CEAS Aeronautical Journal
https://doi.org/10.1007/s13272-025-00924-0

ORIGINAL PAPER

Improving aircraft energy and flightpath management through pilot support functions: demonstration of optimized continuous descent approaches with the Airbus A320neo at Zurich airport

Martin Gerber[1,2] · Marie Goetz[3] · Falk Sachs[3] · Peter Pauly[3] · Fethi Abdelmoula[3]

Received: 14 April 2025 / Revised: 16 October 2025 / Accepted: 3 November 2025

Abstract

Managing aircraft energy and flightpath during descent remains one of the major operational challenges for pilots. Advancements in this area are therefore essential for enhancing the efficiency, safety and environmental impact of modern flight operations. Within the framework of the EU-funded SESAR ALBATROSS project, the Low-Noise Augmentation System (LNAS) was successfully tested on Airbus A320neo aircraft operating along a closed-path Performance-Based Navigation (PBN) transition to Instrument Landing System (ILS) at Zurich Airport (LSZH), Runway 14. In this study, Continuous Descent Approaches (CDA) were flown both with and without LNAS pilot assistance during regularly scheduled Swiss International Air Lines flights, enabling a direct comparison under real-world operational conditions. The aim of the study was to investigate whether real-time visual cues regarding aircraft energy and aircraft configuration could support pilots in reducing fuel consumption and noise by maximizing distance flown at minimum thrust, minimizing the use of speed brakes and applying configuration changes at optimum locations. Skyguide published a temporary PBN-to-ILS transition to give the pilots in both evaluation groups the ability to fly the approach transition laterally in navigation mode, providing them with complete knowledge of the remaining distance-to-go (DTG) to touchdown. The pilots were specifically trained in the use of LNAS. Data were collected over 23 approaches from July to December 2022. The study was complemented by comparison with 547 flights outside of this trial, which were recorded over the same time period without any pilot assistance function or closed-path procedure. This enabled the comparison of energy management, aircraft configuration changes, and fuel burn with current flight operations. Results show that LNAS increased the predictability of the airspeed and the vertical profile. Furthermore, LNAS minimized the need for speed brake deployment at lower altitudes, thus reducing noise near the airport. Quantitatively, average fuel consumption decreased by 8.8% over the final 30 nautical miles to touchdown compared to flights without pilot assistance. The visual cues provided by the pilot assistance system were qualitatively assessed against the EASA pilot core competencies to derive recommendations for future deployment of such novel functionalities. The findings confirm that incorporating such pilot assistance functions into a future *Flight Management System (FMS)* could enhance the management of the aircraft's energy state. Besides fuel saving, better aircraft energy management supports approach stabilization and minimizes flightpath deviations, thereby contributing to flight safety.

Keywords Continuous descent approach · Vertical flight efficiency · Fuel efficiency · Noise reduction · Sustainable aviation · Pilot assistance system · Air traffic control

✉ Martin Gerber
martin.gerber@skylab-aerospace.com

Marie Goetz
marie.goetz@dlr.de

Falk Sachs
falk.sachs@dlr.de

Peter Pauly
peter.pauly@dlr.de

Fethi Abdelmoula
fethi.abdelmoula@dlr.de

1 SWISS, Swiss International Air Lines Ltd., Zurich Airport, 8058 Zurich, Switzerland

2 SkyLab, Swiss Skylab Foundation, Switzerland Innovation Park Zurich, Wangenstrasse 68, 8600 Dübendorf, Switzerland

3 DLR (German Aerospace Center), Lilienthalplatz 7, 38108 Brunswick, Germany

Published online: 12 November 2025

Abbreviations

ACDA	Advanced continuous descent approach
ADS-C	Automatic dependent surveillance-contract
AGL	Above ground level
AID	Avionics interface device
AMSL	Above mean sea level
ATC	Air traffic control
ATCO	Air traffic control officer
ATRA	Advanced Technology Research Aircraft
CBT	Competency-based training
CCO	Continuous climb operation
CDA	Continuous descent approach
CDO	Continuous descent operation
DECEL	Deceleration location
DLR	German aerospace center
DTG	Distance to go
EASA	European Union Aviation Safety Agency
EBT	Evidence-based training
EFB	Electronic flight bag
EPP	Extended projected profile
ETSO	European Technical Standard Order
FAA	Federal Aviation Administration
FAF	Final approach fix
FCOM	Flight crew operating manual
FL	Flight level
FMS	Flight management system
FOCA	Federal Office of Civil Aviation
FPA	Aeroplane flight path management–automation
FPM	Aeroplane flight path management–manual control
HMI	Human machine interface
IAS	Indicated airspeed
ILS	Instrument landing system
KNO	Knowledge
LDLP	Low drag low power
LNAS	Low noise augmentation system
ND	Navigation display
PBN	Performance based navigation
PFD	Primary flight display
RNAV	Area navigation
RTA	Required time of arrival
SAW	Situation awareness
STAR	Standard terminal arrival route
TMA	Terminal manoeuvring area
ToD	Top of descent
VFE	Vertical flight efficiency
V_{FE}	Maximum flap extended speed
WLM	Workload management

1 Introduction

Aircraft energy and flightpath management, particularly during descent, is a major challenge for pilots, as recognized by the Federal Aviation Administration (FAA) in its 2022 Advisory Circular (AC) 120–123 'Flightpath Management' [1]. This challenge is described as follows: "*Industry reports and operational data from airlines and aircraft manufacturers indicate that pilots have vulnerabilities in awareness and management of the aircraft's energy state, across multiple phases of flight, which is potentially a significant contributing factor in flightpath deviations, incidents, and accidents*". Effective management of the aircraft's energy state, which involves the control of airspeed, altitude, thrust, and aerodynamic drag, is essential to ensure safe and efficient flight operations. Inadequate energy management can lead to flightpath deviations, increased fuel consumption, and elevated aircraft noise, impacting both operational safety and environmental sustainability. Chapter 6 of this AC explains: "*[…] The pilot needs to understand how to manage the vertical flightpath and aircraft energy during the arrival and approach phases; how the pilot does that will vary based on the type of approach flown (e.g., Area Navigation (RNAV) Standard Terminal Arrival (STAR) to an Instrument-Landing System (ILS) approach or to a visual approach) and ATC interventions. Pilots need to be able to plan the tasks related to the desired aircraft energy state for the arrival and approach, in a timely manner. If the approach clearance or aircraft energy changes, the pilot needs to have the knowledge and skills to recognize actual or pending energy state changes to decide what actions need to be made to manage the flightpath and aircraft energy accurately and efficiently.*"

The FAA [1] lists common errors in energy management, operational traps, and potential threats that could lead to errors, such as:

- Late changes in assigned routing, clearance limit, altitude assignment, or arrival procedure.
- Untimely speed assignment changes, traffic avoidance altitude constraints, and other unexpected Air Traffic Control (ATC) restrictions.
- Current forecast and unexpected weather conditions (winds, icing, high density altitude, etc.) that affect aircraft performance and energy state.

A necessary prerequisite for determining the energy state of an aircraft and the pilot's strategy for energy dissipation is the on-board knowledge of the remaining distance from the current aircraft position to the runway, the Distance-to-Go (DTG). Closed-path performance-based navigation to instrument landing system (PBN-to-ILS) procedures offer the advantage of completely eliminating the uncertainty of the path distance, [2]. At the same time, the air traffic controller's options for intervention are limited to speed instructions, which can be challenging in dense traffic situations [3].

1.1 Research objective

The objective of this study, conducted within the EU-funded ALBATROSS project under the SESAR Joint Undertaking (Exercise #3), was to evaluate the benefits of the Low Noise Augmentation System (LNAS) to enhance aircraft energy management along a closed-path PBN-to-ILS transition. Specifically, the study investigated whether real-time visual cues on aircraft energy and configuration could help pilots reduce fuel consumption and noise emissions by maximizing idle-thrust segments, minimizing speed brake usage, and applying configuration changes at optimum locations.

The analysis focussed on quantifying the environmental benefits and assessing the impact on human factors and flight safety [2]. LNAS was demonstrated during Continuous Descent Approaches (CDAs) performed with Airbus A320neo aircraft operating in regular line operations at Zurich Airport (LSZH), Runway 14. Pilot performance when flying the closed-path arrival transition, with and without pilot LNAS support, was evaluated using key performance indicators including vertical and speed profiles, fuel burn, and the timing of configuration changes for high-lift devices, speed brakes, and landing gear.

1.2 Background and literature review

According to ICAO, 'Continuous Descent Operation' (CDO) is defined as [3]:

"*An operation, enabled by airspace design, procedure design and ATC facilitation, in which an arriving aircraft descends continuously, to the greatest possible extent, by employing minimum engine thrust, ideally in a low drag configuration, prior to the final approach fix / final approach point. […] An optimum CDO starts from the top of descent and uses descent profiles that reduce segments of level flight, noise, fuel burn, emissions and controller/pilot communications, while increasing predictability to pilots and controllers and flight stability.*

The aim of this study is to achieve CDOs that are as close as possible to the optimum defined above. The emphasis lies on maintaining idle thrust for the greatest portion of the descent and minimizing avoidable drag, such as speed brake deployment at low altitudes or early extension of the landing gear.

Research on aircraft energy management began as early as the 1980s at NASA, where flight tests on a modified Boeing 737 demonstrated energy-optimized descent profiles [4]. The controller logic developed for these trials adjusted speed and thrust to maintain a predefined specific-energy rate of change. In contrast, a fuel-optimized approach maintains thrust continuously at idle. According to the equivalence principle of kinetic and potential energy, a reduction in airspeed requires a corresponding temporary decrease in flight-path angle to preserve a nearly constant total-energy rate of change. LNAS applies this same principle by continuously computing a reference vertical and speed profiles that enable a continuous idle-thrust descent.

The default vertical profile applied in this study corresponds to a CDA, as illustrated in Fig. 1. In this profile, deceleration to comply with consecutive speed restrictions or new target speeds occurs during a descending flight

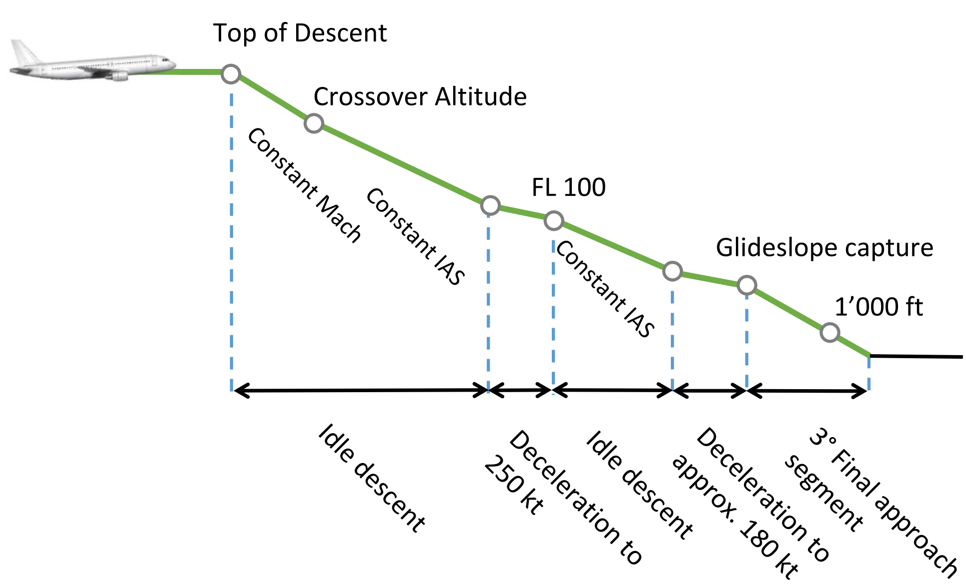


Fig. 1 Continuous Descent Approach (CDA) profile with descending deceleration segments. This profile was applied as default profile in this study

segment, and the ILS glideslope segment is intercepted from below. This differs from a Low-Drag Low-Power (LDLP) profile, where deceleration is achieved during a level segment and from an Advanced CDA (ACDA), in which the glideslope is intercepted from above [5]. Nevertheless, both LDLP and ACDA profiles can also be flown entirely at idle thrust and are therefore considered forms of Continuous Descent Operations (CDO).

The benefits of CDO are well established. A recent study by Xue et al. quantified average fuel savings of approximately 139 kg per flight through the implementation of CDOs at seven major Chinese airports [6], while also emphasizing the operational challenges of maintaining continuous descents in high traffic density. Flight trials in the United States at Louisville International Airport demonstrated fuel savings between 181 and 227 kg and noise reduction of 3.9 to 6.5 dB(A) for noise abatement approach procedures [7]. The European CCO / CDO Action Plan [8] similarly highlights the advantages of optimized CDO across Europe, estimating annual savings of up to 350′000 t of fuel per year and noise reductions of 1 to 5 dB(A) compared with conventional, non-CDO operation, representing a theoretical upper limit of achievable benefit.

In current operations, actual flight paths vary significantly with traffic density and time of day, as shown by Pasutto and Zeghal [9]. Against this background, the present study compares the results of the flight trials with 547 baseline approaches flown to the same runway under prevailing operational conditions and without the pilot assistance system. The challenge of enabling optimized CDOs in complex traffic environments has motivated research into solutions that maintain energy-neutral idle-thrust descents while accommodating variations in the required time of arrival (RTA). Saez and Prats [10] demonstrated that idle-thrust descents can be achieved within certain arrival-time windows, while Toratani et.al [11] highlighted the feasibility of CDO implementation in congested airspaces, albeit allowing limited thrust modulation to sustain a fixed flight-path angle. In the present work, LNAS dynamically adapts the reference vertical profile to tactical, ad-hoc speed instructions from ATC, prioritizing idle-thrust over adherence to a pre-defined vertical path. Consequently, the study proposes that energy-neutral, idle-thrust descent profiles should be integrated into a future FMS with the capacity to dynamically recompute the reference vertical profiles following speed changes.

Executing an idle descent effectively requires accurate knowledge of the remaining distance to the runway. The descent is essentially a process of managing the dissipation of the aircraft's potential and kinetic energy. In the current operational environment, however, the DTG is often unknown or only becomes available at a late stage to the pilots. Earlier studies and flight tests with LNAS have demonstrated its effectiveness under *radar vectoring* conditions, where air traffic controllers communicated the DTG values via radio, which were then manually entered into the assistance system. Such flight trials were previously conducted with DLR's A320 Advanced Technology Research Aircraft (ATRA) at Zurich and Frankfurt airports [12–15]. In the present study, by contrast, LNAS was evaluated along a closed-path trajectory flown in navigation mode, instead of radar vectoring scenarios. Furthermore, the flights were conducted as part of regular airline operations, which required additional preparation for operational approval and pilot training.

Executing an idle-thrust descent effectively requires the provision of intuitive visual cues to the flight crew. In its current implementation, LNAS operates on an Electronic Flight Bag (EFB) for demonstration purposes. However, displaying guidance cues on a peripheral device is not optimal for operational use. Future developments should therefore focus on integrating energy-management information directly into the pilots' primary field of view, such as within the Primary Flight Display (PFD). Research by Amelink et al. [16] has investigated the presentation of aircraft energy-state information on the PFD. The present study examines benefits for human performance in relation to pilot competencies, providing an initial assessment of how such assistance cues can support pilot energy-management skills.

Modern flight management systems (FMS) are capable of calculating a vertical profile, either based on LDLP or CDA logic, depending on the system version. However, these systems are limited to simplified computations and cannot dynamically determine the optimal points for configuration changes. For example, current FMS do not predict or display the landing gear extension in support of optimized descent operations. Additionally, reference profiles cannot be recalculated below 10′000 feet in response to speed interventions by ATC. The current research contributes with these early prototype solutions in LNAS to the future integration of these functionalities into an integrated avionics environment and FMS [17–19].

1.3 Outline of the paper

Section 2 presents the methodology, including the datasets collected, the modification to the operational arrival procedure, and a description of the integration of the pilot assistance system LNAS into regular airline operations. Section 3 presents the results, covering aircraft trajectories (vertical and speed profiles), quantitative analyses of thrust, fuel consumption, and configuration changes, as well as a qualitative assessment of human-factors aspects related to the use of novel pilot cues for aircraft energy management.

