VALIDATION OF LOW NOISE PROCEDURES IN SIMULATOR AND FLIGHT TESTS

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ABSTRACT

One option to reduce noise levels in airport vicinity is to increase the distance between aircraft and populated areas by flying a steeper flight path during departure and approach. This can be achieved by new noise abatement procedures (NAPs) as they have been developed in the European AWIATOR project.

All NAPs are continuous descent approach procedures (CDA), which are designed for an Airbus A340 in standard configuration and for an Airbus A340 with adaptive elements “Mini Trailing Edge Devices, (Mini TED)” that can be extended to allow steeper descents. Flight simulations of new NAPs were performed on an Airbus A340 Level D Full Flight Simulator to measure pilot workload, flight performance, pilot acceptance, operational feasibility, safety, economics and passenger comfort.

This paper describes how the flight simulations were prepared and conducted and how the simulator test results were analysed and compared with flight tests. The work was part of the European AWIATOR program.

ABBREVIATIONS

AGL	above ground level
ALT	altitude
A/P	auto pilot
A/THR	auto thrust
AW	AWIATOR devices in use
CAS	calibrated airspeed
CDA	continuous descent approach
CDB	common data base
CONFIG	flaps / slats position
FPA	flight path angle
G/S	glide slope
ILS	instrument landing system
N1	engine rotor speed
NAP	noise abatement approach procedure
ND	navigation display
PFD	primary flight display
SP6	spoiler 6
TED	AWIATOR mini trailing edge devices
TLX	NASA task load index
TUB	Technical University of Berlin
UW	head- / tailwind

1 INTRODUCTION

International noise regulations are becoming more stringent due to increasing public complaints on noise around airports. To reduce noise levels in airport vicinity, two options exist: (i) to reduce aircraft source noise that comes from engines and aerodynamic surfaces, (ii) to increase the distance between aircraft and populated areas, which can be achieved by steeper flight paths during departure and approach.

Steeper climbs and descents can be supported by the additional aerodynamic devices that are developed and tested in the European AWIATOR project. AWIATOR (Aircraft Wing with Advanced Technology Operation) is an European Commission (EC) co-financed project of the 5th Framework Program. The aim of the project is proof of concept and in-flight validation of mature wing technologies for future transport aircraft application. It started in July 2002 and was successfully terminated in June 2007. This paper describes the work that was performed by TU Berlin in the work package “Low Noise Assessment and Operations”.

The work package aimed at defining and validating suitable NAPs for landing by flight simulations. An Airbus A340 Level-D full flight simulator was modified for this study to include the additional control devices that were developed in AWIATOR.

The Mini TEDs were selected as promising for the NAPs. The other devices that were developed in AWIATOR (large winglets, sub boundary layer vortex generators and wake vortex devices) were not used, as their potential for noise abatement is low.

Mini TEDs are small devices that can be deflected at the lower side of the wing trailing edge flap. FIG 1 and FIG 2 show how they are mounted at an Airbus A340 wing. The maximum Mini TED deflection is 60 deg. To further increase drag for steep descents, spoiler 6 is extended to 20 deg in addition.

To supplement the Airbus A340 simulator software with aerodynamics of the control devices, aerodynamic data from wind tunnel tests were used. Furthermore, various features were developed to monitor, document and

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analyse the flight simulation results.

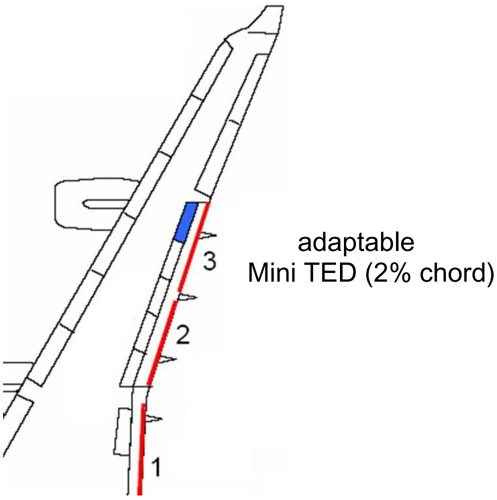

FIG 1. AWIATOR specific devices Mini TEDs (marked in red) and spoiler 6 (blue)

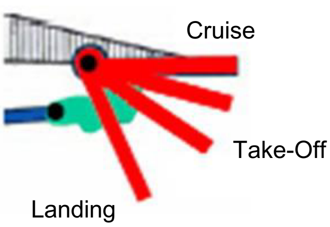

FIG 2. Mini TED deflections

Following these simulations, flight tests were performed in 2006 to finally demonstrate the feasibility and safety of NAPs and to acquire the corresponding far field noise database, necessary for the subsequent calculation of noise footprints.

2 NEW NOISE ABATEMENT APPROACH PROCEDURES

The general concept of the NAPs for the baseline and the modified Airbus A340 aircraft was developed and optimized for noise reduction by Airbus with means of desktop simulations. Next the operational feasibility of procedures was tested in the flight simulator.

A procedure is operationally feasible if it meets the following requirements:

- The pilot is able to execute the instructions on the test card.
- The airplane is stabilised on G/S at 1000ft AGL.
- The airplane reaches an altitude of 1000ft within the approach speed (range +10kt or -5kt).
- The thrust is above idle below 1000ft AGL.

