraft reaches H_{FAF}.

The second application of this algorithm concerns the calculation of the minimum ETA to reach the FAF from the IAF. In particular, the aircraft begins its descent from IAF, but the input to the algorithm remains the velocity IAS_{IAF}, until the last possible time step to start decelerating. Consequently, the goal of the second algorithm, before calculating the minimum ETA, is to find the time, where the input to the algorithm will have to shift to idle thrust and allow the aircraft to reach H_{FAF} with the desired velocity IAS_{FAF}. A straightforward solution to estimate this time step is to start checking iteratively all possible time steps starting from $t = 1s$ with a step of $\Delta t = 1s$.

However, this can lead to a high computing time, so a calculation logic using the bisection method was developed for this purpose. For the first iteration, the first point to calculate the trajectory is the earliest deceleration T_{min}, hence at $1s$, the third point is the last point for deceleration T_{max}, so an extreme time point can be used (for example the maximum ETA) and the second point is the average of the first and third time points T_{mid}. In this logic, each trajectory is checked whether it provides a valid solution, hence if it reaches H_{FAF} with IAS_{FAF}. The first point will always deliver a valid solution, since it is the earliest deceleration. Then, if the second point also delivers a valid solution, it means that the time step that results to the last possible deceleration is located between the second and third time points and in the next iteration the three calculation points are arranged accordingly. If the second point does not result in a valid solution, that means that the solution is positioned between the first and second points and in the next iteration the calculation points are adapted in the same manner. The logic of each iteration is presented through a flowchart in Figure 4. When the time to start decelerating is found, then the general trajectory algorithm is executed by imposing velocity (IAS_{IAF}) as input until that time step, and then switching to idle thrust and the minimum ETA can be calculated.

The third application of this algorithm is to calculate the IAS profile that will lead to a selected ETA, hence a RTA, which will be between the ETA limits. Since the project's aim is to keep the pilot engaged in this process, the IAS profile is chosen, while considering this fact and limiting its complexity to a stepwise profile representing pilot's commands to the autothrottle. However, the velocity profile, in the form of multiple steps, that leads to the RTA can not be calculated directly in a deterministic way.

By having the boundary conditions and setting the constraints, this application can be shaped as an optimization problem. Since the two aforementioned trajectory calculation cases are programmed in MATLAB®, the built-in non-linear optimization functions of MATLAB® are considered for this problem to facilitate its implementation. The decision variables of this optimization procedure are the values of n intermediate IAS steps, assuming that all steps have equal duration and the first and last steps are IAS_{IAF} and IAS_{FAF} accordingly. To that end, a function is created, that has as

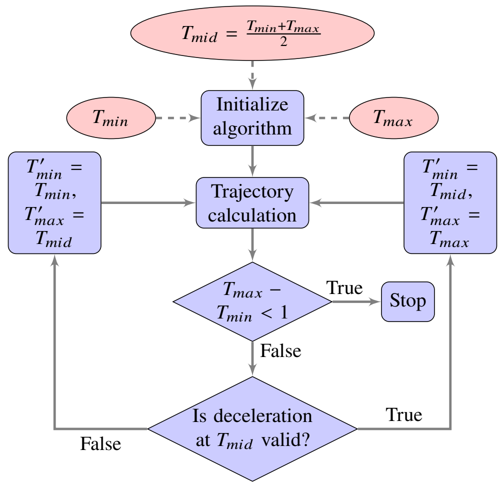


Fig. 4 Minimum ETA calculation flowchart

its main input the IAS values, calculates the trajectory for the selected RTA and its output is the objective function. The two-fold objective function J (Equation 5) has as its first segment the squared difference of H_{FAF} and the altitude at the last time step of the calculated trajectory $H_{t=RTA}$ and the second segment being the inverse of sum of the decision variables.

In detail, apart from the main goal of being time punctual at the specified altitude, it is preferable not to decelerate early to final velocity, in order to be able to compensate for any unforeseeable factors during the approach, such as a wind velocity change. So, the values of design variables are forced to be as high as possible, by using the second segment of the objective function to maximize their value. The two objectives to be minimized, have the same weights in the optimization procedure, since favoring one side or the other did not converge to a different solution.

$$J = \begin{bmatrix} (H_{FAF} - H_{t=RTA})^2 \\ \frac{1}{\sum_{n=1}^{N} IAS_n} \end{bmatrix} \tag{5}$$

The constraints of this optimization can be formulated as inequalities. The main constraint that is imposed is that the calculated velocity values corresponding to each step would not exceed the initial velocity or be less than the final velocity.

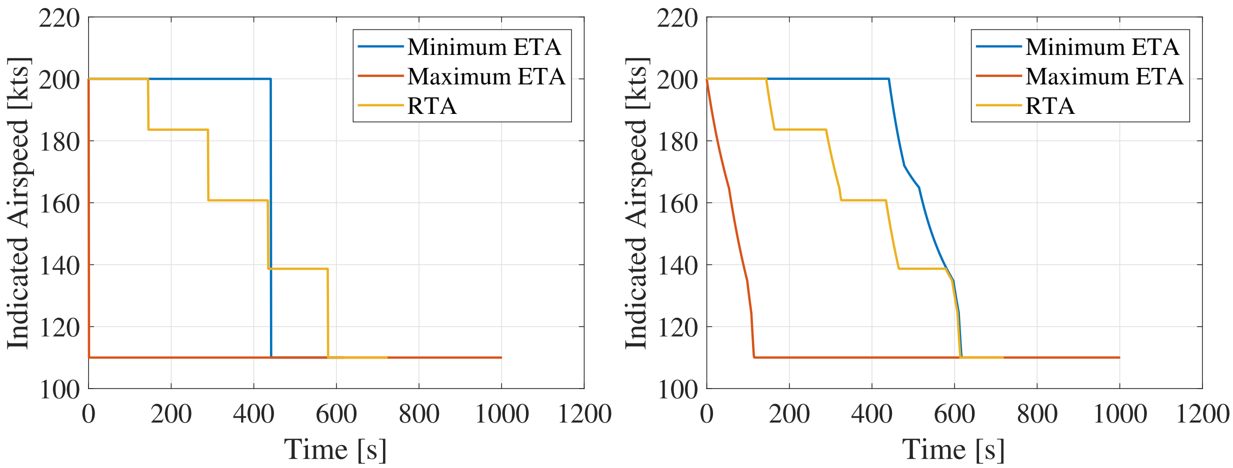
$$IAS_{FAF} \leq IAS_n \leq IAS_{IAF} \tag{6}$$

The results from the three different applications of the trajectory calculation algorithm can be observed, in terms of IAS profiles and the corresponding response from the point mass model. Then, the third application's response (RTA goal) is compared to the response of DASMAT nonlinear model for the same IAS input, with the intention of validating the accuracy provided by the simpler point mass model. The conditions for these simulations are presented in Table 2 and the trajectory of the aircraft is depicted in Figure 1.