Section 4 summarizes the conclusions and recommendations for future work, with a particular emphasis on the transition from research to operational and industrial application.

2 Methodology

2.1 Test scenarios and datasets

The study's goal was to evaluate the impact and benefits of LNAS on aircraft energy and flightpath management during regular airline operating conditions. To this end, three distinct operational scenarios and datasets were collected and analysed, see Fig. 2.

The 3 test scenarios are characterized as follows:

1) **Baseline Flights (Radar Vectoring, n = 547)**: This group includes all approaches conducted by the A320neo fleet to Zurich Airport (LSZH) runway 14 under ATC radar vectoring between July and December 2022. Radar vectoring represents the standard operational procedure at Zurich and serves as the status quo benchmark for analysing aircraft energy characteristics during the descent and approach phase. The baseline dataset reflects typical operational variability in energy management, fuel burn and configuration changes, comprising a total of 547 flights.
2) **Reference Flights (PBN-to-ILS without LNAS, n = 11)**: These flights were performed within the study framework using a closed-path PBN-to-ILS transition instead of radar vectoring, but without LNAS assistance. Conducted between July and August 2022, prior to the pilot-assistance trials, they were designed to represent manually flown, optimized descents. Pilots were instructed to manage speed manually and to cross the Final Approach Fix (FAF) at 170 knots, aiming for minimum fuel burn and noise. No additional ATC speed constraints were issued to ensure consistency and comparability. A total of 11 reference flights were conducted.
3) **Optimum Flights (PBN-to-ILS with LNAS, n = 12)**: These demonstration flights, conducted between September and December 2022, were supported by the LNAS pilot assistance system, which provided real-time guidance for speed schedules and aircraft configuration changes. The same operational constraints as in the reference flights applied, including the target to cross the FAF at 170 knots. Data from the optimum flights were analysed in direct comparison with both the reference and baseline scenarios. A total of 12 reference flights were recorded.

During all flight trials, the following flight data was recorded for each approach: GPS altitude, indicated airspeed and fuel consumption, along with the locations of configuration changes such as speed brake use, deployment of high-lift devices, and extension of landing gear.

The key distinction between the baseline dataset and the reference/optimum flight sets lies in the implementation of a closed-path PBN-to-ILS transition. This dedicated procedure was temporarily established and published by Skyguide to enable aircraft to fly in navigation mode instead of heading mode. Figure 3 illustrates the baseline flight tracks under radar vectoring (grey) alongside the fixed lateral trajectories of the reference (orange) and optimum (blue) flights. Two dedicated PBN-to-ILS transitions were

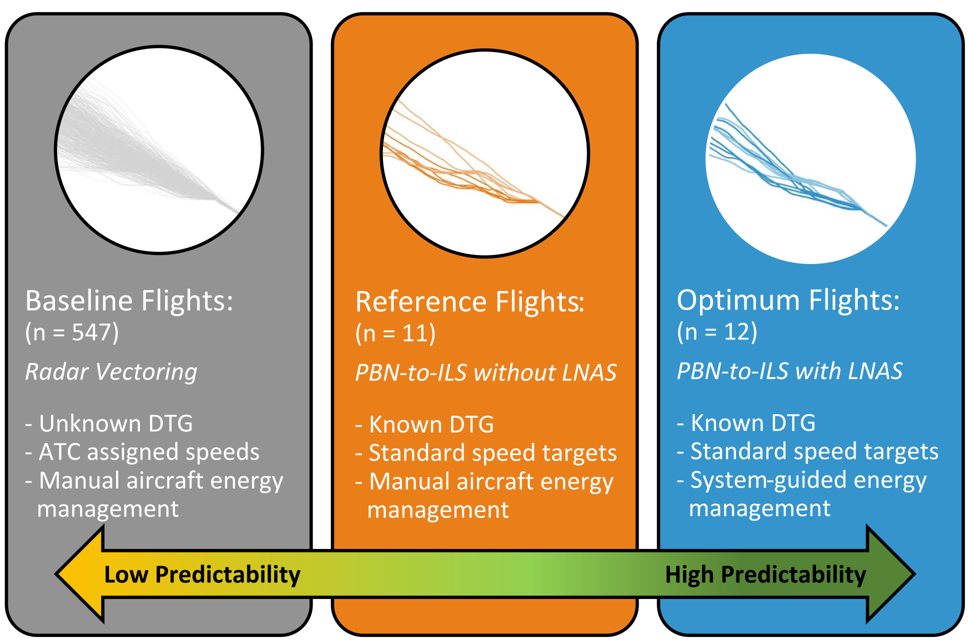


Fig. 2 Test scenarios for the assessment of the benefits of closed-path navigation and using the pilot assistance system LNAS

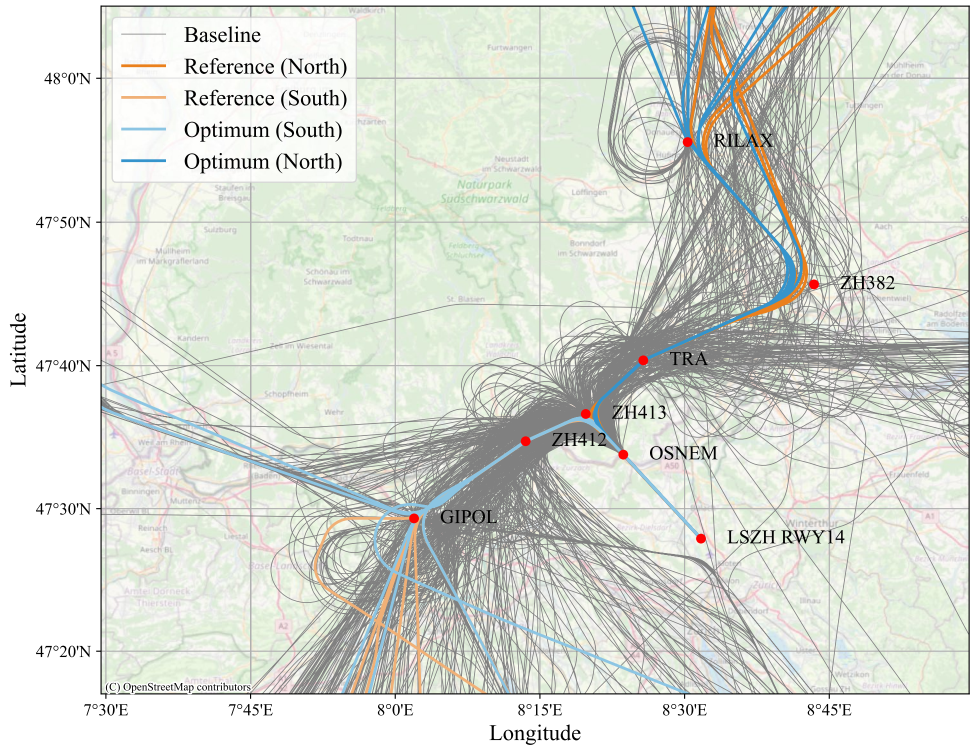


Fig. 3 Baseline flights under radar vectoring (grey) vs. PBN-to-ILS procedure (blue and orange). Reference flights without LNAS in orange and optimum flights with LNAS in blue to Runway 14 inbound southwest via GIPOL (light colour) and inbound northeast via RILAX (dark colour). Source of map: OpenStreetMap

established for this research, one providing approach guidance from the northeast (darker shades) and the other from the southwest (lighter shades).

In contrast to the baseline flights, which represent routine daily flight operations used for comparison, both the reference and optimum flights were conducted with the objective of crossing the FAF, with the waypoint named OSNEM, at an indicated airspeed of 170 knots. In the reference flights, pilots manually determined the appropriate location to begin decelerating from the initial Terminal Manoeuvring Area (TMA) speed, typically 220 knots, to the target speed at FAF of 170 knots. By contrast, in the optimum flights the location at which deceleration had to be initiated, was automatically computed and displayed by LNAS as the pseudo-waypoint named DECEL on the EFB screen, providing precise real-time guidance for initiating the deceleration.

2.2 Test equipment

The pilot assistance system LNAS operates as a demonstrator application on an EFB, receiving real-time flight data via an Avionics Interface Device (AID), see Fig. 4.

LNAS consists of three core components: pre-planning, real-time prediction, and an energy-based display. For more details refer to Abdelmoula and Scholz [13].

1) **Pre-Planning**: This module employs a simplified aircraft performance model to generate an initial lower fidelity ideal vertical approach profile that can be adapted to any aircraft type using database-derived parameters. Ideally, pre-planning is performed before to the actual approach and identifies optimal timing for speed reductions, high-lift device deployment, and landing gear extension. The goal is to enable an idle-thrust low-drag descent, thereby avoiding noise-intensive speed brake use whenever possible. These optimal timing points are calculated based on forecasted wind condition at the destination airport and the measured wind at the aircraft's current altitude.
2) **Real-Time Prediction**: This module incorporates a complete six degree-of-freedom (6-DoF) aerodynamic flight model that performs high-frequency forward simulations to provide a high-fidelity trajectory to optimize the timing of speed reductions and configuration changes. The aim is to satisfy operational constraints such as target speed at FAF or stabilization at 1000 ft above ground level (AGL). This simulation also captures transient effects such as ballooning during flap extension. This real-time prediction module acts as a synthetic pilot agent, continuously adjusting the simulated flightpath according to operational rules (e.g., extending the landing gear only after flap configuration 2).
3) **Energy-Based Display**: This Human–Machine Interface (HMI) on the EFB provides visual cues for the pilots to follow the optimum vertical profile and execute configuration changes at the appropriate moments, as illustrated in Fig. 5. The display shows two reference

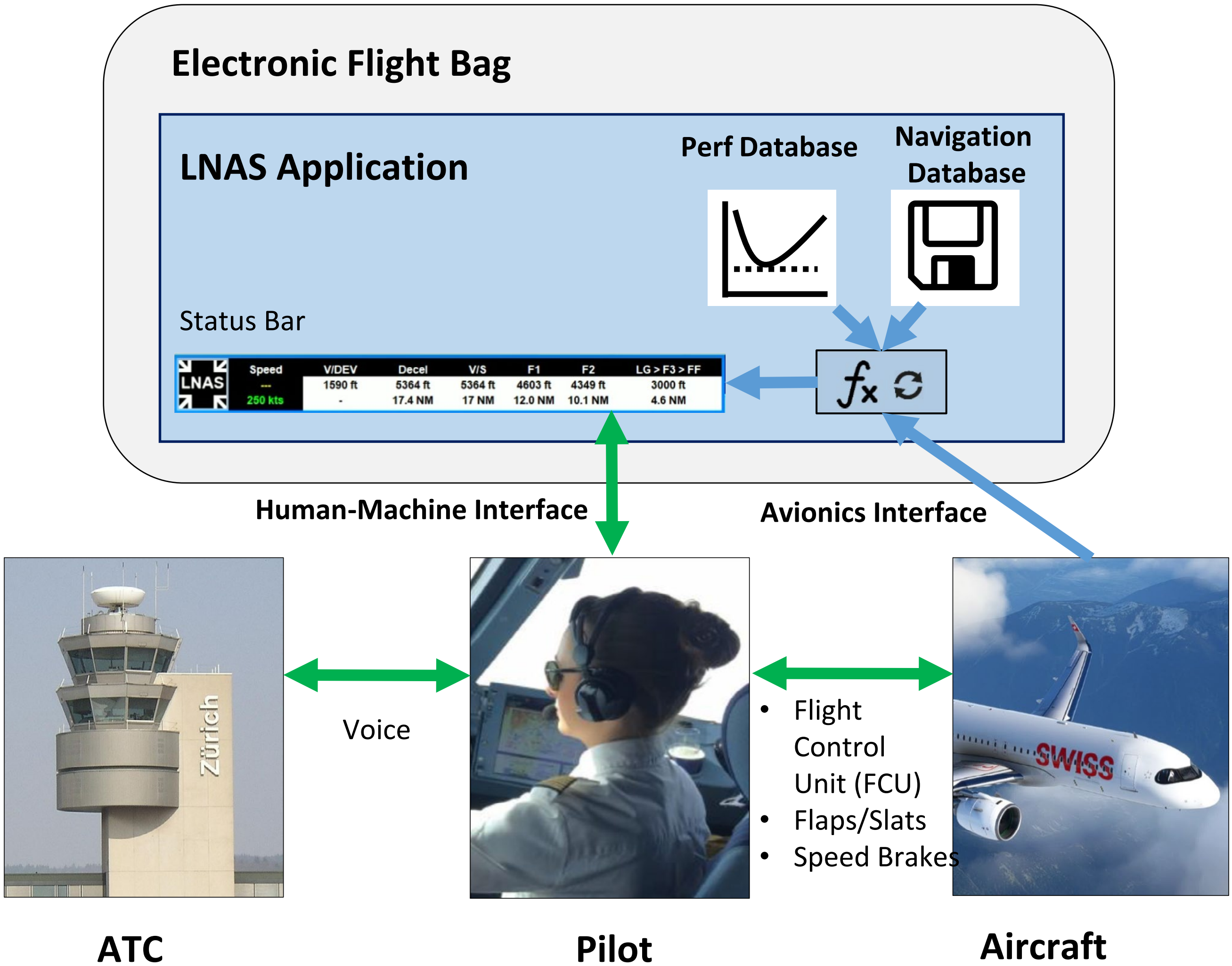


Fig. 4 LNAS application in the operational environment receiving aircraft data and providing recommendations for aircraft guidance through a dedicated human–machine interface

profiles: the initial pre-planned trajectory (white) and the real-time optimized trajectory computed by the high-resolution simulation (green). In addition, a simplified status bar can be overlaid on the EFB approach map, providing a compact visualization of vertical deviation, as well as the timing and location of vertical-mode transitions (e.g., OPEN DES to V/S), speed-mode changes, and configuration actions such as flap or landing-gear deployment, as shown in Fig. 6.

For use in the ALBATROSS project, the LNAS performance model was adapted to represent the specific flight characteristics of the A320neo. To achieve this, DLR modified the internal flight mechanics model using an extensive dataset of A320neo flight data. The parameters of the existing A320ceo model were adjusted to account for engine-performance differences and revised aerodynamic coefficients, following the methodology described by Deiler [20]. Both the engine and aerodynamic sub-models were updated and subsequently verified through shadow-mode flights by Swiss International Air Lines and Lufthansa during 2021 and early 2022. The avionics interface between LNAS and the Airbus A320neo was implemented on the Swiss Airline's A320neo fleet to provide LNAS with real-time data from the avionics bus. This interface underwent ground testing prior to the commencement of the demonstration flights.

2.3 Test preparation

For the demonstration flights, several enhancements were implemented in the existing LNAS HMI. These enhancements were internally tested using the DLR AVES research simulator in Braunschweig [2]. Following simulator trials, training videos were produced to facilitate pilot familiarization, necessitated by COVID-19 travel restrictions and internal airline constraints that precluded in-person training.