The feasibility tests were carried out by engineering pilots who used the autopilot in flight path angle and approach mode, extended the slats/flaps and the landing gear at predefined positions to verify that a procedure fulfils the requirements.

2.1 Procedures Overview

FIG 3 illustrates an overview of the trajectories of the NAPs for a conventional Airbus A340. All NAPs are continuous descent approach procedures. An ILS standard approach is used as reference procedure (REF). Four different NAPs have been flown in the simulator and can be described as follows:

1) Procedure 2CDA uses a Flight Path Angle (FPA) of -2 deg for the descent in combination with a deceleration.
2) Procedure 10CDA is a procedure with a FPA of -2 deg and an increased glide slope (G/S) angle of -4 deg.
3) Procedure 19CDA is a standard approach with an increased deceleration altitude (7000ft).
4) Procedure 20CDA is a procedure with a G/S interception from above with a FPA of -5 deg in configuration full with approach speed.

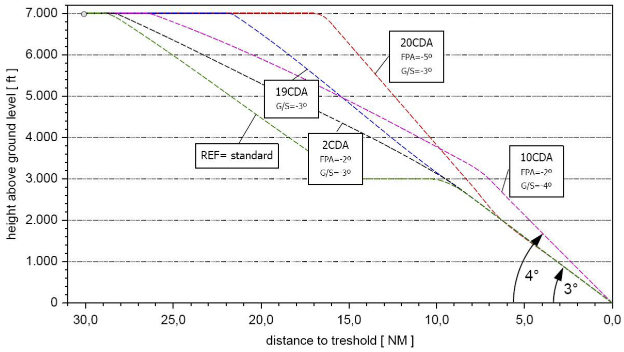

FIG 3. Trajectories of tested procedures for a conventional Airbus A340

AWIATOR specific NAPs are based on NAPs for a conventional Airbus A340, but use the Mini TEDs and spoiler 6 to decrease the FPA, compare FIG 3 and FIG 4.

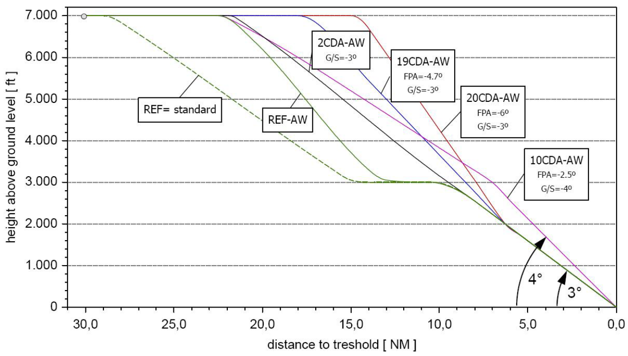

FIG 4. Trajectories of tested procedures for an Airbus A340 with AWIATOR devices

NAPs for an Airbus A340 with AWIATOR devices are:

1) Procedure 2CDA-AW is a standard approach with an increased deceleration altitude (7000ft)
2) Procedure 10CDA-AW is a procedure with a FPA of -2.5 deg and an increased G/S angle of -4 deg.
3) Procedure 19CDA-AW is a procedure with a G/S interception from above with a FPA of -4.7 deg.
4) Procedure 20CDA-AW is a procedure with a G/S interception from above with a FPA of -6 deg in configuration full with approach speed.

3 SIMULATOR PREPARATION

The TUB flight simulator study consisted of two campaigns. In the first campaign the pilots flew with the standard indications of an Airbus A340-300 cockpit. The simulator software was supplemented with an aerodynamic model of the new AWIATOR devices. As the pilots expressed the need for more information with respect to their actual position relative to the predefined flight path, especially for NAPs with ILS glide slope interceptions from above, TUB developed enhanced indications and re-evaluated the feasibility of the proposed NAPs in a second simulator campaign.

3.1 Basic Flight Simulator Description

FIG 5 shows the Airbus A330/A340 Full Flight Simulator that was used for the AWIATOR NAP study. This simulator is operated by the Zentrum für Flugsimulation Berlin (ZFB). It is JAA Level D certified and equipped with a state-of-the-art visual system. The master aircraft is the Airbus A340-311 D-AIGA S/N 020, which is operated by Lufthansa. It has CFM International engines.

FIG 5. External view of the Airbus A330/340 Full Flight Simulator

The series 500 digital motion system as manufactured by CAE Electronics Ltd. provides six degree of freedom motion and includes a comprehensive safety system ensuring fail-safe protection for the flight compartment and for the occupants. The motion system generates realistic cues to the flight compartment using 6 servo actuators, supplied by a hydraulic power unit.

The flight deck, shown in FIG 6, is a complete replica of the original. All instruments and controls are present and active, as in the master aircraft. The only difference is the presence of two simulator freeze buttons and the addition of the instructor station behind the left hand pilot seat.

The training host computer and its back-up are not available for research. Instead, an identical computer with a copy of the training software, called “Scientific Research Facility, (SRF)” is available. The software of this computer can be modified and adapted to the needs of research projects. An Ethernet-switch allows switching between training and research computers quickly. All simulation computers are from the IBM RS 6000-580 series.

FIG 6. Airbus A340 full-flight-simulator flight deck

3.2 AWIATOR Devices Implementation

The aerodynamic coefficients of an Airbus A340 aircraft model with and without AWIATOR devices were measured in the Large Low Speed Facility of the German-Dutch Wind Tunnel (DNW-LLF) and in Airbus’s Low Speed Wind Tunnel (LSWT) in Bremen. The wind tunnel data were used to model the impact of all AWIATOR wing devices on the aerodynamic coefficients. Those models were integrated into the flight simulation software. FIG 7 shows an overview of the new (blue) and modified software modules (grey).