By implementing the first and second applications of trajectory calculation, two IAS profiles are defined, as well as the ETA bounds. For the selected conditions, the minimum ETA is 619 s and the maximum ETA is 1,002 s. In this time range, a RTA of 720 s is selected and four IAS steps are used for the optimization algorithm, whose solution indicates that the intermediate IAS steps are 184 kts, 161 kts and 139 kts. The outcomes of the three applications are presented in Figure 5a, which are used as input for the point mass model and the IAS responses are presented in Figure 5b.

Table 2 Simulation conditions

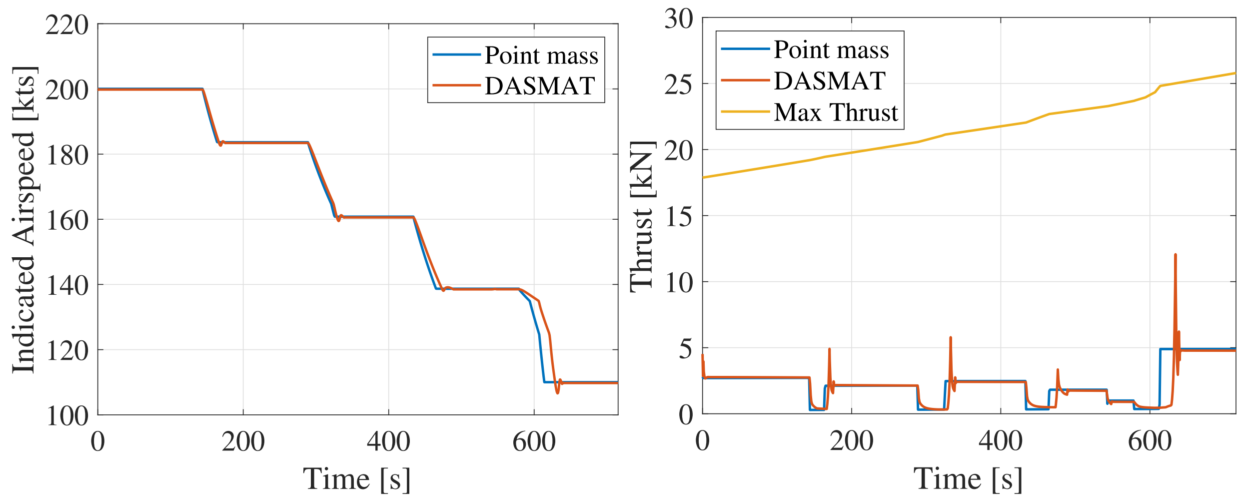
Variable	**Value**
H_{IAF}	8,000 ft
IAS_{IAF}	200 kts
H_{FAF}	100 ft
IAS_{FAF}	110 kts
γ_{CDA}	$-2°$
$\gamma_{G/S}$	$-3°$
H for G/S intercept	2,000 ft
Flaps 15° IAS	165 kts
Flaps 40° IAS	125 kts
Gear Down IAS	135 kts
Mass	4,696 kg
Wind velocity	0 kts



(a) Input IAS profiles **(b) IAS responses**

Fig. 5 Point mass model simulation for minimum/maximum ETA and RTA

The last demonstration of the point mass model is performed against the response of DASMAT model for the stepwise profile in order to achieve the RTA of 720 s. In DASMAT model, a flight path angle hold loop, with an integrated pitch damper, and an airspeed hold loop were implemented, so the desired flight path angle and IAS profile can be tracked. The PID gains of these controllers are constant and were manually tuned by using the linearized symmetric model of the aircraft. For the same input profile of Figure 5a, a deviation of the response of the point mass model from the nonlinear model, is noticeable in the last velocity step in Figure 6a, but it does not have an impact on the overall performance, since the values of ETA differ by 5 s. An additional comparison is performed between the thrust responses of the point mass and DASMAT model, to demonstrate the accuracy of the former model. As it is depicted in Figure 6b, the steady state values of thrust for each IAS step are nearly identical, while DASMAT model, due to its modeling, is able to capture transient phenomena. In addition, the distribution of maximum thrust proves that although this CDA is not entirely performed with idle thrust, as in its principal form, thrust level remains low during the approach.



(a) IAS responses for the two models **(b) Thrust responses for the two models and maximum thrust**

Fig. 6 Comparison of the point mass and DASMAT models

III. Interface Design

The needed interface to support the pilot's mission, is developed by considering which variables can facilitate this task and are not provided by the standard flight instruments. The depiction of this information on a display is based on previously applied concepts [14, 20, 21], which have as a common base the EID, which is suited towards planning and controlling a system [25].

The execution of a CDA with an end time goal requires solid planning and, during its progress, monitoring, so the calculated commands are followed timely and further corrective actions can be taken, if required. Following the principles of EID [23], it was pursued to design an interface, which has integrated the necessary information of the work domain in a way that its constraints are directly perceivable [26, 27]. Therefore, the trajectory analysis of Section II.A is suitable for this goal, since by applying the fundamental kinematic equations [20] and the aircraft's performance data, the higher order variables can be approximated for the operation of the interface.

In particular for this setup, the pilot, when planning the CDA with the IAF and FAF being constant, needs to know the range of feasible CDA flight path angles and then, after choosing one value, the ETA bounds. This logic can be followed also in the reverse order, if the pilot has a RTA to be met from the ATC, then the flight path angles, that can accommodate this requirement, can be estimated. Then, during the execution, a typical procedure is that the pilot uses the autopilot to insert the commands for the target state, and in this case the autothrottle is the function of interest. However, this supervisory role of the pilot requires some additional information to confirm that the CDA is being executed as planned and the RTA goal will be met. This information mainly concerns time performance, hence the ETA for the current state of the aircraft and its deviation from the RTA. This led to developing a new display that provides the necessary time performance information and possible solutions to deal with deviations from the goal.