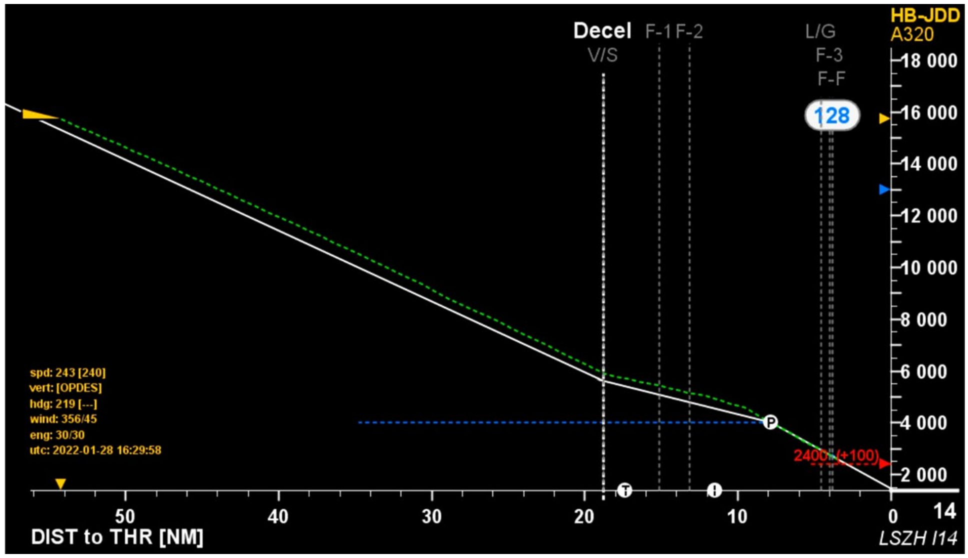


Fig. 5 LNAS-CDA human–machine-interface on the demonstration device displaying the optimum pilot actions for vertical path adjustment, speed reduction, and configuration changes

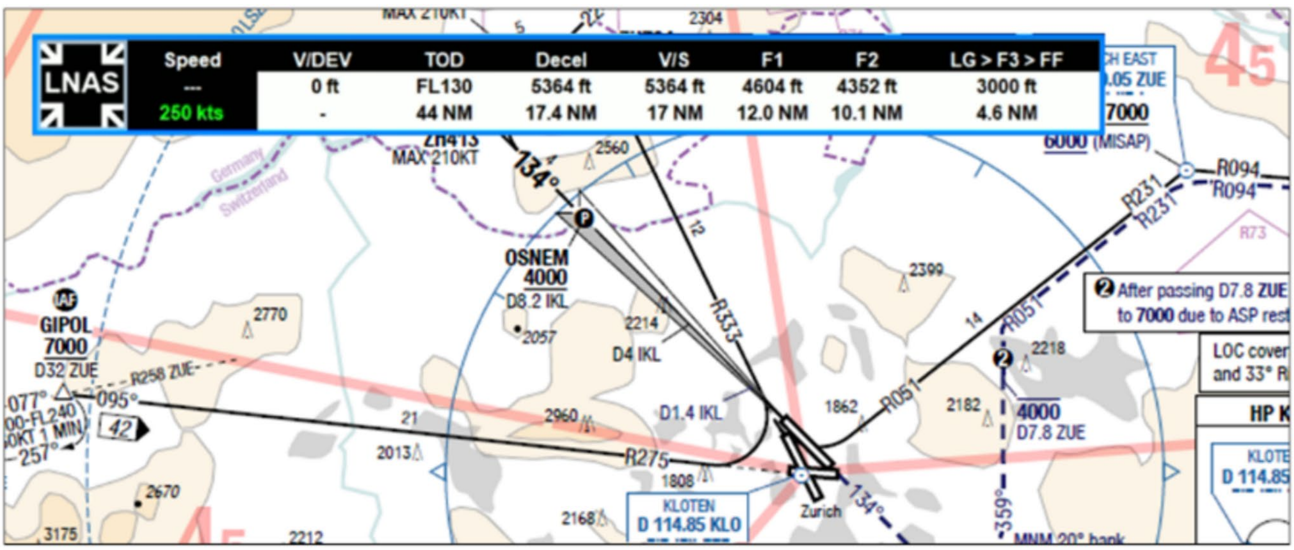


Fig. 6 A simplified HMI with a status bar that provides the necessary information for an optimised descent

Prior to the LNAS demonstration flights, an operational risk assessment was conducted to identify potential hazards and corresponding mitigations. Although not applicable from a regulatory perspective in the context of this study, since LNAS was never used as a primary means of guidance and therefore fell outside of formal regulatory certification requirements, nevertheless, international standards, such as the European Technical Standard Order (ETSO) '*Electronic Map System for the Graphical Depiction of Aircraft Position*' [21], were considered.

The following risk mitigations were defined:

1) Optimization of the HMI and training program to improve data acquisition and to reduce pilot head-down time.
2) Inclusion of LNAS system limitations awareness in the training program.
3) Inclusion of awareness for managing data-entry errors and understanding their consequences into the training program.
4) Validation of flight model using historical flight data. LNAS to be tested in shadow-mode during actual flight, without providing active guidance.
5) Selection of a dedicated, trained pilot group for demonstration flights. LNAS use is restricted to trained pilots.
6) Implementation of an LNAS function to warn pilots if data quality becomes unreliable.
7) Availability of a backup EFB stored in the cockpit's checklist compartment.

In addition to the mitigations identified during the risk assessment, a flight data monitoring process was established to ensure approach stabilization, a prerequisite by the Federal Office of Civil Aviation (FOCA) approval. As a result, FOCA formally authorized the conduct of the ALBATROSS demonstration flights using LNAS on August 29, 2022.

For the execution of the temporary PBN-to-ILS procedure, Skyguide issued an Operational Service Order to all air traffic controllers, enabling the initiation of the reference flights along the closed PBN-to-ILS trajectory. Pilots could request an '*ALBATROSS Approach*' during initial contact with approach control and clearances for a PBN-to-ILS transition were granted subject to traffic conditions and within pre-defined time windows.

All participating pilots completed specific training on LNAS operation prior to the trials. The training syllabus included analysis of representative approaches recorded on the AVES simulator and hands-on familiarization with LNAS before executing assisted approaches to Runway 14 at Zurich Airport. The training material contained instructional videos covering the topics explained in the following sub-sections:

2.3.1 General software introduction

Pilots received an overview of LNAS to develop a clear understanding of its core principles and the computational logic behind its trajectory and energy predictions. This familiarization ensured that flight crews could interpret the displayed guidance cues and understand how the system derives its optimized descent solutions.

2.3.2 Entry of wind data and flight plans

The waypoint sequence from the active flight plan had to be entered manually into LNAS to provide the algorithm with the DTG. In addition, surface wind information from the latest meteorological report had to be entered into LNAS to ensure accurate prediction of the descent trajectory.

2.3.3 Management of high-energy and low-energy situations

Although LNAS assists pilots in following the optimum vertical and speed profile, the training syllabus also covered non-nominal energy states. Recorded simulator videos were used to demonstrate both high-energy and low-energy recovery scenarios. In the high-energy case, this meant to apply speed brakes until the forward prediction (green line on the EFB display) reconverged with a valid continuous trajectory. Conversely, the low-energy case illustrated how to adjust the flight path to recapture the optimum profile after undershooting the ideal energy state**.**

2.3.4 Handling of tactical early speed reductions assigned by ATC

During the demonstration flights, pilots were generally permitted to follow the LNAS-suggested speed profile. However, tactical speed interventions by ATC could still occur. A dedicated training video illustrated how to manage such early speed-reduction instructions, which trigger a recalculation of the vertical profile within LNAS to maximize idle-thrust descent segments.

2.4 Test data analysis

The recorded flight data were post-processed to derive key performance metrics, including fuel burn, engine thrust settings, and aircraft configuration changes as a function of distance to threshold. To quantify the observed difference between the test groups, a statistical analysis was conducted on the fuel burn data. Welch's t-test was applied to compare mean fuel consumption across the baseline, reference, and optimum flight sets, accounting for small sample sizes and unequal variances.

3 Results and discussion

3.1 Vertical profiles

The closed-path PBN-to-ILS transition enabled improved aircraft energy management in both the reference and optimum flights. However, the analysis revealed that the vertical profiles varied depending on the direction of arrival, southwest or northeast. Figure 7 illustrates the 3D trajectories over approximately the last 18 NM before landing, with approaches from the northeast shown in darker colours.

Figure 8 presents the vertical profiles of the reference flights (PBN-to-ILS without LNAS) in comparison with those of the baseline flights. Despite the predefined lateral path provided by the PBN-to-ILS procedure, several reference flights exhibit level-off segments, indicating challenges in manual energy management. These level segments likely reflect a conservative pilot strategy to ensure compliance with the speed constraint at the FAF/glideslope intercept. Level-off segments at 6′000 ft were frequently observed on the approaches from the southwest, whereas the flights from the northeast typically levelled off at 5,000 ft, a difference attributable to airspace constraints in the respective arrival sectors. The objective for the reference flights was to reach the waypoint OSNEM, the beginning of the

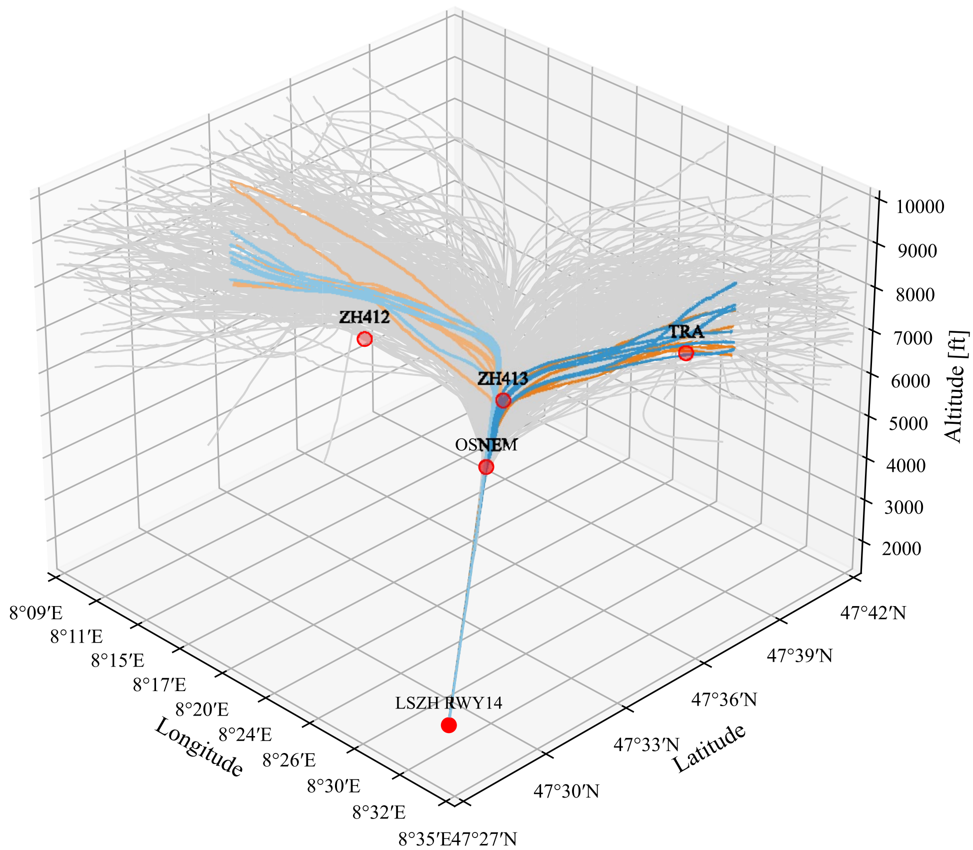


Fig. 7 3D trajectories for baseline flights (grey), reference flights (orange) and optimum flights (blue), for the last 18 NM before touchdown

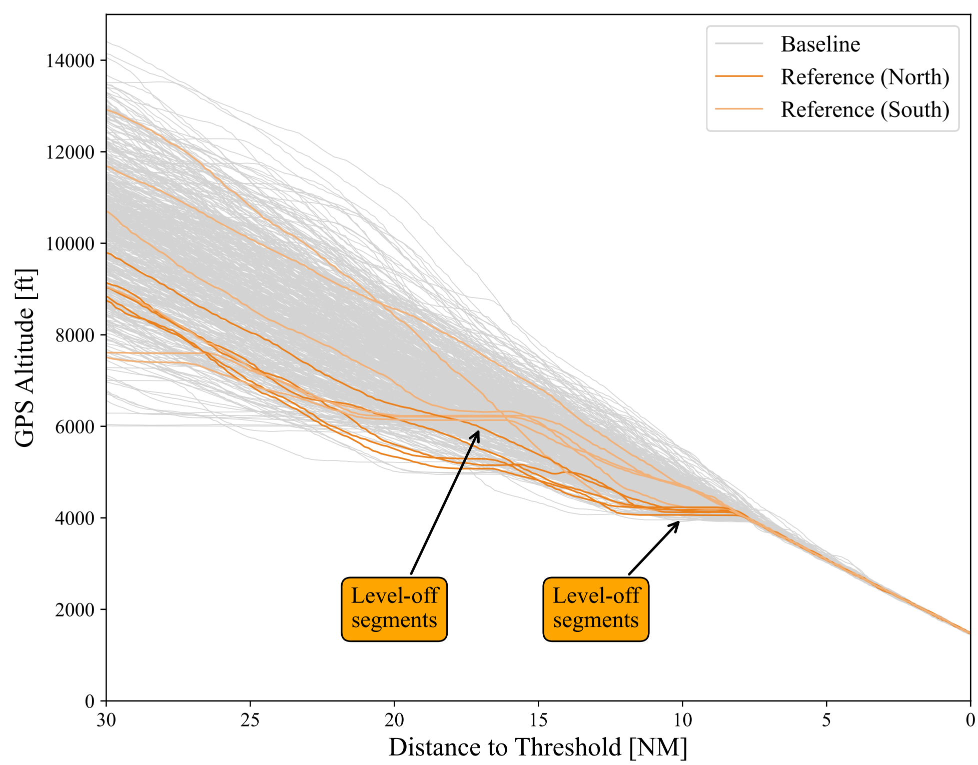


Fig. 8 Vertical profiles of reference flights together with baseline flights along the projected distance to threshold

glideslope segment, located 8 NM from the threshold, as fuel-efficiently as possible while adhering to the standard configuration sequence outlined in the Flight Crew Operating Manual (FCOM) and achieving a stabilized approach.

Figure 9 compares the vertical profiles of baseline flights with those of to the optimum flights conducted along the PBN-to-ILS transition using LNAS. The data clearly show that level-offs segments were almost entirely eliminated in all LNAS-assisted flights, enabling pilots to consistently perform CDAs. Moreover, vertical speed (V/S) segments with a descent rate of approximately 500 ft/min are observed to be horizontally aligned within each subgroup for the two localizer intercept directions, indicating a high degree of repeatability among flights conducted on different days and under varying environmental conditions. From 16 NM onward, all optimum flights established a stable V/S segment leading into the glideslope, at or just before the FAF. This structured CDA profile not only supports optimum energy management for glideslope intercept but also enhances trajectory predictability from an ATC perspective. Regarding noise impact, the higher vertical profiles observed in the optimum flights compared to the reference flights are favourable, as they contribute to a reduced noise footprint on the ground.

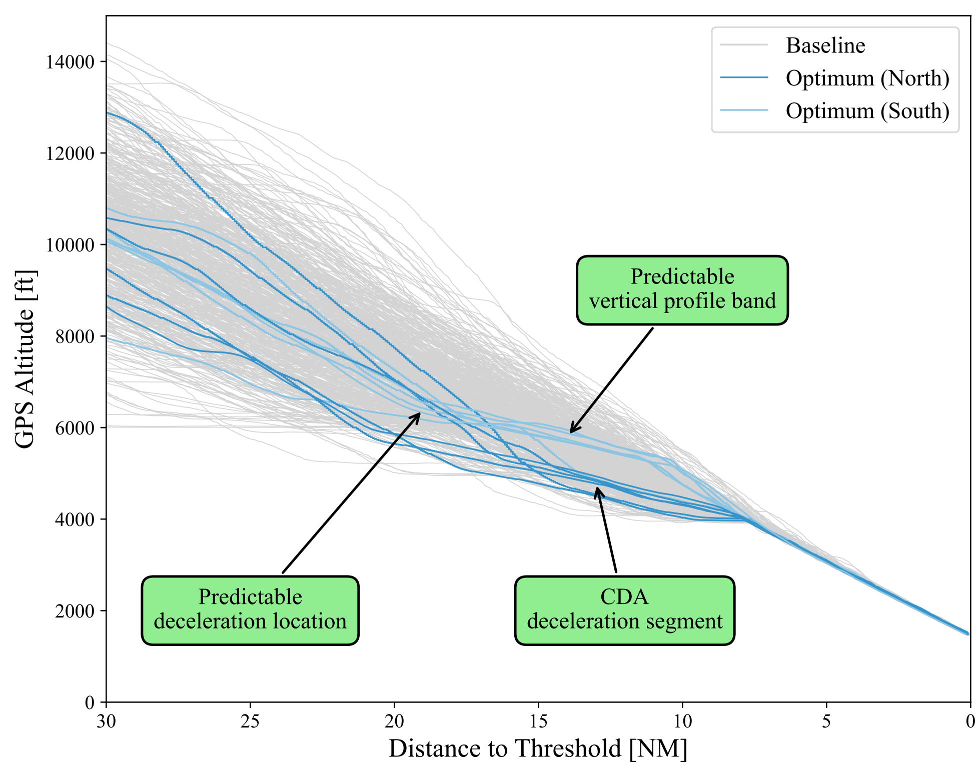
3.2 Speed profiles

The baseline flights (grey) encompassed a wider range of operational conditions, including approaches under tight ATC speed control as well as those without any speed restrictions. However, in the reference flights (orange) the pilots aimed to initiate continuous deceleration at idle thrust toward the target speed of 170 knots, without system assistance, ideally reaching it precisely at the point of glideslope intercept, see Fig. 10. Although most reference flights achieved the target speed of 170 knots at approximately 8 NM from the runway threshold, some aircraft reached it considerably earlier in the approach, indicating suboptimal energy management and variability in manual descent planning. The broad spread of deceleration initiation points also complicates ATC coordination, as it reduces the predictability required for precise sequencing and spacing, particularly in traffic-constrained environments.