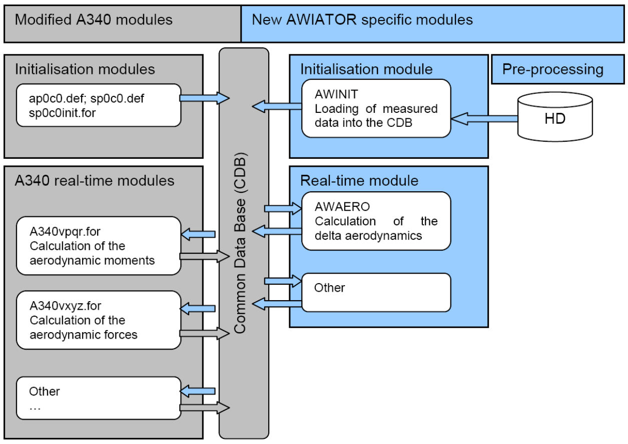

FIG 7. Overview of additional flight simulation software

The new AWIATOR specific modules calculate the additional aerodynamic force and moment coefficients that the new devices generate (delta aerodynamics). They are added to the aerodynamic coefficients of the conventional Airbus A340, thus providing the aircraft behaviour with the new devices installed.

The aerodynamic coefficients depend on three inputs:

- the Mini TED deflection angle,
- the flap deflection angle, and
- the angle of attack.

Aerodynamic coefficients between measured wind tunnel conditions, that means at intermediate Mini TED and flap deflection angles are calculated by an Akima spline interpolation. Interpolation between measured angle of attack data points is linear.

3.3 Cockpit Modifications for 2nd campaign

During the first simulator campaign it became obvious that pilots needed additional information for flying the steeper segments of the NAPs. A possible solution is to implement additional symbols on the Airbus A340 displays. This means to add (i) a second index on the Primary Flight Display (PFD) to indicate the vertical deviation from the steeper approach slopes (magenta diamond) and (ii) a symbol for the intercept point on the Navigation Display (ND) to indicate the positions where the intercepts will occur (green circles).

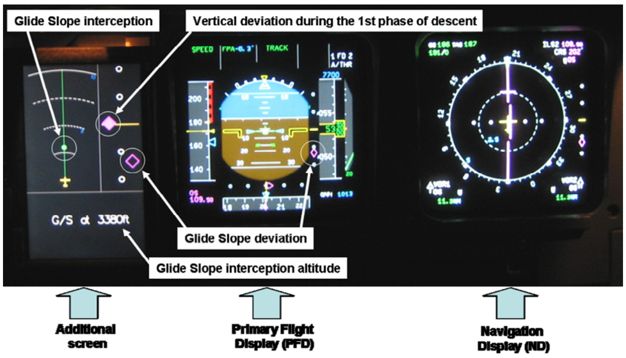

FIG 8. Additional screen, PFD an ND as installed on the flight-deck in the A340 Full Flight Simulator

Since, the effort to modify the original Airbus A340 displays was too high, it was decided to implement this information on an additional screen, which is placed left of the PFD, see FIG 8.

FIG 9 and FIG 10 show how the additional information was implemented:

(1) Positions for transition from level flight to descent (green circle),
(2) Positions for transition from 1st phase of descent to -4 deg or -3 deg G/S (green circle),
(3) G/S interception altitude (barometric altitude),
(4) Vertical deviation during the 1st phase of descent.

In the simulation, the G/S signal for the 1st descent phase is generated as if there is a virtual G/S station, which provides vertical deviations during the 1st phase of descent. These deviations are indicated to the pilot by a magenta diamond (see FIG 10). The division of the scale corresponds to that of the G/S. However, it is not intended to suggest a 2nd G/S station for an operational system. The deviations for the first descent phase should be computed by signals that are already available onboard - like GPS positions.

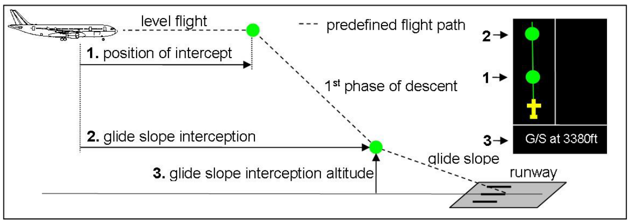

FIG 9. Predefined path with additional information (part I)

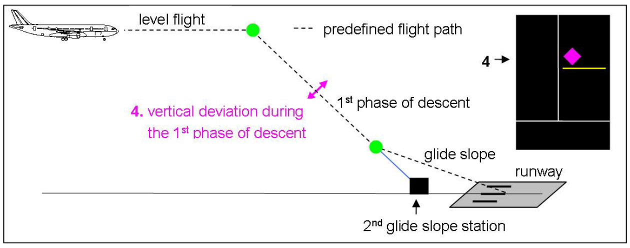

FIG 10. Predefined path with additional information (part II)

3.4 Test Program

3.4.1 Test Procedure

Each simulation test consisted of three steps:

1. Pilot briefing,
2. Simulator session,
3. Pilot debriefing.

During a simulator session the pilots flew 4 different NAPs and the two reference procedures in the 1st campaign respectively 6 NAPs in the 2nd campaign. Three of those were flown with the conventional Airbus A340 and three with the Airbus A340-AWIATOR configuration. All pilot information required for flying the selected NAPs was provided on procedure test cards, see FIG 11.