A. Main display type

The basic display type to incorporate in the interface is the Vertical Situation Display (VSD), which has been adopted in similar projects of CDA planning and execution and here it is used in presenting an example CDA trajectory in Figure 1. Some of the initial studies concerning VSD [28, 29] focused on the situation awareness of the pilots for the vertical axis and provided a better grasp of the operation of automation. In these projects, the VSD was integrated on the lower part of the Navigation Display screen, which provides guidance in the horizontal plane. Then, VSD's use was expanded [30] to offer terrain avoidance capabilities and display the space for potential maneuvers. Recently, the VSD was adopted with a visualization feature concerning the flight envelope and the changes of the envelope caused by the deployment of flaps and gear [21]. Therefore, VSD has demonstrated its agility and can contribute to structure a pilot support interface to be utilized for CDA planning and execution.

In the subsequent step of this project, this interface was tested in an experiment to evaluate its effectiveness to achieve the RTA goal. Therefore, the VSD was not developed as an independent entity, but as a part of a complete experimental platform in MATLAB®/Simulink®, having as a base the DASMAT model. Taking into account that during a simulation, the pilot has to interact with the interface, in terms of planning the CDA, as well as to execute the IAS/flaps/gear commands and monitor the performance in parallel, led to splitting the pilot support interface into two sections. The basic layout of the VSD is used as a concept to be augmented in both sections, which are notably the CDA Graphical User Interface (GUI) and the CDA monitoring display. The VSD of the GUI presents the possible combinations of flight path angle and ETA, while during the flight simulation it assists the interaction with the pilot and the CDA monitoring display provides real time information about the current position of the aircraft, the future trajectory and the space of possibilities, regarding the ETA.

B. CDA Graphical User Interface (GUI)

In App Designer of MATLAB®, a GUI was structured gradually, starting from the need to plan the CDA for the given conditions, by presenting the possible solutions to the pilot during this process. Afterwards, the next goal of executing a simulation of a CDA, by using the DASMAT model, led to creating an accompanying platform to provide the interaction between this model and the pilot, thus inserting the IAS/flaps/gear commands during the flight.

The GUI is divided into three control areas, following the logic of the simulation, as presented in Figure 7. At first, for a constant flap/gear schedule, IAF and FAF, on the left area of the GUI, the pilot selects the aircraft's mass and the wind velocity, so the feasible range of the CDA flight path angle is calculated and presented in the light green region of the VSD bounded by the dark green lines. Then, the pilot selects the desired flight path angle, which is highlighted with a magenta line on the VSD and the range of the ETA is given in the corresponding slider, by using the minimum and maximum ETA calculation algorithms. The last step to fully define the approach plan is to choose the ETA, hence an RTA, and the number of IAS steps. Then, the optimization algorithm calculates the IAS commands and their position on the trajectory is indicated on the VSD. They are presented with vertical lines on the VSD [14, 20] with their labels being above the plot.

When the CDA is fully defined, the pilot initiates the simulation from the GUI and, by tracking in real time the CDA monitoring display, can enter, in the lower centre section of the CDA GUI, the IAS/flaps/gear commands. If, during the simulation, there is a deviation of the calculated ETA from the RTA, the pilot may opt to re-plan the rest of the approach, for the same flight path angle, on the right control area of the CDA GUI, thus a new ETA and number of IAS steps can be defined.

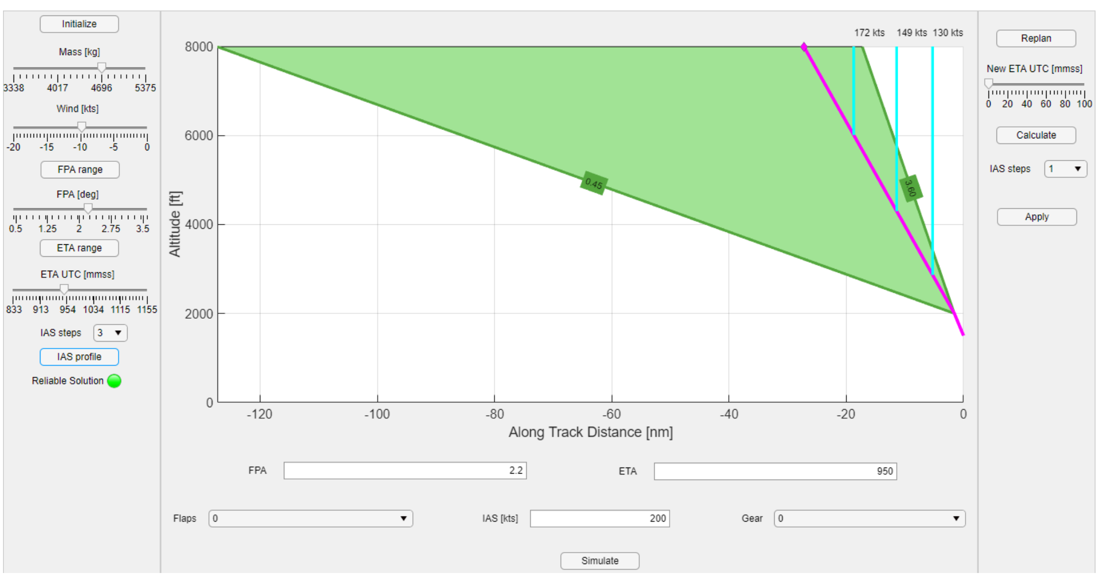


Fig. 7 Example CDA GUI

C. CDA monitoring display

During the simulation, the pilot's main focus is to use the designed VSD, which is continuously updated with the background calculations, and achieve the RTA goal. The aim of these calculations is not only to provide a new ETA, using the aircraft's current position and the IAS profile, but also to support the ecological aspect of the interface. This functionality concerns the depiction of the system's bounds and the affordances [27], namely the ETA limits, the RTA and the effect on the ETA of changing the timing of the IAS commands.

In Figure 8, a screenshot of the VSD is presented, following the CDA plan of Figure 7. The aircraft position is represented with a magenta triangle on the upper left corner of the display and stays fixed at that position, so the scale of the axes of altitude and Along Track Distance (ATD) are updated, as the flight simulation is executed. The IAS commands are displayed in the same way as in the CDA GUI, and move towards the aircraft symbol (triangle) during the simulation. A main characteristic of this VSD is the right panel, which is independent from the trajectory plot [21], and concerns the space of possibilities regarding the time performance. The upper and lower limits of the axis, are the maximum and minimum ETA accordingly, and they are updated using the current state of the aircraft. The ETA, based on the future IAS commands and the state of the aircraft, is depicted with a magenta circle on the axis, which has been suggested as an important cue for this type of mission [14]. Finally, the RTA, as defined during the CDA planning, is represented with a green circle of larger diameter and around this value an error bar of ±30s was placed.