The baseline flight dataset (grey lines) further illustrates that, in the absence of intermediate speed restrictions, aircraft frequently remained in a high-energy state over the final 15 NM. This often resulted in non-standard configuration sequences, such as early landing gear extension before deploying high lift devices or the use of speed brakes, both of which increase drag and fuel consumption.

In contrast, speed management was significantly improved in LNAS-assisted optimum flights, see Fig. 11. The deceleration initiation point became highly predictable, consistently occurring within a narrow range of 19 to 21 NM from the runway threshold for approaches from the southwest, and around 14 NM for approaches from the northeast. Optimum flights exhibit a smooth and consistent deceleration pattern.

Fig. 9 Vertical profiles of the optimum flights supported by the pilot assistance system show an increased and a more predictable vertical path before glideslope intercept



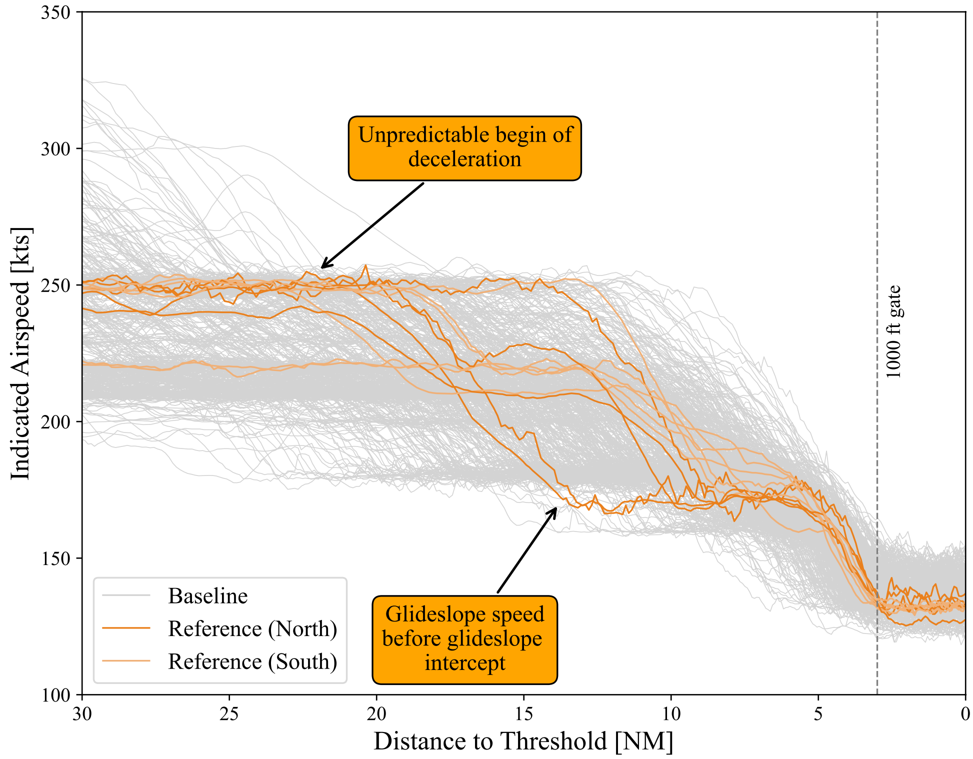


Fig. 10 Speed profiles for the reference flights along the PBN-to-ILS transition

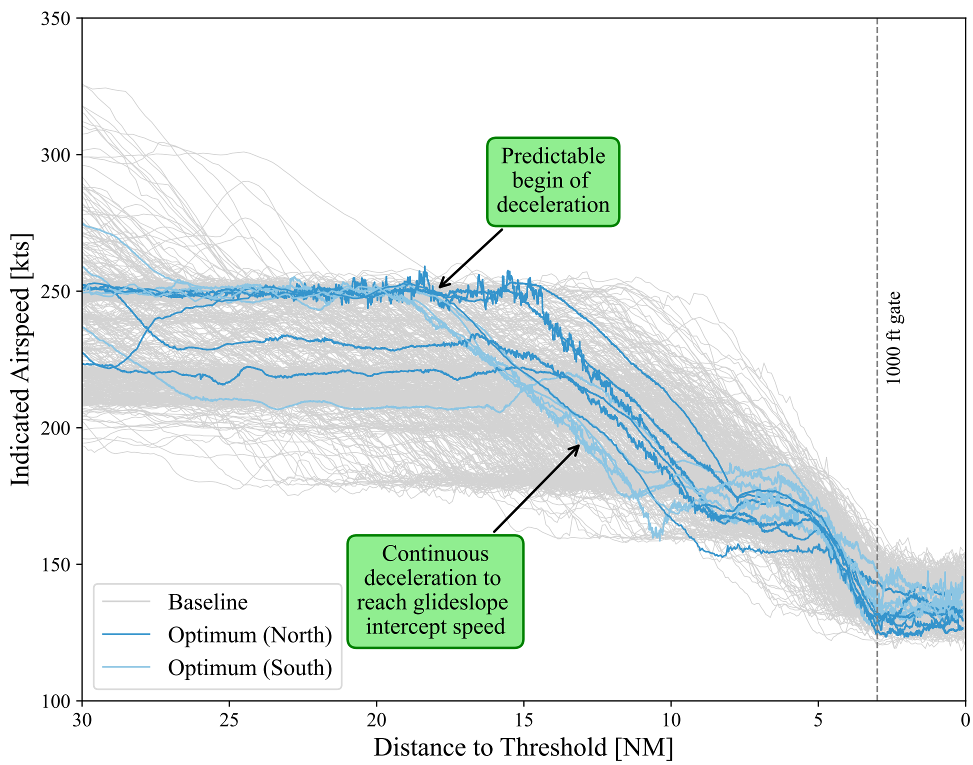


Fig. 11 The initiation of the speed reduction to cross the Final Approach Fix at 170 knots for the optimum flights was significantly more closely located within a narrow band compared to the reference flights

This higher speed predictability is particularly advantageous from an ATC perspective, as it enables more reliable sequencing and separation planning. Looking ahead, future developments could enable the transmission of the onboard-calculated deceleration point to ATC via datalink, e.g., through Automatic Dependent Surveillance—Contract (ADS-C) Extended Projected Profile (EPP) reports to ATC from the aircraft. Such capability would allow controllers to assess the aircraft's default deceleration point in advance and determine whether earlier or additional speed instructions are required to optimize spacing and maintaining arrival flow efficiency.

3.3 Fuel burn

In this section, N1 values, representing fan rotational speed as a percentage of maximum, are used as a qualitative proxy for fuel burn in the graphical analysis. The analysis begins with an examination of engine thrust levels in the baseline dataset, comprising 547 flights, see Fig. 12. The median N1 shows a gradual reduction in thrust over the final 90 NM of flight, with a minor increase near the FAF at 8 NM, and a more pronounced rise around 4 NM, corresponding to approach stabilization.

However, analysing the 75th percentile, representing the N1 value below which 75% of all flights operate, reveals additional patterns. A distinct thrust spike appears around 18 NM, later linked to a pronounced level-off segment, with further increases near the glideslope interception point at 8 NM and again around 5 NM, coinciding with landing gear deployment. These findings demonstrate that the 75th percentile of the N1 profile values provides valuable insights into current operational practices at any airport when using full flight data, particularly regarding energy management and vertical flight efficiency (VFE). This is especially true when applied to large-scale datasets representative of typical airline operations during descent.

This percentile-based methodology offers a practical framework for comparative analyses across different airports and runways. In contrast, the 25th N1 percentile reflects near-idle thrust conditions, serving as a lower-bound reference for minimum thrust operations within the baseline dataset.

Next, the 75th-percentile N1 values were overlaid as a colour map on the vertical and speed profiles of the baseline flight dataset to investigate the correlation between vertical geometry, airspeed, and engine thrust. For this analysis, the data were binned with a resolution of 0.1 NM in distance-to-go, 50 ft in altitude, and 1 kt in airspeed. Within each bin, the 75th percentile of all N1 values from trajectories intersecting that bin was computed. In the resulting diagrams, each non-empty bin was colour-coded according to its corresponding N1 percentile value, providing a detailed visualization of thrust distribution across the descent profile. This represents a novel visualization method for assessing the efficiency of descent trajectories, developed specifically for this study. The resulting **75th-percentile N1 thrust values for the vertical profiles** are presented in Fig. 13. Three distinct features emerge from the analyses. First, the horizontal level segment at 6′000 ft, clearly visible in the vertical profile, is associated with a notable thrust increase. Second, several trajectories exhibit a continuous descent below the optimum idle-thrust vertical profile, requiring elevated thrust settings to maintain the flight path. Finally, a third cluster of thrust increases is observed just before the glideslope intercept at 4′000 ft.

Further insights are obtained from the analysis of the 75th-percentile N1 values for the speed profiles **of the**

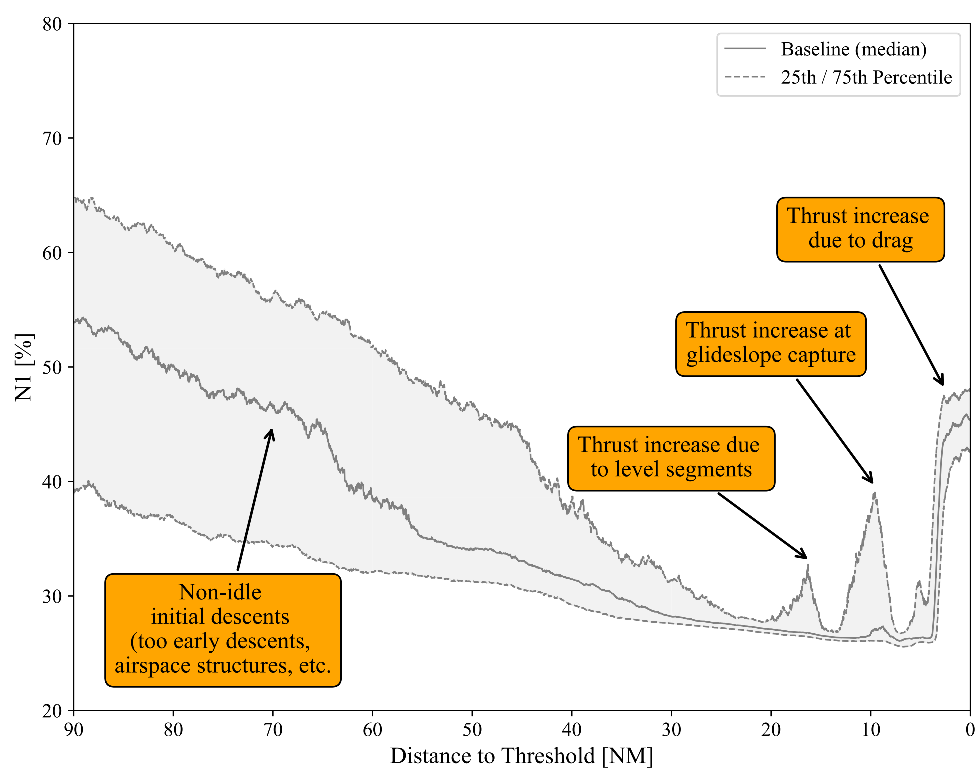


Fig. 12 Median, 75th and 25th Percentile of N1 fan speed for the baseline flight dataset to LSZH runway 14 with Airbus A320neo

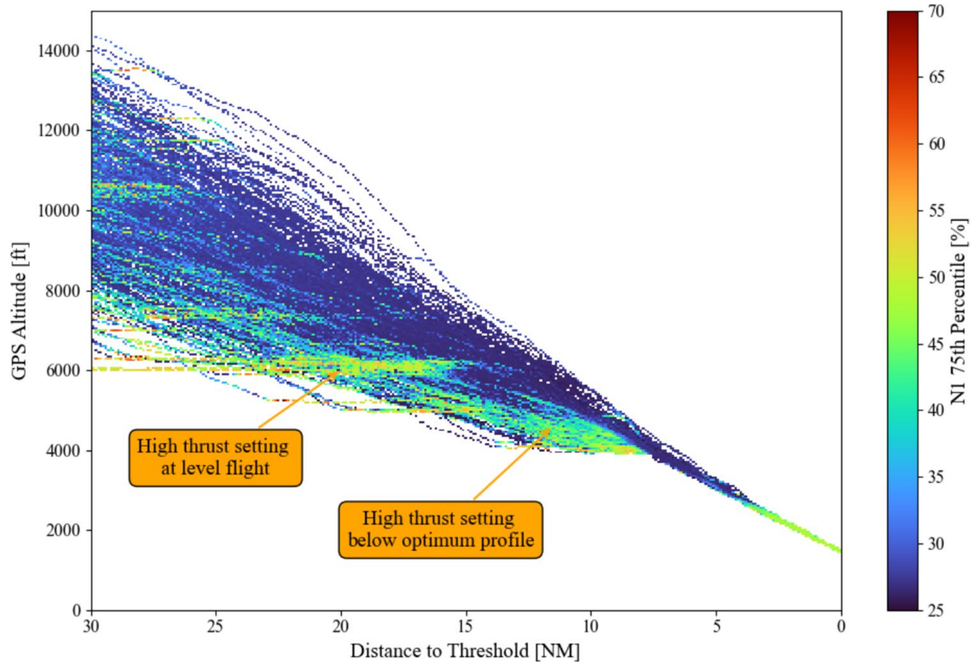


Fig. 13: 75th percentile of N1 along the vertical profiles of the baseline flight dataset

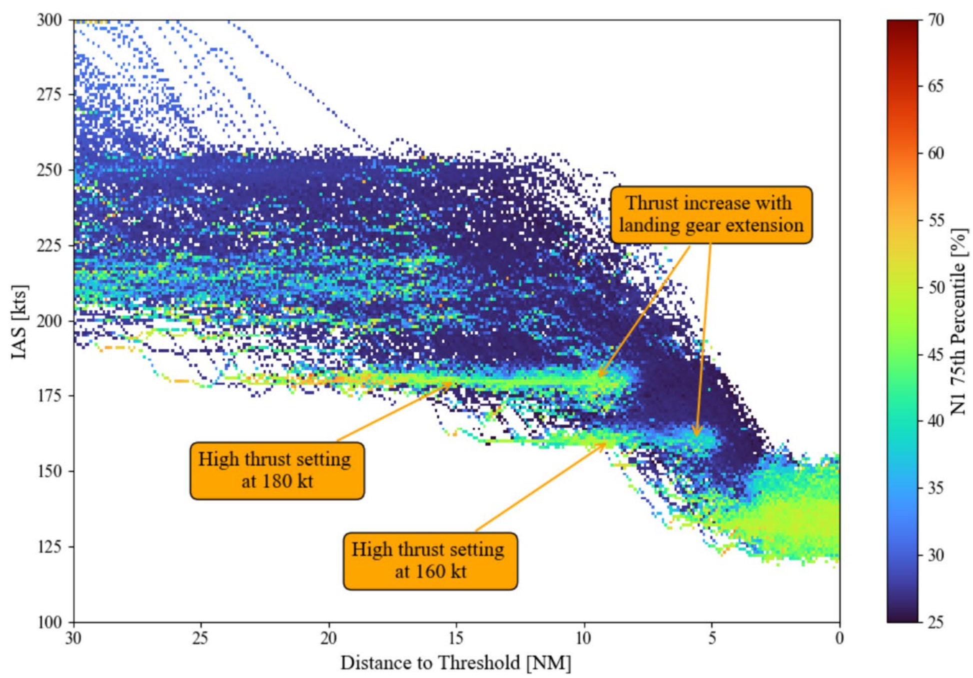


Fig. 14: 75th percentile of N1 along the speed profiles of the baseline flight dataset

baseline flight data set, see Fig. 14. At Zurich Airport, the initial speed assigned upon TMA entry typically corresponds to minimum clean, an aircraft- and weight-dependent value of around 220 knots, representing the lowest permissible speed for clean configuration. This is reflected in the data by thin, elevated thrust traces within that speed range. The next common ATC speed instruction is 180 knots, applicable to most arriving flights. This intervention is clearly visible as a pronounced thrust band at 180 knots, indicating that aircraft are flying below the optimal idle-thrust descent profile and thus require increased thrust. This 180-knot feature transitions into a broader, cloud-like pattern corresponding to the onset of landing gear deployment. A similarly distinct thrust line appears at 160 knots, another frequently assigned ATC speed, terminating with a sharp thrust increase near 5 NM from the threshold, again associated with landing gear extension. Finally, thrust levels in the landing segment are dispersed across a wide range of speeds, reflecting variations in aircraft weight and final landing configuration (e.g., Flaps 3 versus Flaps Full).