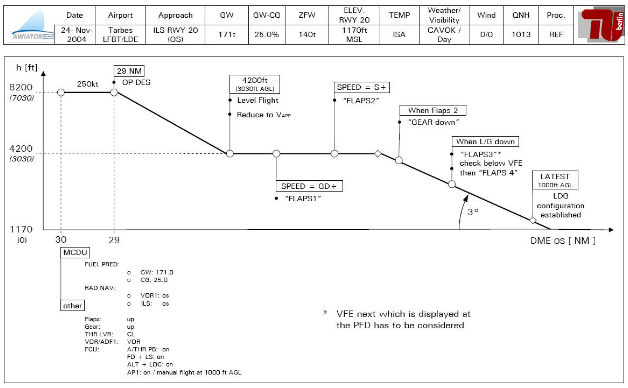

FIG 11. Procedure test card for the reference procedure

3.4.2 Test Matrix and Participation of Pilots

In the 1st campaign, 10 pilots evaluated 120 approaches in 12 simulator sessions. 10 different procedures were defined for the simulation tests and were flown in automatic and in manual mode. "Automatic mode" means that the auto pilot (A/P) and the auto thrust (A/THR) are engaged. Eight of these procedures were NAPs. In total, each approach procedure has been tested 12 times.

The 2nd campaign with the additional display was conducted with 3 pilots. Three sessions, four hours each, were carried out in order to analyse the impact of the enhanced indication. The number of investigated procedures was reduced to 3 approach procedures for a conventional A340 (2CDA, 10CDA and 20CDA) and 3 approach procedures for an Airbus A340 with AWIATOR devices (10CDA-AW, 19CDA-AW and 20CDA-AW) in automatic and in manual mode (total 36 approaches).

The study has been conducted at TU Berlin in November 2004 and May 2006. Only certified airline pilots and test pilots took part; most of them had an Airbus A340 type rating. The mean flight time of the pilots was 11.180 hours with a range from 4.000 to 22.000 hours.

3.4.3 Test Data

During the tests subjective and objective data were recorded. Whereas objective data are independent from pilot's opinion, subjective data comprise pilots' assessment opinion of their workload and pilot ratings of various aspects of the NAPs.

Objective data are 145 flight parameters that were recorded at 60Hz and stored on hard disk.

For acquisition of the subjective data two questionnaires were developed:

- A questionnaire that pilots have to answer after each approach and that is based on the NASA Task Load Index (TLX) [6] is used to inquire pilots' assessment of their workload when flying the NAPs;
- A special questionnaire that is filled in during debriefing inquires how pilots rate several aspects of the NAPs regarding safety, passenger comfort, training demand, operational feasibility, additional indicators, additional automation and overall of the procedures.

4 SIMULATOR RESULTS

In this section, the objective and subjective results are presented and discussed. For objective data the *arithmetic mean value* was calculated and for subjective data *the median* is used to analyse pilot ratings. For both values a confidence interval of 95% is depicted that is bounded by two triangles, as FIG 12 with the general layout shows.

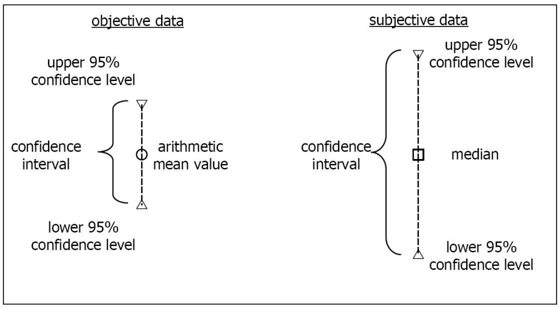

FIG 12. General layout of the figures

The NAPs were designed such that they reduce noise levels significantly – depending on the noise criteria that are used. However, assessment of the simulator results requires post-processing, which was not available when this paper was written. So, the achieved noise reduction is not discussed here.

4.1 Assessment of Objective Data

The fuel consumption (FIG 13) and the required time (FIG 14) are measured between the initial procedure point and the point where the airplane reaches a radio altitude of 50ft. The reference procedure (REF) requires 496s and 345kg fuel.

Procedure 20CDA-AW that is the procedure with the highest fuel consumption requires 56% more fuel (approximately 200kg) than the standard approach procedure (REF). This higher fuel consumption is a direct result of the early slat/flap extension in procedure 20CDA-AW – that increases drag - and the resulting higher thrust demand. The philosophy of procedure 20CDA-AW is to fly high as long as possible, while extending flaps to full and decelerating to V_{app} to reduce speed-related noise, and descent as steep as possible with approach speed until the –3 deg glide slope is intercepted from above. The REF procedure requires an adapted thrust for 1 NM, only. At the final segment (on the –3 deg G/S) the procedure 20CDA-AW requires an adapted thrust again to maintain the approach speed for the last 7.2NM. The REF procedure requires an adapted thrust, which is roughly 15% above idle, to maintain the approach speed for the last 3.6 NM.