Therefore, the first augmentation of the basic VSD concept with the adoption of EID, is the presentation of the space of possibilities for the ETA for the aircraft's current state. The subsequent augmentation of the VSD concerns supporting the pilot's cognition, in case of a deviation from the RTA. Since the flap/gear schedule and the values of the IAS commands are constant, then a considered degree of freedom is modifying the nominal timing of the next IAS command and observing the result of this action on the ETA cue. Thus, the development of mental model for the pilot for this strategy requires the creation of cues that correlate the magnitude of the deviation from the nominal IAS schedule, with the effect on the ETA.

In detail, the background calculations estimate for the upcoming IAS command, the position of the cues that will result to a ±15 s and ±30 s change on the ETA. This is achieved by structuring a loop and starting to reposition, in terms of time, the next IAS command from the nominal time step, so when the desired values of ±15 s and ±30 s are achieved, the loop is terminated. These cues move towards the magenta triangle, along with the initial IAS commands, and the pilot decides either to enter the new IAS to the autothrottle at the nominal time or to change the timing of this command, if the ETA needs adjustment. In parallel, above the aircraft symbol, a text cue will appear, in order to alert the pilot when the aircraft's velocity is close to deploying flaps/gear. As mentioned in Section III.B, if the pilot cannot reduce a possible time deviation with the assistance of the cues on the trajectory line, then there is the possibility to re-plan the remaining approach in the CDA GUI by taking into account a potentially updated wind velocity and the new plan is transferred to the CDA monitoring display.

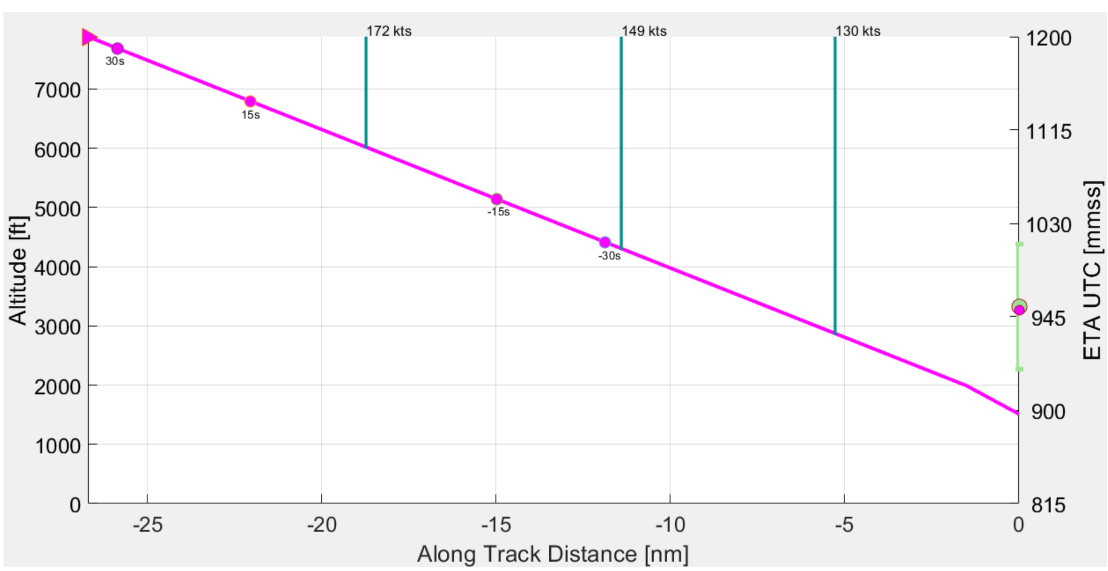


Fig. 8 Example CDA monitoring display

IV. Experiment Design

An experimental plan was created to get feedback from pilots, regarding the usability of the support interface and evaluate the accuracy with which they could achieve the RTA goal with the means they are given.

A. Participants

The five Participants of the experiment had licences for different aircraft types, such as Boeing 737, Boeing 777/787, Fokker 70/100 and Cessna Citation II. An ethics approval was granted by the Human Research Ethics Committee of Delft University of Technology. A within-participants experiment design was selected, given the small number of Participants, and the trials had the same order for everyone.

B. Independent Variables

The chosen independent variable was the wind velocity profile used in each trial. During the CDA planning, the Participant was given for each trial a specific wind velocity to use in the GUI and calculate the IAS profile. Then, during the simulation, this wind velocity was either staying constant, hence allowing the Participant to easily achieve the goal, or a deviation from the initial wind velocity started being imposed at 20% of the total ATD and reached the final value at 30%. In this way, the ETA cue diverged from the RTA cue, and the Participant was forced to use the cues on the VSD to modify the timing of the IAS commands or, as a last resort, to re-plan the approach with the updated wind velocity. The four wind velocity scenarios that were applied in the main experiment are (the negative values correspond to headwind):

- Scenario 1: Initial -5 kts, Final -5 kts
- Scenario 2: Initial -15 kts, Final -10 kts
- Scenario 3: Initial -10 kts, Final 0 kts
- Scenario 4: Initial 0 kts, Final -15 kts

C. Apparatus

The experiment was conducted in the ATM lab at Delft University of Technology. A dual display setup was used at a conventional desktop computer to accommodate the two sections of the pilot support interface, within MATLAB®/Simulink®. In the right screen an altimeter and an airspeed indicator complemented the CDA monitoring display during the simulation, whereas the left screen included the CDA GUI. The aircraft model of the simulation was the same as in the Section II, Cessna Citation I.

D. Procedure & Scenarios

The experiment started with a detailed walk-through of the first training trial. The experiment included five training runs, where for a given aircraft's mass and wind velocity, the Participant had the freedom to select the flight path angle, the RTA and the number of IAS steps, from a provided range. Then, after sufficient proficiency had been attained by the subject, the four experiment trials took place.

Both training and experiment trials included a range of wind velocity (headwind) from 0 to 15 kts, and in particular for the wind velocity deviation, the deviation from the initial velocity was different for each scenario. In this way, the divergence of the ETA from the RTA did not have the same magnitude for each of these scenarios. The experimental conditions were identical as in Table 2, apart from the wind velocity that varied depending on the scenario and the FAF, which was at 1,500 ft with IAS 130 kts. In the main experimental conditions, the RTA was 600 s, as an intermediate duration that can accommodate different combinations of flight path angle and velocity steps for the chosen IAF and FAF, and the Participants needed to be at the FAF as close as possible to the time goal, ideally within the ± 30 s error interval.