Following this examination of the general thrust characteristics during in descent at Zurich Airport, the reference and optimum flight groups were evaluated. Figure 15 shows the actual N1 values for each individual reference and optimum flight.

To further assess the thrust, the **75th percentile method was applied to both the reference and optimum datasets**, see Fig. 16. The analysis reveals elevated thrust levels in the unassisted reference flights between 17 and 23 NM from the runway, consistent with early level-offs at 6′000 feet. A distinct thrust spike is also observed at the glideslope intercept point. In contrast, the LNAS-assisted flights exhibited consistently lower thrust settings throughout the descent, characterized by a smoother and more energy-efficient glideslope capture. These results clearly demonstrate the effectiveness of LNAS in supporting optimized descent profiles and idle thrust operation.

To quantify the associated fuel savings, fuel-flow data were integrated backward from touchdown to 30 NM before the runway threshold. Figure 17 presents the total fuel consumed within this segment for the three flight groups.

Baseline flights that did not meet the engine thrust stabilization criterion, specifically, engine spool-up by 1′000 ft AGL, have a slight advantage in terms of fuel consumption compared to both the reference and optimum flights. However, this effect was not explicitly considered in the current analysis.

The fuel saving percentage was calculated using the following formula:

$$\Delta_{Fuel}\,(\%) = \frac{\overline{\sum Fuel_{Reference}} - \overline{\sum Fuel_{Optimum}}}{\overline{\sum Fuel_{Reference}}} \times 100$$

A comparison between the **unassisted reference flights** and the **LNAS-assisted optimal flights** along the PBN to ILS trajectory indicates an average **fuel saving of 8.8%** in favour of the optimum flights. Additionally, **LNAS-assisted optimum flights** consumed **6.1% less fuel than the baseline flights** over the same 30 NM segment, demonstrating the operational efficiency gains achievable through pilot assistance systems under real-world conditions.

While the mean fuel consumption of the optimum flights was lower than that of the reference flights, the Welch's *t*-test did not confirm a statistically significant difference at the 95% confidence level ($p=0.162$). This corresponds to a 16.2% probability that the observed difference could have occurred by random variation. Similarly, the probability that the optimum flights belong to the same population as the baseline flights is 13.7%. Although not statistically significant, the consistent trend toward reduced fuel burn with LNAS active suggests a promising benefit that warrants confirmation with a larger sample size in future studies. Boxplots of the fuel-burn distribution are shown in Fig. 18 (left panel).

To complement the fuel-consumption analysis, the total energy, defined as the sum of kinetic and potential energy, was evaluated at 30 NM from the runway threshold for all three flight groups, see Fig. 18 (right panel).

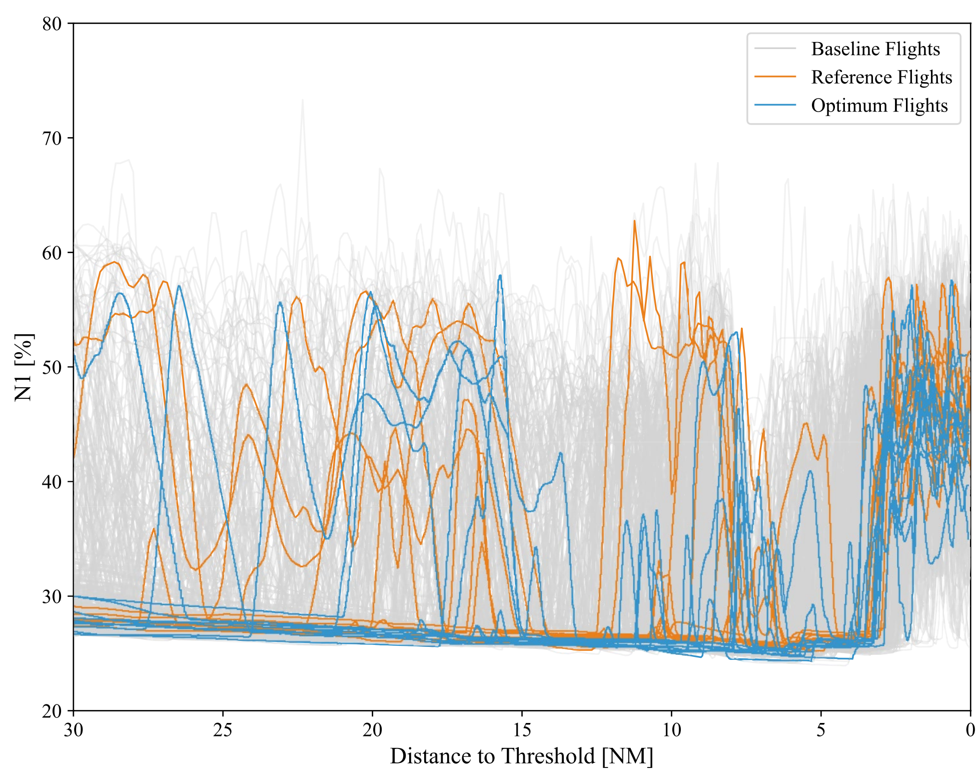


Fig. 15 Actual N1 values for all three groups of flights

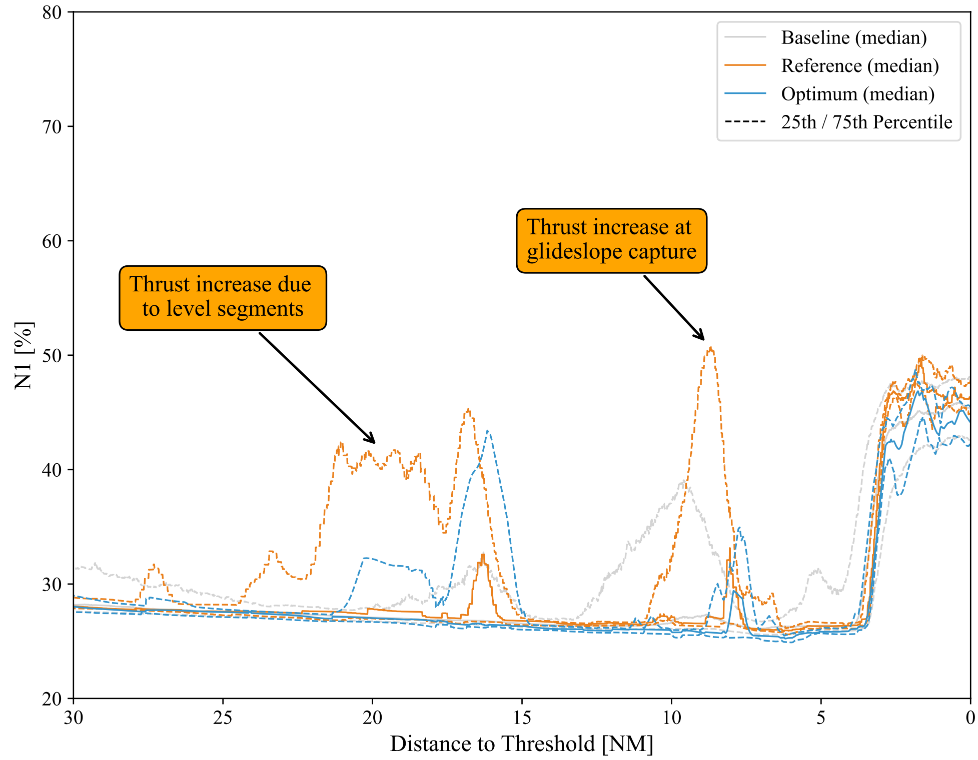


Fig. 16 Median and 75th N1 percentile for baseline, reference and optimum flights

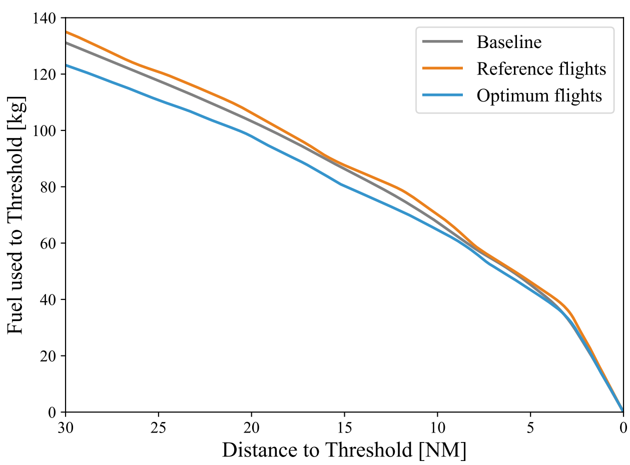


Fig. 17 Fuel used for the baseline, reference and optimum flights

- **Baseline flights** exhibit the highest total energy levels, with a wide distribution and several outliers on both the high and low ends, indicating greater variability in initial descent conditions.
- **Reference flights** start with a slightly lower median energy compared to the baseline, but still show a wider spread than optimum flights. This may contribute to the higher fuel burn observed in reference flights, as additional thrust is required to manage lower total energy during descent.
- **Optimum flights**, in contrast, display the lowest variability in total energy and a median close to that of the baseline group. The lower spread of the fuel burn distribution suggests an earlier and more optimized initial energy state, enabling a more efficient optimum descent, consistent with the guidance provided by the LNAS system.

3.4 Aircraft configuration and aircraft noise

Although this study did not include direct noise measurements, the mechanisms by which the optimized descents reduce acoustic emissions have been quantified in recent work by Wunderli et al. [17]. This analysis, based on high-fidelity simulations and pilot-in-the-loop trials with the DYNCAT system, representing the first implementation of the LNAS concept within an integrated avionics environment, demonstrated that during approach the airframe noise, originating primarily from high-lift devices and landing gear, generally dominates over engine (fan) noise once the aircraft is in descent configuration. Consequently, reducing airspeed, delaying the extension of flaps/slats and landing gear, and maintaining idle thrust directly decreases the acoustic energy radiated toward the ground. The mentioned study confirms that airframe noise is in general dominant over engine noise in descent. Contributing factors to noise reduction are attributed in this study to later flaps/slats and landing gear extension, and less use of speed brakes [17]. In the context of the present study, and in the absence of quantitative noise modelling, the assessment for noise impact is

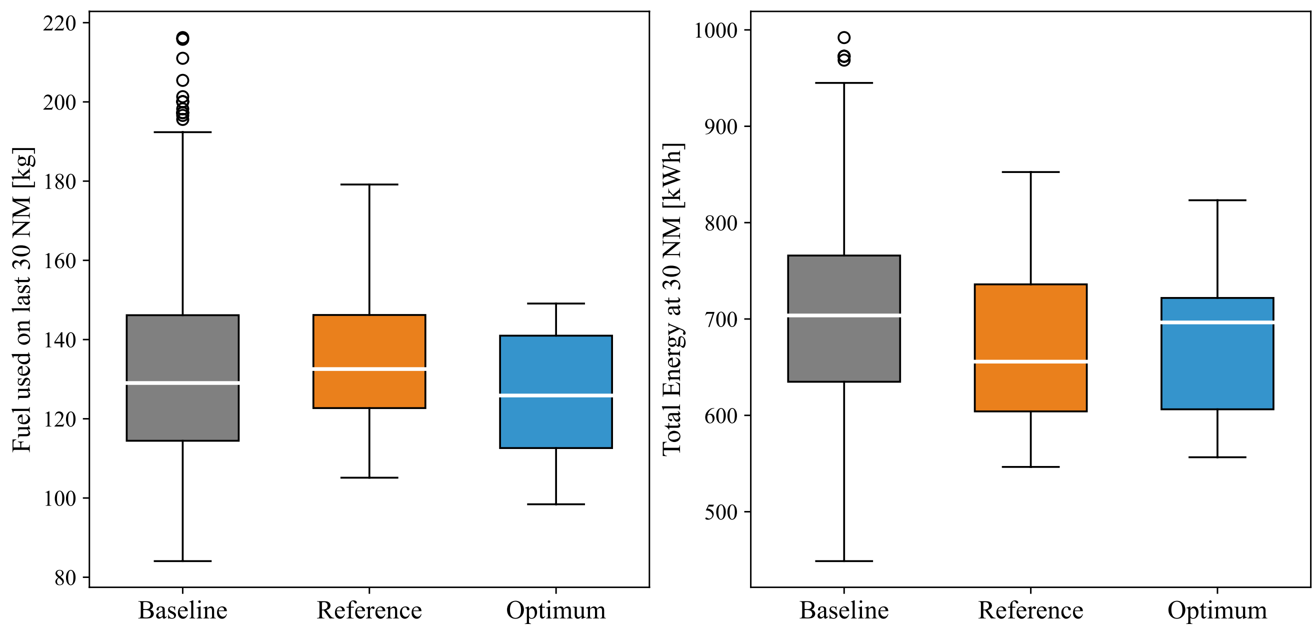


Fig. 18 Boxplot of fuel used (left) and total energy at 30 NM from touchdown (right)

therefore limited to observing changes in influencing factors, namely, later configuration deployment and reduced use of speed brakes, across the three flight datasets.

Speed brakes are commonly used to dissipate excess energy during descent. However, when deployed at lower altitudes and in proximity to the runway, they become a significant contributor to increased aircraft noise. To evaluate their use in daily operation, an analysis of speed brake application rate was conducted for the baseline flights, expressed as a percentage of deployment time. The data were binned by altitude (50 ft resolution) and distance-to-go (0.1 NM resolution), and within each bin the percentage of active speed brake instances was computed. The resulting colour-coded map visualizes speed-brake usage as a function of altitude or airspeed versus distance.

Figures 19 and 20 confirm the expected behaviour in the baseline dataset: speed brakes are predominantly used to manage excess energy in the upper portions of vertical profiles and in the higher speed range near glideslope interception. The figures also show that during segments flown at a stabilized assigned speed of 180 knots, speed brake usage is rare, consistent with previous findings of increased thrust settings in this speed band. This indicates that speed brakes are primarily deployed to correct vertical deviations, rather than to comply with speed restrictions, underscoring their role as a reactive measure to compensate for non-optimal descent profiles.

When comparing speed brake usage across the three flight groups, a distinct pattern emerges as visible in Fig. 21. Reference flights following the PBN-to-ILS transition exhibit increased speed brake deployment around 13 NM from the runway, just before glideslope intercept. In contrast, optimum flights supported by the LNAS pilot assistance system tend to activate speed brakes earlier, between 27 and 17 NM, allowing energy correction at higher altitudes, where such interventions have less acoustic impact. This shift in timing not only contributes to noise abatement, by avoiding speed brake use at lower altitudes near the airport, but also reflects improved situational awareness. The pilot assistance system enables pilots to take timely, proactive action to manage the aircraft's energy state well before the final approach.