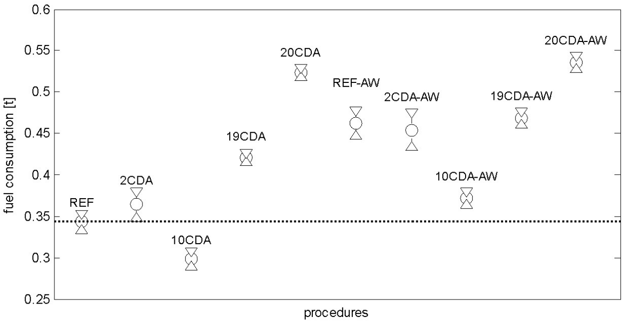

FIG 13. Fuel consumption

The standard ILS approach (REF) is the procedure with the lowest fuel consumption, except procedure 10CDA. The lower fuel consumption of procedures 10CDA and 10CDA-AW is a result of the steeper G/S angle as both procedures are flown on a -4 deg G/S. The thrust to maintain V_{APP} on a -4 deg G/S is 7% lower as compared to a -3 deg G/S. This reduces the fuel consumption in combination with the reduced time required for this procedure. Procedure 10CDA-AW requires a little bit more fuel than the standard ILS approach. The extra fuel is used in the beginning of the approach as the descent in 10CDA-AW starts approximately 5 miles later than in REF.

The fastest procedures are procedure 10CDA and 10CDA-AW. Procedures with a steep approach (19CDA, 20CDA, 19CDA-AW, 20CDA-AW), where speed reduction in combination with flaps extension starts early, require significantly more time than the standard approach procedure, see FIG 14. Differences of 108 seconds between different procedures occur. Procedure 20CDA requires 91 seconds more time from the initial point to touchdown. Especially the earlier speed reduction (for lower speed-dependent noise) is responsible for the increase of time needed for the procedures. Such long durations hinder traffic flow at congested airports and may not be acceptable for air traffic control.

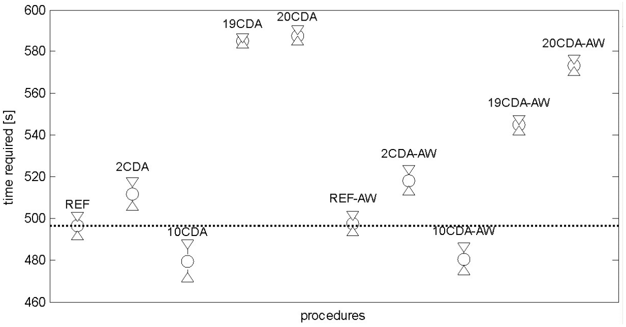

FIG 14. Time required

4.2 Assessment of Subjective Data

Operational applicability

Each pilot rated the operational applicability of the procedures. The results in FIG 15 show that all procedures are rated as operationally applicable. However, there are some concerns regarding procedures with a G/S interception from above (20CDA, 19CDA-AW, 20CDA-AW) and regarding procedure 10CDA that has -4 deg G/S angle. It is important that procedure 10CDA-AW that has also a –4 deg G/S angle received the best average ratings (“disagree”).

Therefore, it can be concluded that a G/S interception from above is less accepted. An increased G/S angle of -4 deg can be accepted, especially when additional devices like the Mini TEDs increase the manoeuvring margin in sink rate.

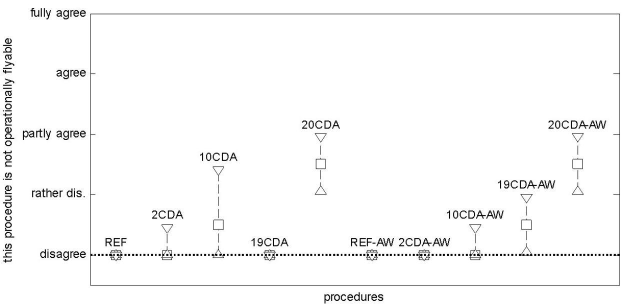

FIG 15. Operational applicability: “Do you agree with the statement that even after sufficient training this procedure is not operational flyable?”

Training demand

All pilots in this study had no previous experiences with these types of NAPs. The pilots familiarised themselves with the NAPs during the briefing just prior to the simulation. On average, they could fly the procedures as instructed.

The pilots rated the training demand of the NAPs, without taking into account any additional training that may be required to operate the Mini-TEDs. The objective of this question was to get a procedure related rating.

Procedures REF, 19CDA, REF-AW and 2CDA-AW were rated to have the lowest training demand. The pilots believe that normal training is sufficient to fly these procedures. Some additional training – but not much - is required for all other procedures, especially for the procedures with a -4 deg G/S or a G/S interception from above, see FIG 16. That was demonstrated as all pilots could fly the new procedures after the short briefing before the simulation and using the test cards in the simulator.

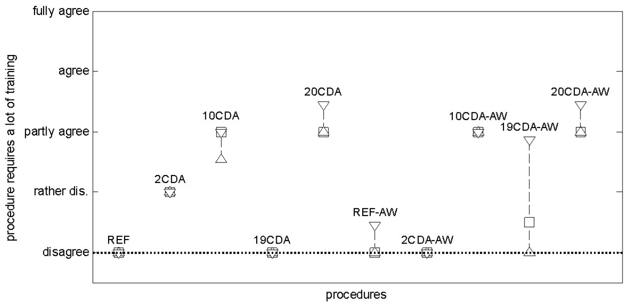

FIG 16. Training demand

Safety

FIG 17 shows that procedures REF, 19CDA, REF-AW and 2CDA-AW received a “good” safety rating on average.