E. Dependent Measures

All the variables associated with aircraft performance, such as altitude, IAS and time, to determine the Actual Time of Arrival (ATA), were recorded, as well as the Participant's inputs during the simulation. In addition, before beginning the experimental trials the Participant was asked to declare any experiences regarding flying a CDA and using a VSD in a flight deck, by completing a questionnaire. After each trial, the questionnaire followed by asking the Participant which cues and functionalities were found to be helpful during the simulation, if a re-plan was performed and how the Participant would rate his/her mental load with the Rating Scale Mental Effort (RSME) (Range: $0 - 150$) [31].

At the end of the experiment, further open questions were addressed to the , regarding the CDA GUI usability, the comprehension of the cues of the VSD and further comments/suggestions for the interface.

F. Hypotheses

It is hypothesized that by using the support interface, Participants will not deviate more than 30 s from the RTA goal in all the scenarios. Moreover, if there is a deviation from the initial wind velocity and the Participant does not re-plan the approach, the mental load will be higher than the cases, where a re-plan does not take place. Finally, the case where there is no wind deviation, the mental load will be the lowest.

V. Results & Discussion

The results of this experiment come from the flight performance data, which are indicative of the pilots' strategies to meet the end time goal, and from the questionnaire they were asked to fill before the experiment, after each trial and at the end of the experiment. Although the number of participants is not sufficient to perform a formal analysis, these initial results offer an insight of a potential application of this interface in the flight deck.

A. Flight performance analysis

In the initial overview of the flight performance results, two trials out of the twenty executed (five participants with four scenarios) are not considered successful, since at the termination of the simulation they were not below $2,000$ ft with IAS of 130 kts. The first variable that is examined is the ATA that was achieved for each scenario. The time performance of the trials is presented in Table 3. As mentioned in Section IV.D, the approach was planned for an RTA of 600 s, but the trials could terminate between $2,000$ ft and $1,500$ ft, so it should be taken into account that all the pilots were expected to be approximately 20 s earlier than the RTA. During the analysis of each pilot's IAS commands, it

Table 3 ETA [s] deviation for each scenario and Participant

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Participant 1	-30	-12	-	-12
Participant 2	-10	-12	-10	-11
Participant 3	-24	-9	-27	-18
Participant 4	-30	-30	-30	-24
Participant 5	-33	-	-36	-18

was noted that they did not use the re-plan function, except from one of the two trials, which have already been excluded. Three out of five pilots opted to skip an intermediate IAS command in order to delay their deceleration and compensate for a time deviation. In addition, one pilot used IAS commands between the nominal values. These strategies are not preferable, although it was not mentioned explicitly in the briefing document. For example, in the first scenario, since there was no wind velocity perturbation, the pilots did not deviate significantly from the nominal IAS profile, as it is demonstrated in Figure 9. On the other hand, for the scenario 4, where there was the highest wind deviation from 0 kts to -15 kts, only Participant 2 used the second IAS command, while Participant 4 decelerated directly to the final IAS. Moreover, in Figure 10, it is demonstrated that all pilots delayed the first deceleration to compensate for the increased headwind, which caused the ETA to increase. For the second scenario of Figure 11, Participants 2 and 4 had a uniform performance with similar deviations from the nominal IAS profile, while Participant 1 followed the same strategy, except from the last deceleration, which was executed earlier than the other participants. In addition, it is noted that Participant 3 skipped the third deceleration to 158 kts and selected the final IAS. In the third scenario, Participant 3 decelerated directly to a velocity close to the third IAS command of 162 kts and then to 130 kts. Participants 2 and 5 had a similar IAS response, as it is presented in Figure 12, while Participant 4 seemed to have a slightly different approach to this case.

B. Questionnaire analysis

In the initial part of the questionnaire, the pilots were asked to provide their past experience with flying a CDA and also if they have used a VSD. All of them had performed a CDA, either for commercial flights with Boeing 737/787 or

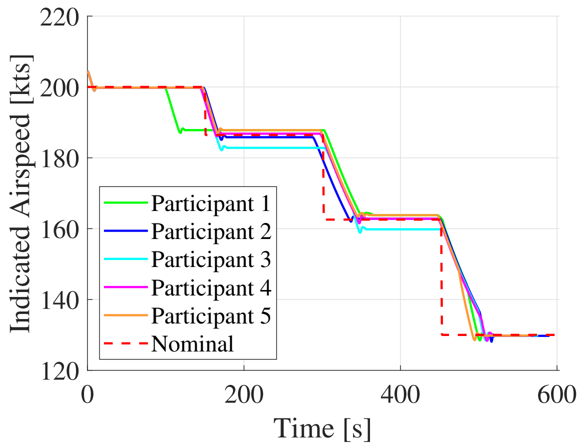


Fig. 9 Nominal IAS profile and corresponding aircraft response for scenario 1

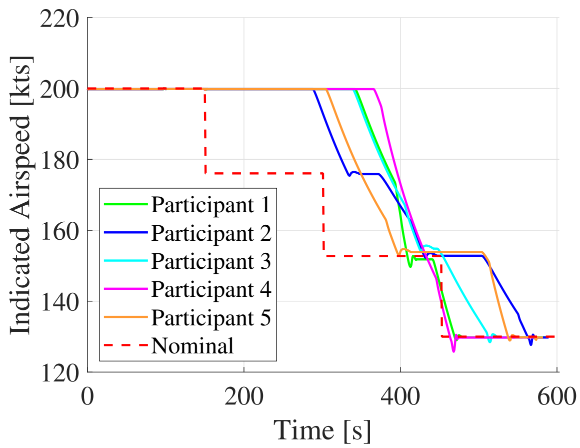


Fig. 10 Nominal IAS profile and corresponding aircraft response for scenario 4

during past experimental projects and they mentioned that CDA is becoming standard, but it takes place in non-peak traffic hours, without a strict RTA. In addition, one pilot suggested that each approach is aimed to be a CDA, but the ATC may eventually ask the flight crew to deviate from the optimal flight path. Regarding the VSD, one pilot had not used it in the past, while the others mainly interacted with this type of display in previous experiments for terrain and weather depiction. In addition, this display has been installed in some Boeing 737 aircraft, but it has found limited use, and in Boeing 787 for the full flight envelope visualization to assist correcting flight path deviations.