At a target speed of 170 knots, the typical aircraft configuration for an A320 at glideslope intercept, especially at or near maximum landing weight, is Flaps 2. A comparison between the reference and optimum flights shows that Flaps 2 was extended slightly earlier in the optimum, LNAS-assisted flights as seen in Fig. 22. Flaps 2 extension occurred along the deceleration segments in vertical speed (V/S) mode, prior to glideslope capture as seen Fig. 23. However, Flaps 2 extension in the optimum flights took place at lower airspeeds, maintaining a larger margin to the V_{FE} (Maximum Flap Extended Speed) as shown in Fig. 24. This not only contributes to reduced aerodynamic noise but also results in lower structural loads.

In the baseline dataset, landing gear extension frequently occurred at higher airspeeds, suggesting its use as an additional drag source in undesired high-energy situations, as shown in Figs. 25, 26, and 27. By contrast, an energy management system such as LNAS offers a distinct advantage by enhancing pilot situational awareness of the aircraft's energy state earlier in the descent. This improved awareness helps prevent the need for late-stage energy dissipation

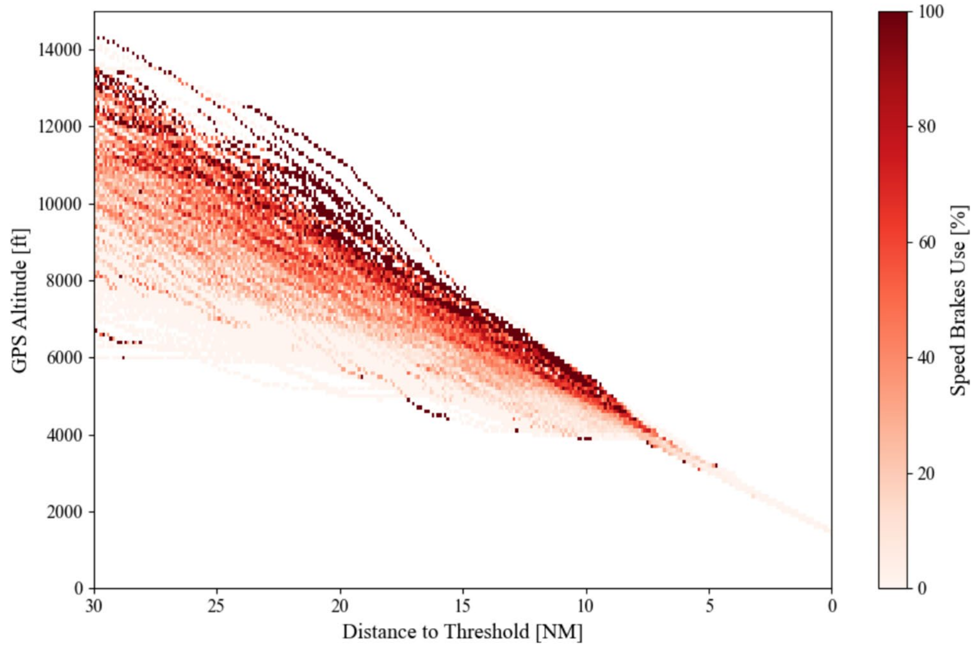


Fig. 19 Speed brake use depending on the vertical profile location

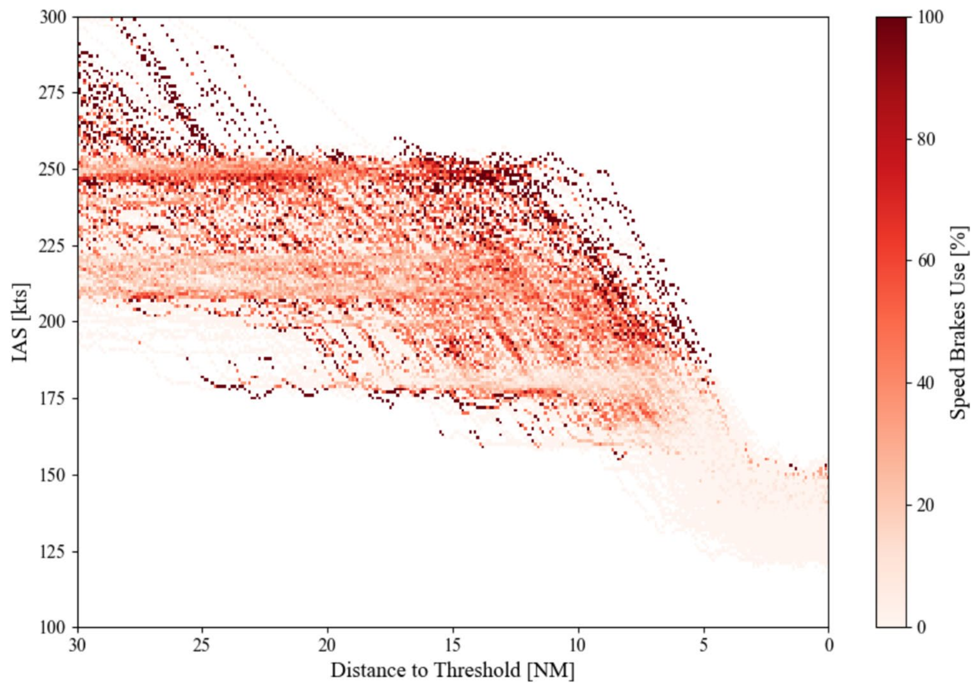


Fig. 20 Speed brake use depending on the current airspeed

using landing gear. As a result, landing gear extension can be performed later and at lower airspeeds, consistent with noise-reduction operational practices.

Except for a single outlier in the reference flight group, the landing gear extension points for both the reference and optimum flights are closely aligned. The combination of a defined target speed at glideslope intercept and the absence of additional ATC constraints contributed to consistent aircraft stabilization along the glideslope, enabling uniformly late gear deployment. Nevertheless, integrating an advisory cue into a pilot assistance system, indicating the latest recommended landing gear extension point to ensure approach stabilization at 1′000 ft AGL, could further enhance safety margins and help prevent unstable approaches.

3.5 Human performance

3.5.1 Cognitive workload and situational awareness

Modern flight decks are increasingly integrating multiple levels of automation to assist pilots in managing complex

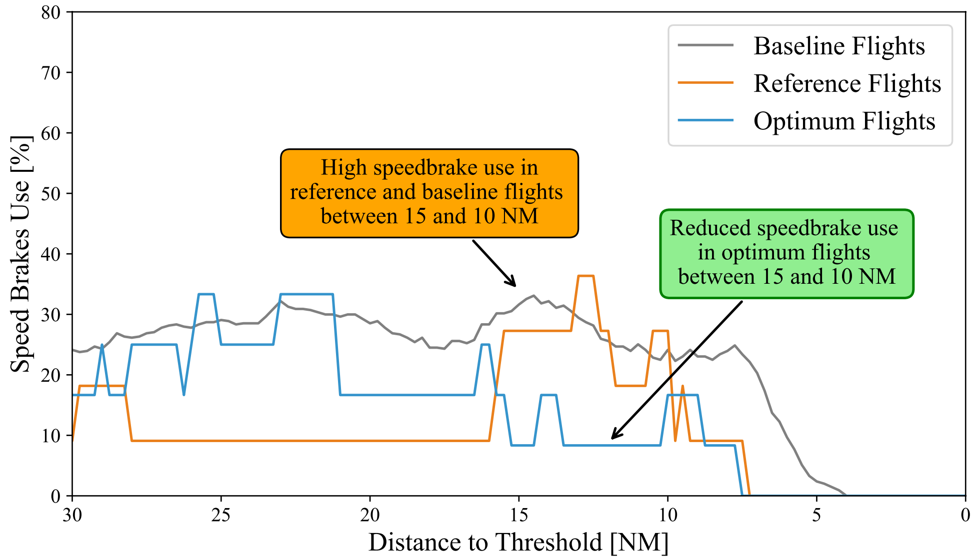


Fig. 21 Percentage of speed brake usage for the 3 groups, baseline flights, reference flights, and optimum flights

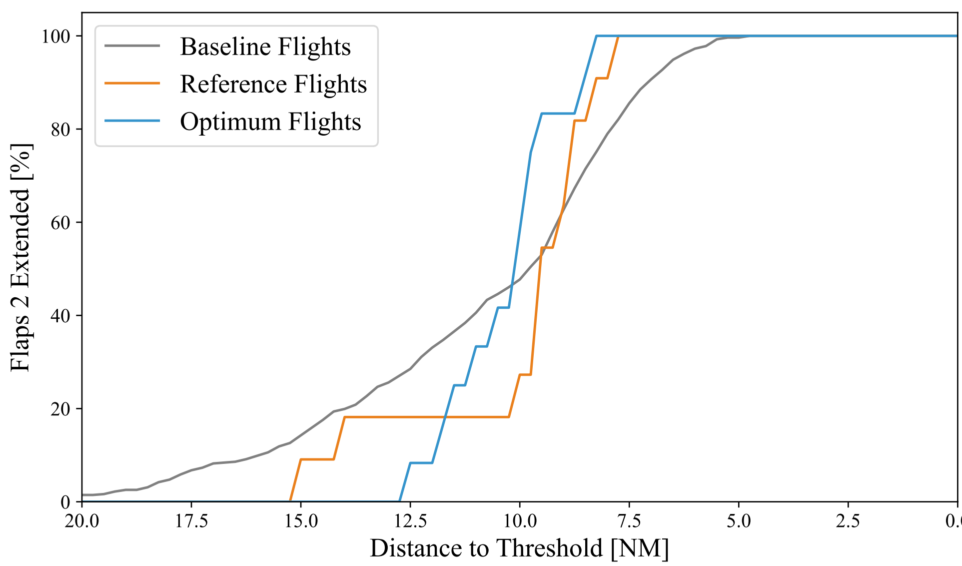


Fig. 22 Cumulative percentage of Flaps 2 extension along the last 20 NM before the threshold

tasks, particularly during high-workload phases such as descent and approach. Pilots must not only monitor and respond to real-time information, but also anticipate the aircraft's behaviour in relation to its energy state. This cognitive demand is further intensified by external factors such as dynamic ATC instructions, adverse weather conditions (e.g., strong winds), or atypical situations such as glideslope intercept from above when managing excess energy [22].

Because the present study was conducted under real-world airline operations, a detailed assessment of cognitive workload and situational awareness was not feasible. Nevertheless, qualitative feedback collected from the participating pilots supports earlier research and highlights the benefits of LNAS [14, 23]. Pilot feedback particularly emphasized how the system improved aircraft energy management and reduced workload during the approach phase.

3.5.2 Pilot feedback and observed benefits

Overall, pilot feedback consistently reported a perceived reduction in workload when using LNAS. Many stated that the system provided validation of their intended descent strategy, reinforcing confidence that their plan would results in a stabilized approach. Instead of constructing an energy management plan from scratch, pilots typically found that they only needed to assess and confirm the solution proposed by LNAS. This support proved especially valuable in dynamic operational environments, where last-minute changes in the approach sequence, such as ATC-issued shortcuts, can easily disrupt pre-planned descent strategies.

Pilots also reported enhanced situational awareness, beginning with the procedural clarity. The precise knowledge of the remaining DTG, enabled by the closed-path PBN-to-ILS transition, offered a major advantage over conventional

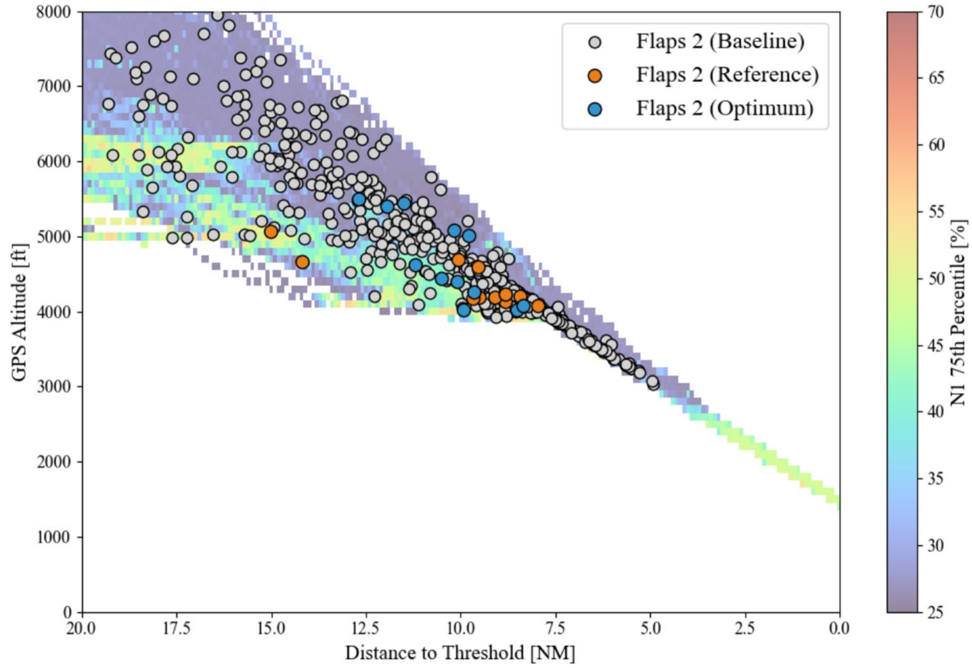


Fig. 23 Location of Flaps 2 extension across all flight groups for the vertical profile, overlaid on the 75th percentile N1 profile of the baseline flights

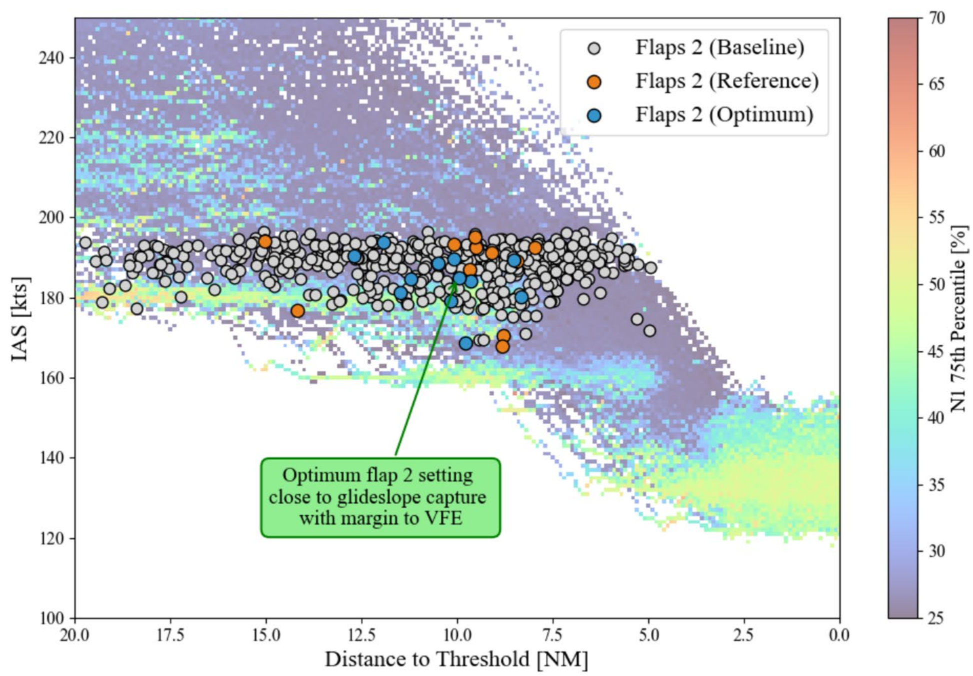


Fig. 24 Location of Flaps 2 extension across all flight groups for the speed profile, overlaid on the 75th percentile N1 profile of the baseline flights

radar vectoring, where remaining distance is often uncertain. This predictability, combined with the defined target speed of 170 knots at the FAF, simplified descent planning and reduced ambiguity in the descent profile.