NAPs with steep approaches (-4 deg G/S or G/S interception from above) received ratings lower than “satisfactory” (20CDA, 19CDA-AW, 20CDA-AW, 10CDA and 10CDA-AW). The confidence interval for procedure 19CDA-AW is very large and pilot ratings range from “good” to “poor”.

For a standard ILS approach the upper 95% confidence level of the safety rating is “good”. Therefore, a safety rating worse than “good, is unacceptable, as a new procedure must have at least the same safety rating as a current standard ILS approach.

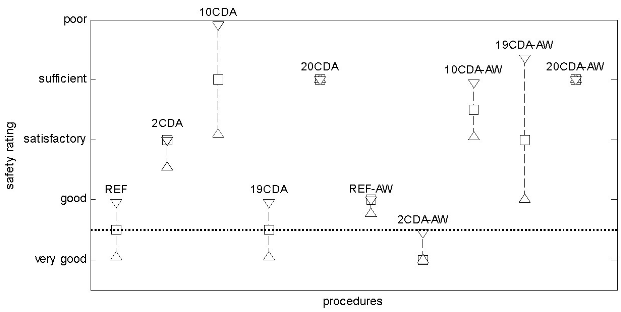

FIG 17. Safety rating: “Please rate the safety of the procedure”

During the 2nd simulator campaign the pilots had better information about the nominal flight path and their deviations. This information improved the average ratings in all procedures by one level, as FIG 18 shows.

The average ratings for procedures 10CDA, 20CDA and 20CDA-AW that were only “sufficient in the 1st campaign improved to “satisfactory”. 10CDA-AW improved from “satisfactory/sufficient” to “good/satisfactory”. Both procedures 2CDA and 19CDA-AW received the ratings “good”.

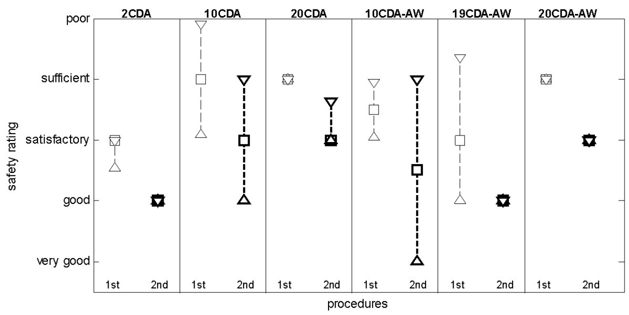

FIG 18. Safety rating without and with additional indicators

Workload

The NASA TLX is used to analyse the workload of the pilots to perform the NAPs. This workload index is a multi-dimensional rating scale that provides an overall workload score based on a weighted average of ratings on six subscales: mental, physical, and temporal demand as well as the frustration, own performance and effort.

All procedures are acceptable in terms of pilot workload (see FIG 19). However, the procedures can be divided into two categories. The first category with the lowest workload includes procedures with a workload of 30% on average and less. The standard ILS approach (REF), 2CDA, 19CDA, REF-AW and 2CDA-AW are procedures of the first category with the lowest pilot workload.

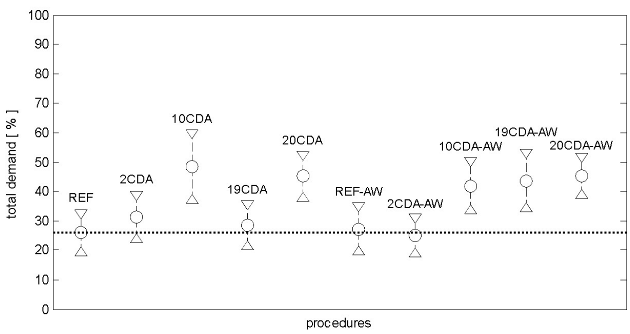

FIG 19. Pilot workload

The second category includes procedures with a workload between 40% and 50%. Procedure 10CDA, 20CDA, 10CDA-AW, 19CDA-AW and 20CDA-AW are procedures of the second category. All procedures with a G/S interception from above and procedures with a G/S angle of -4 deg are in the second category with a higher workload.

FIG 20 depicts the results of the weighted workload score of the approaches from the 1st and 2nd campaign that have been rated during the AWIATOR flight simulations. Except for procedure 2CDA and 10CDA-AW in the 2nd campaign the average pilot workload is less.

Pilots mentioned that the additional display required an adaptation of their scanning pattern. This can be avoided by integrating the additional information into PFD and ND.

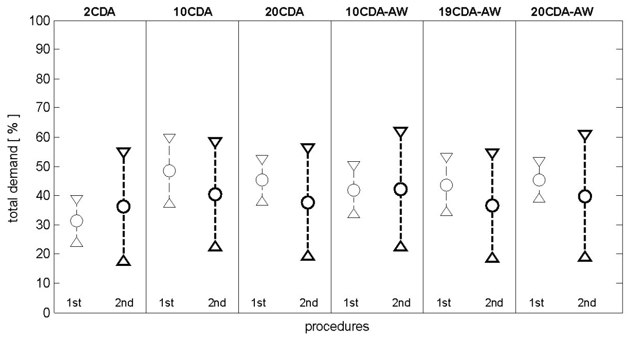

FIG 20. Pilot workload without and with additional indicators

5 COMPARISON WITH FLIGHT TESTS

Four of the AWIATOR NAPs were demonstrated under real world conditions in a flight test. The NAPs that were flown in the flight tests were the same procedures that had been tested in the flight simulator before.