After each trial, the pilots were asked some closed questions regarding their performance and strategy during the simulation. In sixteen out of the eighteen valid trials, the pilots declared that they used the cues on the trajectory line for the early/delayed deceleration and a re-plan of the remaining trajectory was not preferred. When questioned regarding the cues that proved to be more useful to achieve the RTA goal, the pilots indicated the information presented of the right panel (RTA and errorbar, ETA) and the cues on the trajectory line. Finally, the pilots were presented with the RSME scale and they provided an overall mental load rating for the past trial, as it is presented in Figure 13.

After all the trials, the pilots filled some closed and open questions regarding the overall experience interacting with the two sections of the pilot support interface. It was indicated by their feedback in the closed questions, that they strongly believe in the usage of the time cues on the right panel, while for the cues for IAS and the early/delayed deceleration are also somewhat helpful to achieve the time goal. In addition, it was declared that the CDA planning application gave a moderately good overview of the solution space depicting the flight path angle and the ETA.

Regarding the open questions, at first the pilots were inquired about the CDA GUI and how it can be improved. A pilot suggested that rounded values of IAS could be more easy to use. Furthermore, it was suggested that the selection of the flight path angle should be done for discrete values (i.e. $-2°$, $-2.2°$, $-2.4°$) for the convenience of the pilot and ATC and

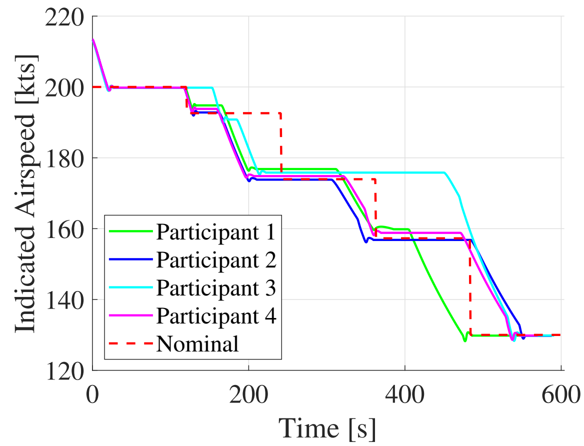


Fig. 11 Nominal IAS profile and corresponding aircraft response for scenario 2

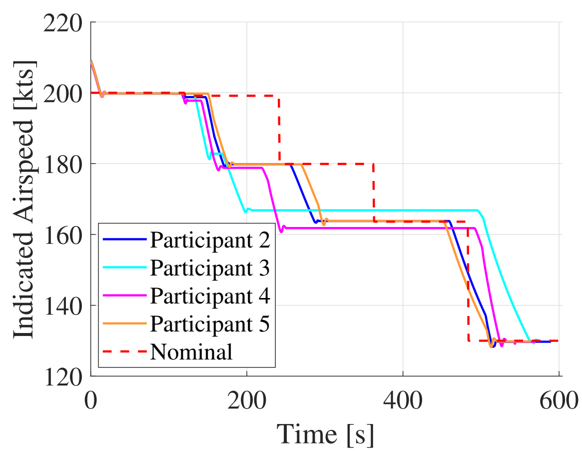


Fig. 12 Nominal IAS profile and corresponding aircraft response for scenario 3

the number of IAS steps should be limited to a maximum of three to avoid excess workload. An additional proposal, was to create a wind velocity profile depending on the altitude and not assume a constant wind velocity for the full approach. The last open questions focused on the CDA monitoring display, as the most complicated object of the experiment and which elements of it were not used or needed to be altered. It was mentioned that the flap/gear text cue was easy to be missed and the errorbar around the RTA may have been superfluous. In addition, on the time axis, the ETA value and its deviation from the RTA could be also printed as numerical values and the majority of the pilots proposed that it is more convenient to have a fixed time scale and not continuously adapt the axis limits and scale. Moreover, it was noticed that as soon as the next IAS command reached the aircraft triangle symbol, its cues for a delayed deceleration would disappear, so that the calculations for the upcoming command can take place and be presented, but this proved not to be convenient. On this topic, it was also recommended that a single cue on the trajectory line, which will minimize the time deviation, can be depicted to avoid confusion and show a trend arrow on the ETA cue to demonstrate the immediate effect of a pilot's IAS command. In terms of general presentation of the trajectory, it was recommended to have the flexibility to zoom in/out on the ATD axis and it was proposed to investigate if the VSD is definitely needed for this mission, or the cues can be incorporated in the existing conventional displays of flight deck.

C. Discussion

The main goal of each simulation, being in FAF at the RTA, is achieved in accordance with the hypotheses, as it is demonstrated in Table 3, since an ATA of 600 − 20 = 580 s is expected. The earlier termination of the simulation is attributed to the fact that the trajectory calculation algorithms, may not converge to the desired final state when the