In addition, LNAS continuously processed real-time flight data to provide instantaneous feedback on the aircraft's energy state, allowing pilots to determine early whether a stable approach was achievable under prevailing conditions. This transparency proved essential for proactive decision-making and further reinforced confidence in energy-management strategy. Pilots described LNAS as a direct feedback mechanism that supported learning and continuous improvement in managing aircraft energy.

3.5.3 Relation to pilot core competencies

The framework for the pilot performance used in this study draws upon ICAO Doc 9995 [24], which introduced the concept of '*Pilot Core Competencies*', clusters of observable behaviours, that describe proficient performance. The

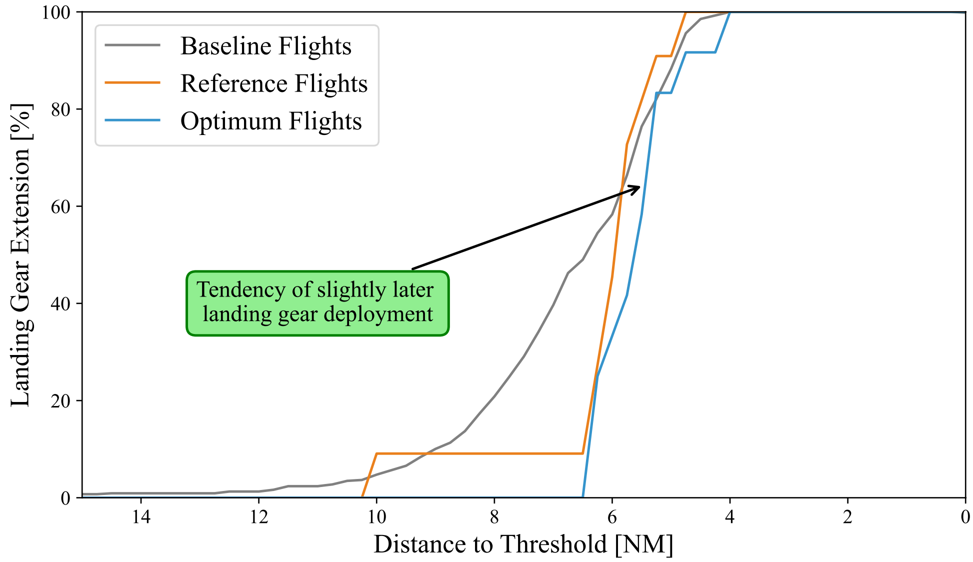


Fig. 25 Cumulative percentage of landing gear extension along the last 15 NM before the threshold

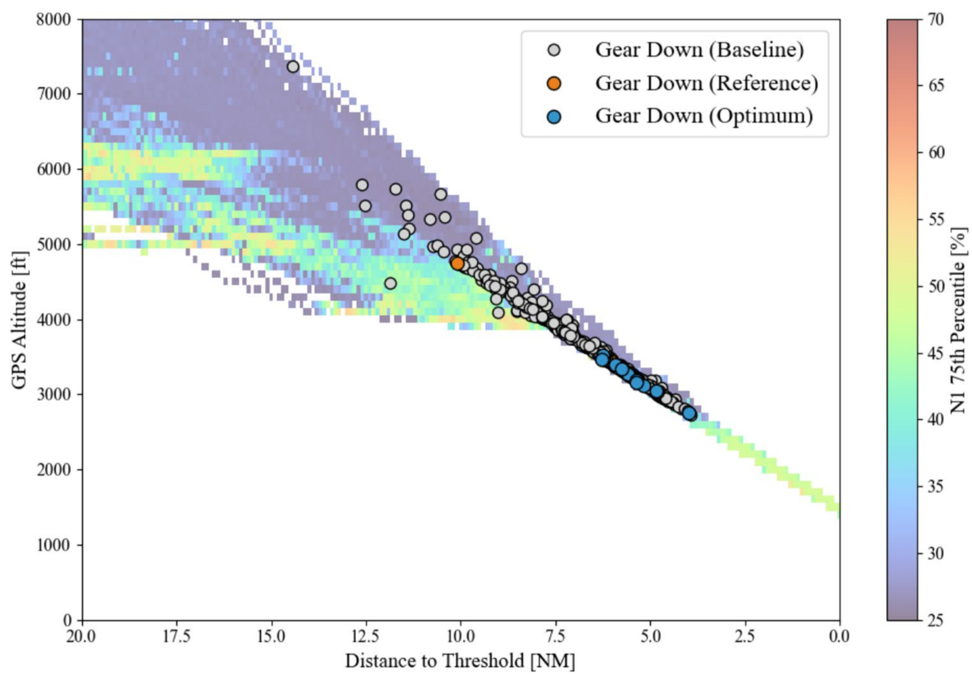


Fig. 26 Location of landing gear extension across all flight groups for the vertical profile, overlaid on the 75th percentile N1 profile of the baseline flights

European Union Aviation Safety Agency (EASA) adopted this approach in its '*Evidence-Based and Competency-Based Training Manual*' [25]. This regulatory framework marks the transition from task-based to Competency-Based Training (CBT), focusing on measurable development of key behavioural skills essential for safe and efficient flight operations.

Evidence-Based Training (EBT) leverages empirical data from flight data monitoring, line operations safety audits, and operational experience to ensure relevant training. CBT, on the other hand, emphasizes measurable skill acquisition and assessment, structured around nine pilot core competencies, each with defined observable behaviours (OBs) that reflect the level of mastery.

Within the context of aircraft energy management, several competencies are particularly relevant to the LNAS concept:

1) Application of Knowledge (KNO)
2) Situation Awareness and Management of Information (SAW)
3) Workload Management (WLM)
4) Aeroplane Flight Path Management – Automation & Manual (FPA & FPM)

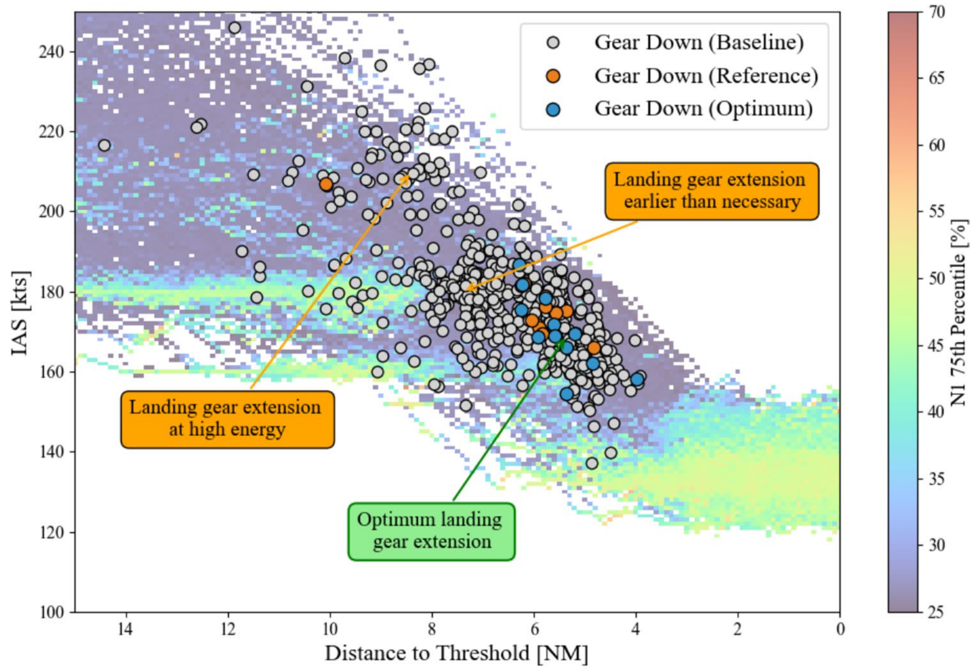


Fig. 27 Location of landing gear extension across all flight groups for the speed profile, overlaid on the 75th percentile N1 profile of the baseline flights

These competencies provide a robust framework for evaluating the benefits of pilot-assistance systems such as LNAS. They also align with the concerns expressed in the FAA Advisory Circular cited in the introduction of this study: "*Industry reports and operational data from airlines and aircraft manufacturers indicate that pilots have vulnerabilities in awareness and management of the aircraft's energy state, across multiple phases of flight, which is potentially a significant contributing factor in flightpath deviations, incidents, and accidents.*" [1].

Pilot feedback and observations indicate that LNAS makes a meaningful contribution to the development of several core competencies. The system's visualization of the predicted vertical trajectory, based on the aircraft's actual energy state, supports an intuitive learning process that strengthens pilots' ability to manage aircraft energy more efficiently. For example, when speed brakes are deployed, LNAS graphically depicts how the actual trajectory converges toward the optimal path, reinforcing cause-and-effect understanding. This immediate visual feedback fosters higher-order cognitive skills, aligned with Bloom's Taxonomy, including *Remembering, Understanding, Applying, Analysing, Evaluating, and Creating* [26].

Over time, pilots reported being able to transfer these insights to other approaches, even without using LNAS. This suggests that the system helps pilots to develop internalized mental models for managing aircraft energy, which can be generalized across varying operational contexts, ultimately strengthening long-term competency in flightpath and energy management.

LNAS provides a predictive visualization of the aircraft trajectory and feedback when deviations from the optimum profile occur. For example, if an idle-thrust descent is no longer achievable, the system estimates how many knots above the intended speed the aircraft will intercept the glideslope if no corrective action is taken.

The resulting human performance benefits are illustrated in Fig. 28, showing how LNAS supports multiple pilot core competencies:

- **Application of Knowledge (KNO)**: Enhances understanding of aircraft-specific performance characteristics, including vertical flight efficiency (VFE) and deceleration behaviour. This competency is reinforced through situational familiarity with local procedures, airspace structures and typical ATC practices, which are essential for anticipating and managing deviations from the planned descent profile.
- **Situation Awareness and Management of Information (SAW)**: LNAS significantly enhances situational awareness by providing a clear, real-time overview of the aircraft's energy state. It enables pilots to evaluate altitude-speed-distance relationships, assess wind effects, and determine whether the aircraft's energy state allows safe acceptance of ATC shortcuts. As shown in Fig. 21, the aircraft's energy cues and flightpath predictions enabled pilots to identify and correct excessive energy early in the descent, reducing the need for speed brakes at low altitudes.
- **Workload Management (WLM)**: Early energy cues allow pilots to identify and resolve conflicts between the

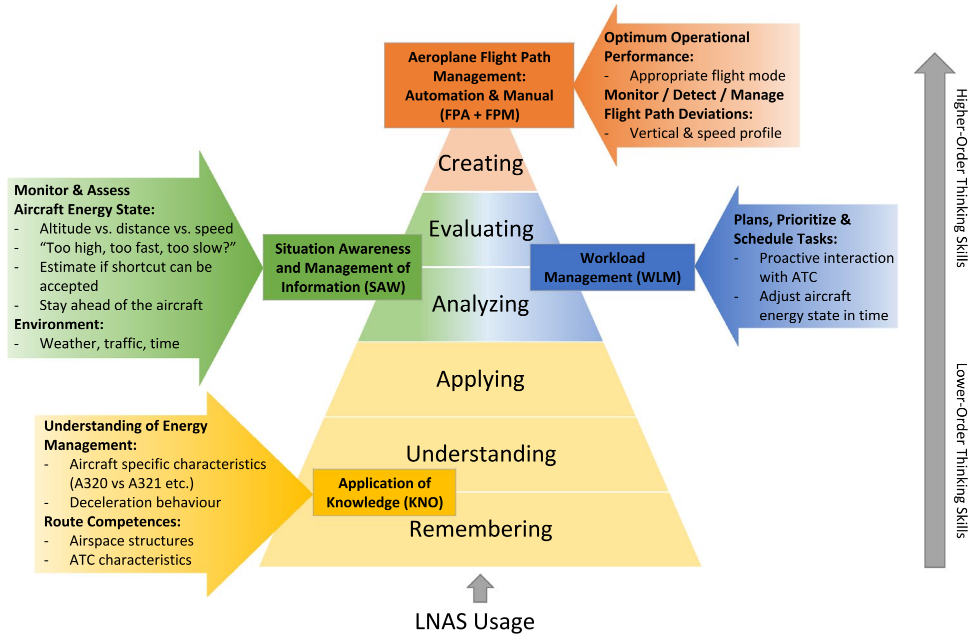


Fig. 28 Benefits of using a pilot assistance system such as LNAS applicable to the CBT pilot competencies and applied to the Bloom's Taxonomy [25, 26]

aircraft's current energy state and required trajectory. This enables proactive communication with ATC, such as requesting a temporary speed increase to achieve a higher descent rate or inquiring about the remaining DTG. Timely adjustments to the aircraft's energy state are far more effective, and safer, than attempting to recover from a critical energy situation at a later stage. By replacing multiple mental calculations (e.g. rule of thumb to estimate the optimum altitude), the usage of LNAS implies a reduction in cognitive workload. Some pilots noted that full integration of LNAS into the PFD and the FMS would further enhance usability and confidence [27]. Such integration would also help to reduce perceived complexity, thereby enhancing the trustworthiness and usability of the system [28].

- **Aeroplane Flight Path Management – Automation & Manual (FPA & FPM)**: LNAS operates within the logic of the existing autopilot modes, enabling more precise control and a proactive flight-path management. It acts as a decision-support tool rather than a directive system, encouraging deliberate pilot judgment [28].

By guiding pilots toward idle-thrust, low-noise descent profiles, LNAS also fosters environmental awareness and encourages pilots to include eco-efficiency considerations into their operational decision-making.

Importantly, LNAS is designed to support, not replace, pilot authority. It is not an automation system that assumes control, but a visual and analytical aid that promotes reflective practice. Pilots can compare their actual or intended flightpath with an idealized trajectory computed by the system. While this trajectory may not always represent a perfect optimum, due to simplified modelling (e.g. wind profile assumption) and built-in safety margins, it offers a valuable reference for self-assessment and improving energy management skills.

When deviation occur, such as maintaining higher speeds due to ATC constraints (typical scenario: 160 knots up to 4 NM at low landing weights), altering the aircraft configuration sequence (e.g. by extending Flaps 3 before the landing gear), LNAS dynamically recalculates and presents an updated trajectory solution without penalizing or overriding the pilot's decision. Over time, this approach enables pilots to internalize more efficient energy management strategies, applicable even in the absence of the system.

4 Conclusion and future work

4.1 Conclusion

The results from this research project demonstrate the operational and environmental benefits of integrating advanced pilot assistance systems, such as LNAS, into daily airline operations. Approaches flown along the closed PBN-to-ILS transition with LNAS exhibit **significantly more predictable vertical and airspeed profiles**, **lower average thrust settings**, and **reduced reliance on speed brakes** at critical altitudes. These improvements resulted in lower fuel consumption over the last 30 NM compared to both unassisted PBN-to-ILS approaches (reference flights) and unassisted conventional radar vectoring approaches (baseline flights). The observed fuel savings did not reach statistical significance at the 95% confidence level due to limited number of flights conducted.

The successful demonstration of LNAS during commercial operations with Swiss International Air Lines confirms the technical maturity and operational feasibility within a complex ATC environment. The study also revealed valuable insights into how enhanced awareness of aircraft energy state supports improved flightpath management and reduced noise emissions. Embedded within the EBT/CBT framework, LNAS fosters the development of several pilot core competencies, including Application of Knowledge (KNO), Situational Awareness (SAW), Workload Management (WLM), and Flight Path Management (FPA/FPM). It also demonstrates how even advisory level assistance systems, when properly designed, can make meaningful contribution in modern pilot training [29].