5.1 Results

To obtain a better understanding of effects observed during flight test the results are compared with corresponding simulator runs. For comparison, simulator test results are selected that give the best fit by means of time/distance histories.

The simulator test runs were performed for “Tarbes Airport” conditions because it was originally planned to perform the flight tests there. Finally, flight tests took place at Toulouse Airport, which explains the difference in airport elevation of 760 ft. However, the procedures were adjusted and the effects of different elevation on results can be neglected.

FIG 21 in appendix shows a comparison of the four flight-tested procedures. Altitude, calibrated airspeed (CAS), wind velocity, aircraft weight and fuel consumption are plotted versus distance to touch down and versus elapsed time.

The reported wind was 10 kts from 280 deg, which means a headwind of 7.7 kts as the landing direction is 320 deg. This agrees with the recorded flight test data. The initial weight differs at about 2 tons from procedure to procedure due to the fuel consumption between successive flights. Both, the decreasing headwind and the real aircraft weight were not considered in the definition of the point of descent and the point of deceleration.

The fuel consumption that is plotted over distance and over time confirms the results from the simulator study. The procedures 19CDA-AW and 20CDA-AW need considerably more fuel due to a longer flight time. The jump in fuel consumption for procedure 19CDA-AW at 15 nm distance from touch down originates from a thrust increase, which was needed to avoid an undershoot of minimum speed (see also FIG 22 in appendix).

As an example, the results of the procedure 19CDA-AW are shown in appendix FIG 22. This procedure was the third flight-tested procedure. Using flap (CONFIG 22) and a Mini TED deflection of 60 deg in combination with 20 deg deflection of spoiler 6, a steep descent at -4.7 deg FPA could be performed. The high thrust activities may be a result of horizontal turbulence (see also FIG 21) and are definitively not caused by the procedure type.

The performance (additional drag) of Mini TEDs in combination with spoiler 6 seems to be correctly modelled, as the speed remains constant during the steep descent.

The 19CDA-AW procedure in flight test shows only small deviations from a simulator test (appendix FIG 22). The main difference is an earlier deployment of landing gear (GEAR) and flaps (CONFIG 26 and 32).

The flight test crew rated all four NAPs flyable but only procedure 2CDA-AW was rated operational feasible.

6 CONCLUSION

The goal of the simulator and flight tests was to analyse the operational feasibility, safety, and pilot acceptance of new NAPs with and without Mini TEDs, and to prepare the flight tests. The simulator tests have also been made to assess account the noise reduction potential of the different NAPs.

The simulator and flight tests demonstrated the performance and the benefits of additional wing devices. It also yielded conclusions on the operational feasibility and safety of the designed noise abatement procedures. The results can be summarized as follows:

- The aerodynamic performance of the Mini TEDs and spoiler 6 combination was confirmed in flight tests. That proves the validity of the aerodynamic simulator model that was based on measured wind tunnel data.
- In the simulator tests, procedure 2CDA-AW received the best overall rating, all other procedures with AWIATOR devices were considered operationally feasible, although safety ratings deteriorated for 10CDA-AW, 19CDA-AW and 20CDA-AW.
- Enhanced information – as demonstrated in the 2nd simulator campaign - improved the average safety ratings for all NAPs by one level - although the proposed indications were by far not perfect. 2CDA and 19CDA-AW reached the level of the standard ILS approach Safety ratings could be further improved by introducing automatic functions
- Flight test results and results from simulator test runs agree well.
- The flight test crew rated all four NAPs flyable but only procedure 2CDA-AW was rated operational feasible.
- The flight test shows the same increase in fuel consumption for 19CDA-AW and 20CDA-AW procedures as the simulator test runs did. Both procedures take significantly more time, as speed is reduced very early. This may be not acceptable for air traffic control.

After the evaluation of pilot comments the following statements can be made:

1) Procedures with a G/S interception from above are significantly higher demanding for the pilots.
2) For such procedures, pilots need additional information and support by automatic functions.
3) Procedures should allow flexible use of the Mini-TEDs/Spoiler6 devices.