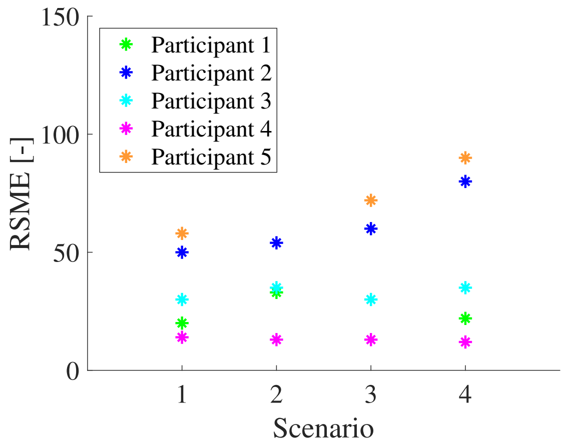


Fig. 13 RSME for each scenario and Participant

aircraft is very close to the calculation stopping point (1, 500 ft) and the simulation will terminate between 2, 000 ft and 1, 500 ft. Although at that point in flight, the future trajectory and the ETA bounds will be of limited use, a potential solution could be a higher time discretization for this segment of flight or stop updating the VSD in the last $1 - 2$ nm.
Regarding the performance of the pilots, as depicted by the aircraft's IAS response, it is concluded that apart from the alterations of the nominal IAS values, the pilots had, in general, similar strategies in the experimental scenarios. Moreover, if Table 3 is correlated with the IAS responses, then it is noted that two pilots may follow the same strategy in a scenario, but they can have a different ATA, due to the fact that their corresponding simulations ended at different flight levels, within the $1,500 - 2,000$ ft interval.
One of the aims of the experiment was to use the calculated IAS commands and manipulate their execution timing if needed, but not to change the number or the values of these steps or skip a command, as mentioned in Section V.A. In addition to this practice that was observed in three pilots, nearly all the pilots asked whether their usual practice of slightly adapting the flap/gear schedule in the pursue of managing the deceleration can be applied in this experiment, but also this tactic was contradictory with the main assumptions of the project.
The CDA, as it is becoming more common in commercial flights, according to pilots' supportive feedback, demonstrates again that there is a need of executing this approach in a timely manner. While the VSD is not yet widely incorporated in flight decks, the pilots seemed to be a bit skeptical about its use and insist on fully defining its role in the flight procedures. During the simulation, the pilots proved that they can work with the augmented VSD and by adopting their experience and the logic of the IAS and time cues, were able to fulfill their role. In the end of each trial, the usage of the RSME, as a subjective indicator, resulted in a wide range of scores for the same scenario as it is presented in Figure 13, proving that each pilot has a different perception and thresholds regarding the mental effort and the workload in general. Participants 2 and 5 had an increasing trend of their workload as the scenarios proceeded, since the deviation from the initial wind velocity was increasing and it could pose additional difficulties to manipulate the ETA.
During the simulation, the pilots experienced the interaction with this novel display and in combination with their past commercial and research flying experience, provided remarks and suggestions. As it is mentioned in Section V.B, the time axis has an important role in meeting the RTA goal, but it needs improvements in terms of its cues, their exact position and the scaling of the axis. A first solution could be to have a constant time scale and create minimum/maximum ETA cues able to move, as the ETA cue. Moreover, it was recommended that the flap/gear cues should be more discernible and for instance they can be presented on the PFD [12]. In addition, the cues on the trajectory line, regarding the effect of a time shift of deceleration, should be reconsidered, so a cue leading to the optimum solution can be presented along with the existing ones or provide a shorter solution space for the time shift of each of the IAS commands, not just for the next one. Therefore, as the next step for this project could be the adaptation of the pilot support interface in a regular flight deck setup, the distribution of more cues in the standard flight deck displays can be performed. In addition, this implementation has to accommodate both segments of the pilot support interface (planning and execution) and, as suggested by a pilot, if the VSD concept is maintained, it should be aimed to fit it on the Navigation Display.

VI. Conclusion

In this project, the concept of executing a CDA with an end time goal was facilitated, by creating and adopting a pilot support interface. While keeping the flap/gear schedule and the flight path angle constant, further possibilities were investigated to define the solution space for the ETA and the IAS commands that lead to a RTA. This trajectory was analyzed through its simplified equations of motion, which proved their accuracy, in terms of the ETA, and created the basis to structure the pilot support interface.

Having the trajectory calculation algorithms and the logic of the VSD elements as a starting point, this pilot support interface can have its two segments combined in the next phase of development. This can be implemented by considering the current avionics capabilities in the flight deck and possible extensions of their operation. In addition, the already encountered trajectory calculation limitations and assumptions can be addressed, in order to ameliorate the robustness of the interface and ensure its reliability. In addition, the optimization procedure, that took place during the planning phase of the CDA to define the IAS profile, can be further developed, so it can be executed during the simulation and its outputs will correspond to the current state of the aircraft and the external conditions. A higher level of interaction between the pilot and the display, during planning and execution, can be considered and alternative forms of velocity profiles for the selected RTA can be evaluated, for instance to have a different time duration of each IAS step. Then, the suggestions from the pilots' side and improvements of the underlying algorithms can be incorporated to the interface, so it can be installed into the flight deck and perform a full scale flight simulation experiment. Therefore, the participating pilots will be in a familiar setup and more accurate metrics will be extracted, in terms of their performance and experience.

References

[1] In 't Veld, A. C., van Paassen, M. M., Mulder, M., and Clarke, J. P., "Pilot Support for Separation Assurance During Decelerated Approaches," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA, 2004. https://doi.org/10.2514/6.2004-5102.

[2] Avery, D., "The Evolution of Flight Management Systems," *IEEE Software*, Vol. 28, No. 1, 2011, pp. 11–13. https://doi.org/10.1109/MS.2011.17.

[3] Erkelens, L. J. J., "Research on noise abatement procedures," Tech. Rep. NLR TP 98066, NLR, February 1998. URL https://core.ac.uk/download/pdf/80112015.pdf.

[4] EUROCONTROL, "CDA: Implementation Guidance Information," Tech. rep., May 2008. URL https://skybrary.aero/bookshelf/books/2846.pdf.

[5] NLR, AENA, AIRBUS, EUROCONTROL, ISDEFE, INECO, and SICTA, "Study of Optimisation Procedures for Decreasing the Impact of Noise II (SOURDINE)," Tech. rep., European Community, August 2006. URL https://trimis.ec.europa.eu/sites/default/files/project/documents/20100310_134424_75167_Sourdine%20II%20Final%20Report.pdf.

[6] Wubben, F. J. M., and Busink, J. J., "Environmental Benefits of Continuous Descent Approaches at Schiphol Airport Compared with Conventional Approach Procedures," Tech. rep., National Aerospace Laboratory NLR, May 2000. URL http://hdl.handle.net/10921/840.

[7] Janssen, J., "Capacity-based Arrival Sequencing and Trajectory Optimization for Continuous Descent Operations," Master's thesis, TU Delft, Faculty of Aerospace Engineering, The Netherlands, December 2019. URL https://repository.tudelft.nl/islandora/object/uuid%3Af483be8e-522b-473c-8e83-08cd514915f7.

[8] Ellerbroek, J., Inaad, M., and Hoekstra, J., "Fuel and Emission Benefits for Continuous Descent Approaches at Schiphol," *International Conference on Research in Air Transportation 2018*, ICRAT, 2018. URL https://repository.tudelft.nl/islandora/object/uuid:85153290-ac20-4005-8901-60d3861a8c75/datastream/OBJ/download.

[9] Clarke, J. P., Ho, N. T., Ren, L., Brown, J. A., Elmer, K. R., Tong, K., and Wat, J. K., "Continuous Descent Approach: Design and Flight Test for Louisville International Airport," *Journal of Aircraft*, Vol. 41, No. 5, 2004, pp. 1054–1066. https://doi.org/10.2514/1.5572.