4.2 Future work

The findings of this study open several promising research directions that build directly on its outcomes:

1) **Integration into Flight-Deck Architectures**: Future work should focus on embedding the LNAS concept into integrated avionics flight-deck architectures to enable operational deployment. Follow-up research is already underway within SESAR projects such as DYNCAT and DYN-MARS, which aim to bridge the gap between advisory systems and fully integrated flight management solutions.
2) **Dynamic Recalculation of Energy-Neutral Descent Profiles**: The present study was based on a closed lateral path and predefined target speed at the Final Approach Fix (FAF) or glideslope intercept. However, in high-density traffic environments, a practical pilot assistance system must accommodate tactically assigned speed reductions issued by ATC. LNAS has demonstrated the ability to recalculate the vertical profile in real-time in response to such speed interventions, maintaining idle-thrust conditions by trading kinetic for potential energy. Simulator results, see Fig. 29, illustrate how LNAS adjusts the descent trajectory following three successive speed reductions tactically assigned by ATC (250 knots ➜ 220 knots ➜ 170 knots).
These results indicate that, when the aircraft enters the descent phase with an adequate initial energy state, it is possible to accommodate tactical ATC speed interventions while preserving idle-thrust vertical trajectories. This forms the basis of a novel '*energy-neutral idle-thrust descent*' concept, see Fig. 30, where vertical profiles remain energy-balanced even in the presence of ad-hoc tactical speed reductions issued by ATC.

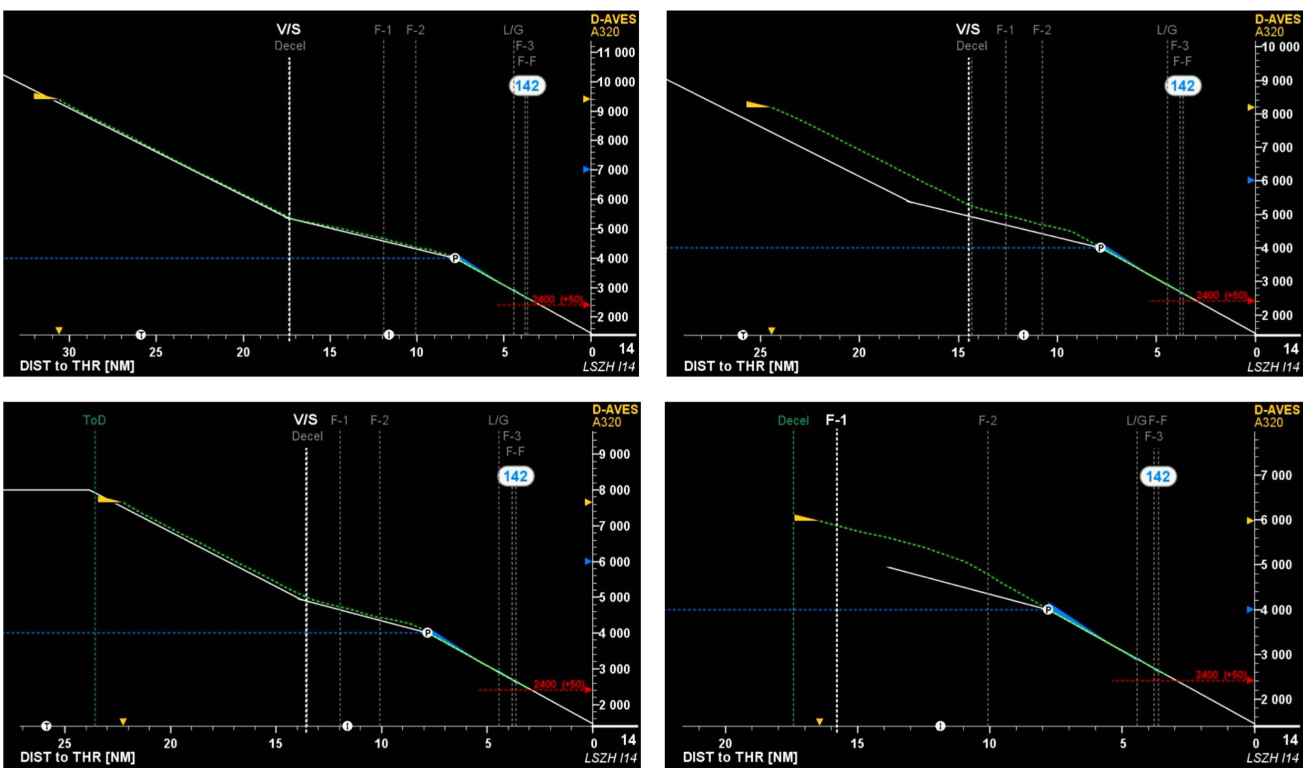


Fig. 29 Dynamic re-calculation of the optimum vertical profile following tactical speed reduction assignment from ATC: initial descent profile from 250 knots (top left), early speed reduction to 220 knots and recalculation of the descent profile in green (top right), established on 220 knots descent profile (bottom left), early speed reduction to 170 knots and profile recalculation (bottom right)

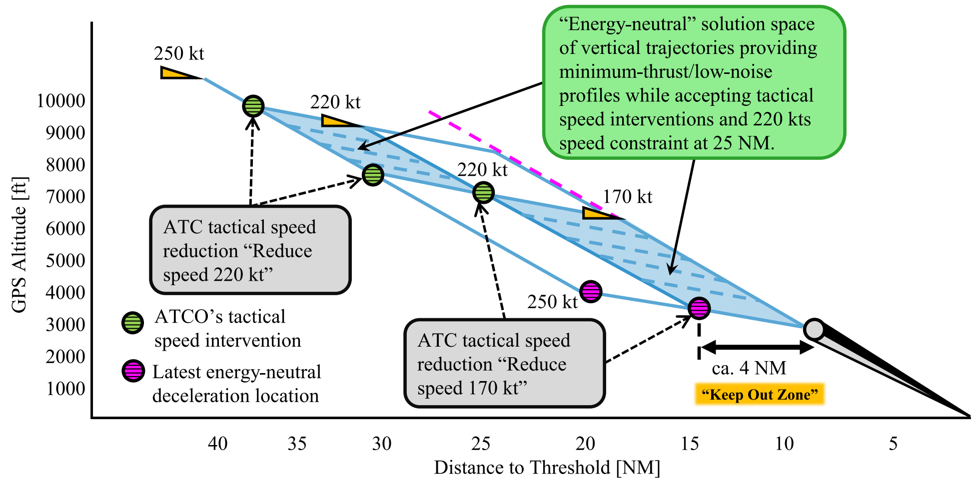


Fig. 30 Concept for energy-neutral idle-thrust descent profiles in a complex high-density air traffic environment

3) **Improved Speed Interventions by ATC**: Controllers may adjust speeds flexibly according to traffic sequencing and separation needs. However, speed instructions should be issued in a manner that allows aircraft to exchange kinetic for potential energy while maintaining idle thrust. Future research should therefore explore optimal ATC speed intervention strategies to support energy-neutral descent. In particular, speed reductions should be issued before to the onboard-calculated deceleration point, as this represents the latest opportunity to decelerate without inducing drag through speed brakes or early landing gear extension. These studies should also examine how improved speed intervention policies affect airport capacity and runway throughput.
4) **Enhanced Air-Ground Information Exchange**: The successful implementation of LNAS-based energy management depends on the early availability of key trajectory information, most notably the remaining distance to go (DTG), ideally defined along a closed lateral path. Future research should investigate how this information can be communicated to the flight deck using datalink systems such as CPDLC route uplinks, providing an early estimated lateral path in the lower Terminal Manoeuvring Area (TMA).
5) **HMI Enhancements**: Subsequent developments should explore the integration of energy-state cues directly into the Primary Flight Displays (PFDs), ensuring that pilots receive critical energy management information in the primary field of view.
6) **Pilot Training and Human-Performance Research**: Building on the human factor benefits observed in this study, future simulator-based research should assess how energy management functions can be incorporated into competency-based pilot training programs. These studies should quantify workload reduction, improvement of situational awareness, and knowledge transfer to line operations.

These improvements are being actively pursued within ongoing SESAR research, notably the DYN-MARS project, which seeks to realize this vision on both the aircraft-avionics and air-traffic-management sides. Together, these efforts aim to transform today's descent procedures into dynamic, collaborative, and energy-aware operations, enhancing both environmental sustainability and flight safety across Europe's airspace network.

Acknowledgements The authors gratefully acknowledge the support of Swiss International Air Lines, in particular Jan Vetsch and Elena Zanaboni for their project management work, and Andreas Bösch for the integration of the LNAS software into the Electronic Flight Bag (EFB) demonstrator. Special thanks are extended to Thomas Muhl and York Schreiber of Skyguide for their roles in developing and implementing a temporary PBN-to-ILS procedure at Zurich Airport. The authors also wish to thank all participating pilots for their dedicated execution of both reference and optimised flights. Appreciation is further extended to the Swiss Flight Data Monitoring Department for providing anonymised flight datasets, and the Flight Operations Department for their support in flight safety assessments and facilitating operational approval. Finally, the authors thank Jean Marc Wunderli, Christoph Zellmann, and Flurin Schwerzmann for their contributions to the analysis of noise characteristics for selected flight profiles.

Author contributions M. Ge. led the flight demonstration campaign, coordinated the training of pilots and operational approvals, and drafted the manuscript, M.Go. and F.A. developed the novel software functionalities and conducted simulator testing of the LNAS software, M.Go. led the human performance assessment task and HMI definition, F.S., P.P. and M.Ge. conducted flight data post processing, data analytics and visualisation, F.A. developed the overall test concept and led the DLR research group. All authors reviewed the manuscript.

Funding This work was funded by the SESAR Joint Undertaking under the Grant Agreement 101017678 and by the Federal Office of Civil Aviation (FOCA) under the Grant Agreement SFLV 2020–089. Skyguide (Swiss Air Navigation Services Ltd.) supported this project with in-kind contributions and the development of a temporary PBN-to-ILS procedure.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

1. Federal Aviation Administration (FAA). Advisory Circular 120–123 – Flightpath Management. 21 November 2022.
2. SESAR DEMO ALBATROSS Report - Part I, Appendix C Demonstration Exercise #03 Report, 20 June 2023.
3. ICAO. Continuous Descent Operations (CDO) Manual. DOC 9931 AN/476, First Edition 2010.
4. NASA B737 Flight test results of the total energy control system, Final Report, January 1987.
5. Sachs, F., Goetz, M., Kurz, J., Abdelmoula, F.: Trials for quiet and efficient flights in advanced continuous descent approach using the low-noise augmentation system LNAS. CEAS Aeronaut. J. (2025). https://doi.org/10.1007/s13272-025-00825-2
6. Xue, D., Du, S., Wang, B., Shang, W.-L., Avogadro, N., Ochieng, W.Y.: Low-carbon benefits of aircraft adopting continuous descent operations. Appl. Energy (2025). https://doi.org/10.1016/j.apenergy.2025.125390
7. Clarke, J.P.B., Ho, N.T., Ren, L., Brown, J.A., Elmer, K.R., Tong, K.O., Wat, J.K.: Continuous descent approach: design and flight test for Louisville international airport. J. Aircr. **41**, 1054–1066 (2004). https://doi.org/10.2514/1.5572
8. EUROCONTROL. European Continuous Climb and Descent Operations Action Plan. European Organisation for the Safety of Air Navigation (EUROCONTROL), Brussels, Belgium, 6 November 2020.
9. Pasutto, P., Zeghal, K.: Exploring and evaluating flight efficiency indicators for arrivals, European Organisation for the Safety Of Air Navigation, Technical Report, September 2023.
10. Sáez, R., Prats, X.: Time-based-fuel-efficient aircraft descents: thrust-idle descents along re-negotiated routes vs. powered descents along published routes. Transp. Res. Part D Transp. Environ. (2023). https://doi.org/10.1016/j.trd.2022.103563
11. Toratani, D., Wickramasinghe, N.K., Westphal, J., Feuerle, T.: Feasibility study on applying continuous descent operations in congested airspace with speed control functionality: fixed flight-path angle descent. Aerosp. Sci. Technol. (2020). https://doi.org/10.1016/j.ast.2020.106236
12. Abdelmoula, F., Roeser, M.S., Kühne, C.G., Gerber, M., Wunderli, J.M.: Impact of ATC speed instructions on fuel consumption and noise exposure: an assessment of real operations in Zurich. CEAS Aeronaut. J. **13**, 1041–1053 (2022). https://doi.org/10.1007/s13272-022-00609-y
13. Abdelmoula, F., Scholz, M.: LNAS - A pilot assistance system for low-noise approaches with minimal fuel consumption. In: Proceedings of the 31st Congress of the International Council of the Aeronautical Sciences, Horizonte, Brazil, 9–14 September 2018.
14. Gerber, M., Schreiber, Y., Abdelmoula, F., Kühne, C.G., Jäger, D., Wunderli, J.M.: Energy-optimized approaches: a challenge from the perspectives of pilots and air traffic controllers. CEAS Aeronaut. J. **13**, 1055–1066 (2022). https://doi.org/10.1007/s13272-022-00607-0
15. Jäger, D., Zellmann, C., Wunderli, J.M., Scholz, M., Abdelmoula, F., Gerber, M.: Validation of an airline pilot assistant system for low-noise approach procedures. Transp. Res. Part D Transp. Environ. **99**, 103020 (2021). https://doi.org/10.1016/j.trd.2021.103020
16. Amelink, M.H.J., van Paassen, R., Mulder, M., Flach, J.M.: Total Energy-Based Perspective Flight Path Display for Aircraft Guidance along Complex Approach Trajectories. In: Proceedings of the 12th International Symposium on Aviation Psychology. April 2003.
17. Wunderli, J.M., Meister, J., Boyer, J., Gerber, M., Bauer, T., Abdelmoula, F.: Pilot assistance systems for energy-optimized approaches: is it possible to reduce fuel consumption and noise at the same time? Aerospace **11**, 450 (2024). https://doi.org/10.3390/aerospace11060450
18. Bauer, T., Abdelmoula, F., Boyer, J., Gerber, M., Meister, J., Wunderli, J.M.: Improved configuration management for greener approaches - evaluation of a novel pilot support concept. CEAS Aeronaut. J. (2025). https://doi.org/10.1007/s13272-025-00846-x
19. Pauly, P., Meister, J., Wunderli, J.M., Gerber, M., Boyer, J., Abdelmoula, F., Bauer, T.: Improved energy management during arrival for lower noise emissions. In Proceedings of the Towards Sustainable Aviation Summit (TSAS), Toulouse, France, 18–20 October 2022; Paper No. 16.
20. Deiler, C.: Aerodynamic model adjustment for an accurate flight performance representation using a large operational flight data base. CEAS Aeronaut. J. **14**, 527–538 (2023). https://doi.org/10.1007/s13272-023-00659-w
21. European Technical Standard Order ETSO-C165a. Electronic Map System for the Graphical Depiction of Aircraft Position. European Aviation Safety Agency, May 2014
22. Heiligers, M.M., Van Holten, Th., Mulder, M.: Predicting pilot task demand load during final approach. Int. J. Aviat. Psychol. **19**(4), 391–416 (2009). https://doi.org/10.1080/10508410902983987
23. Loft, S., Tatasciore, M., Visser, T.: Managing workload, performance, and situation awareness in aviation systems. In Human Factors in Aviation and Aerospace (pp. 171–197). https://doi.org/10.1016/B978-0-12-420139-2.00018-6 (2023).
24. ICAO Doc 9995, Manual of Evidence-based Training, 1st Edition, 2013.
25. EASA. EBT Manual, Version 2.2. 2022. https://www.easa.europa.eu/en/downloads/137656/en
26. Krathwohl, D.R., Bloom, B.S., Masia, B.: Taxonomy of educational objectives: the classification of educational goals, handbook 2: affective domain. McKay, New York (1964)
27. Bailey, N. R. (2004). The effects of operator trust, complacency potential, and task complexity on monitoring a highly reliable automated system. Old Dominion University. https://doi.org/10.25777/wfmq-tv11.
28. Plant, K.L., Parnell, K.J., Banks, V.A., Wynne, R.A., Stanton, N.A.: Human factors on the flight deck: A practical guide for design, modelling and evaluation. CRC Press (2023). https://doi.org/10.1201/9781003384465

29. Dillman, B., Ziakkas, D., Cutter, J.: Selection and implementation of Evidence based Safety Performance Indicators in Aviation Training. In: Pedro Arezes and Anne Garcia (eds) Safety Management and Human Factors. AHFE (2022) International Conference. AHFE Open Access, vol 64. AHFE International, USA. https://doi.org/10.54941/ahfe1002629 (2022).