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APPENDIX

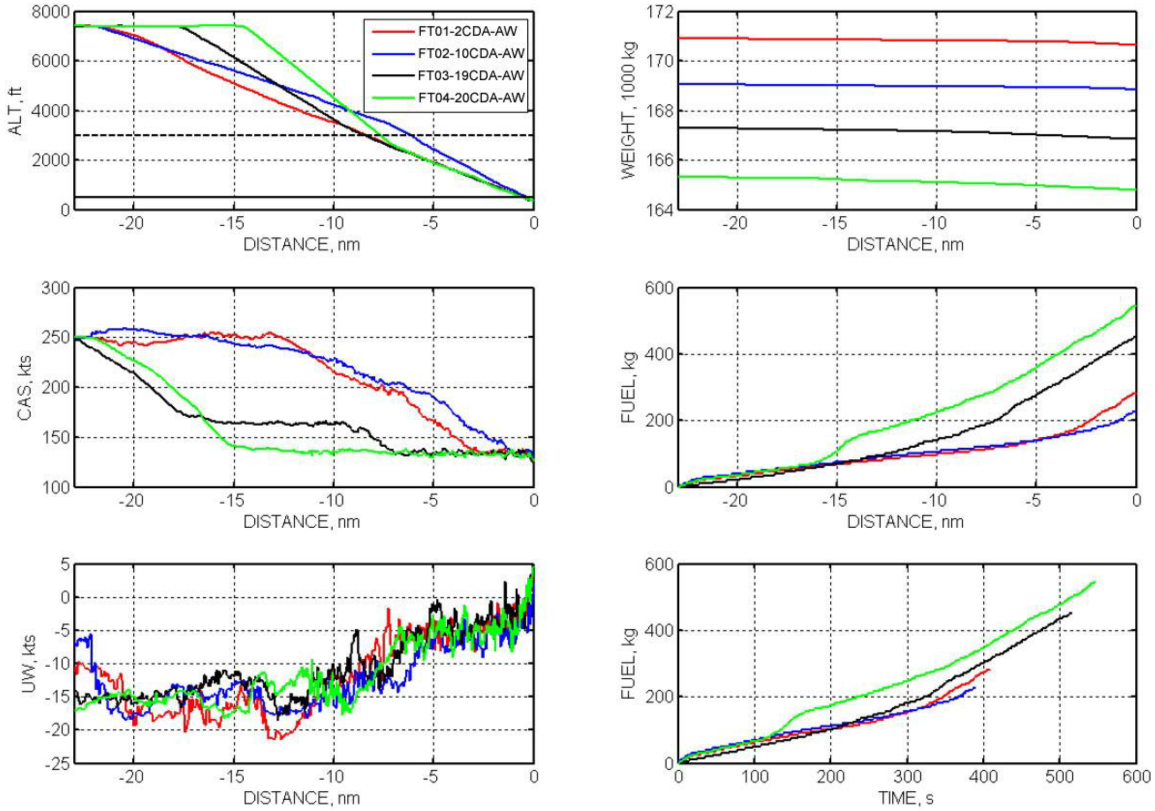

FIG 21. Comparison of flight tested procedures with AWIATOR devices

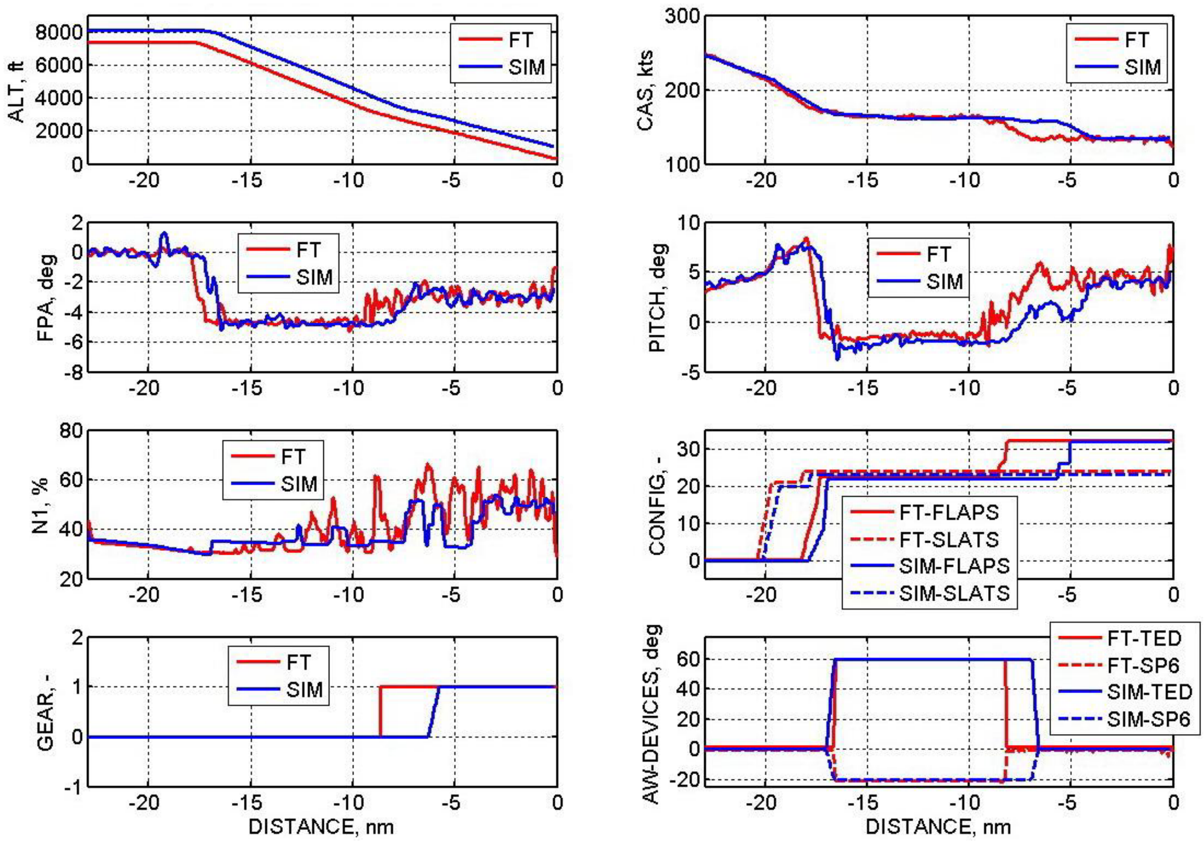

FIG 22. Comparison of flight test segment 03 (19CDA-AW) with a corresponding run from the simulator study