[10] Gerber, M., Wunderli, J. M., and Abdelmoula, F., "LNAS Pilot Assistance System Enables Quieter and More Fuel-Efficient Landing Approaches," Tech. rep., German Aerospace Center DLR, Swiss SkyLab Foundation, Swiss Federal Laboratories for Materials Science and Technology (Empa), June 2020. URL https://www.dlr.de/content/en/articles/news/2020/02/20200622_test-flights-in-zurich-with-the-dlr-a320-atra-research-aircraft.html.

[11] De Prins, J. L., Schippers, K. F. M., Mulder, M., van Paassen, M. M., In 't Veld, A. C., and Clarke, J. P., "Enhanced Self-Spacing Algorithm for Three-Degree Decelerating Approaches," *Journal of Guidance, Control, and Dynamics*, Vol. 30, No. 2, 2007, pp. 576–590. https://doi.org/10.2514/1.24542.

[12] Schippers, K. F. M., De Prins, J. L., Mulder, M., van Paassen, M. M., In 't Veld, A. C., and Clarke, J. P., "Investigation of a Three-Degree Decelerating Approach of a Twin-Engined Jet Aircraft under Actual Flight Conditions," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA, 2005. https://doi.org/10.2514/6.2005-6139.

[13] In 't Veld, A. C., Mulder, M., van Paassen, M. M., and Clarke, J. P., "Pilot Support Interface for Three-Degree Decelerating Approach Procedures," *The International Journal of Aviation Psychology*, Vol. 19, 2009, pp. 287–308. https://doi.org/10.1080/10508410902983938.

[14] Sopjes, R., de Jong, P. M. A., Borst, C., van Paassen, M. M., and Mulder, M., "Continuous Descent Approaches with Variable Flight-Path Angles under Time Constraints," *AIAA Guidance, Navigation, and Control Conference 2011*, AIAA, 2011. https://doi.org/10.2514/6.2011-6219.

[15] Gernaey, J., "Creating Energy Awareness in Noise Abatement Procedures, An Ecological Interface Design," Master's thesis, TU Delft, Faculty of Aerospace Engineering, The Netherlands, December 2005.

[16] Erkelens, L. J. J., "Research Into New Noise Abatement Procedures for the 21st Century," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA, 2000. https://doi.org/10.2514/6.2000-4474.

[17] Ruigrok, R. C. J., and Korn, B., "Combining 4D and ASAS for Efficient TMA Operations," *AIAA Aviation Technology, Integration and Operations Conference*, AIAA, 2007. https://doi.org/10.2514/6.2007-7745.

[18] Mulder, M., Borst, B., and van Paassen, M. M., "Designing for Situation Awareness - Aviation Perspective," *Proceedings of the International Conference on Computer-Human Interaction Research and Applications - Volume 1: CHIRA*, INSTICC, SciTePress, 2017, pp. 9–21. https://doi.org/10.5220/0006796500000000.

[19] de Beer, B. A. F., Mulder, M., van Paassen, M. M., and In 't Veld, A. C., "Development of an Ecological Interface for the Three Degree Decelerating Approach," *AIAA Guidance, Navigation and Control Conference and Exhibit*, AIAA, 2008. https://doi.org/10.2514/6.2008-7158.

[20] Marwijk, B., Borst, C., Mulder, M., Mulder, M., and van Paassen, M. M., "Supporting 4D Trajectory Revisions on the Flight Deck: Design of a Human–Machine Interface," *The International Journal of Aviation Psychology*, Vol. 21, 2011, pp. 35–61. https://doi.org/10.1080/10508414.2011.537559.

[21] van Geel, A., Borst, C., van Paassen, M. M., and Mulder, M., "Design and Evaluation of Vertical Situation Display Reflecting Configuration Changes," *AIAA Scitech 2020 Forum*, 2020. https://doi.org/10.2514/6.2020-1084.

[22] Rasmussen, J., and Vicente, K. J., "Coping with human errors through system design: implications for ecological interface design," *International Journal of Man-Machine Studies*, Vol. 31, No. 5, 1989, pp. 517 – 534. https://doi.org/10.1016/0020-7373(89)90014-X.

[23] Vicente, K. J., and Rasmussen, J., "Ecological interface design: theoretical foundations," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 22, No. 4, 1992, pp. 589–606. https://doi.org/10.1109/21.156574.

[24] Westerlaken, M., in 't Veld, A. C., Mulder, M., van Paassen, M. M., and de Leege, A. M. P., *Conceptual Development of the Free-Degree Decelerating Approach*, 2009. https://doi.org/10.2514/6.2009-5796.

[25] van Paassen, M. M., Borst, C., Ellerbroek, J., Mulder, M., and Flach, J. M., "Ecological Interface Design for Vehicle Locomotion Control," *IEEE Transactions on Human-Machine Systems*, Vol. 48, No. 5, 2018, pp. 541–555. https://doi.org/10.1109/THMS.2018.2860601.

[26] Borst, C., Mulder, M., Mulder, M., and van Paassen, M. M., "A Review of Cognitive Systems Engineering in Aviation," *11th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human-Machine Systems*, 2010, pp. 221 – 226. https://doi.org/10.3182/20100831-4-FR-2021.00040.

[27] Abeloos, A., Mulder, M., and van Paassen, M. M., "An introduction in the ecology of spatio-temporal affordances in airspace," *Conference on human decision making and control, Glasgow*, 2002. URL http://resolver.tudelft.nl/uuid:188b60e8-8aea-4798-9ecc-cb2773090aec.

[28] Prevot, T., "A Display for Managing the Vertical Flight Path - an Appropriate Task with Inappropriate Feedback -," *HCI-Aero '98 – International Conference on Human-Computer Interaction in Aeronautics*, 1998. URL https://human-factors.arc.nasa.gov/publications/Prevot-98-Vertical-Situation-Display-HCI-Aero98.pdf.

[29] Prevot, T., and Palmer, E., "Staying Ahead of the Automation: A Vertical Situation Display Can Help," *2000 World Aviation Conference*, 2000. https://doi.org/10.2514/6.2000-5614.

[30] Suijkerbuijk, M., Borst, C., Mulder, M., and van Paassen, M. M., "Development and Experimental Evaluation of a Performance Based Vertical Situation Display," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA, 2005. https://doi.org/10.2514/6.2005-5961.

[31] Zijlstra, F. R. H., "Efficiency in work behaviour, A design approach for modern tools," Ph.D. thesis, TU Delft, Faculty of Industrial Design Engineering, The Netherlands, November 1993. URL https://repository.tudelft.nl/islandora/object/uuid%3Ad97a028b-c3dc-4930-b2ab-a7877993a17f.