The Aeronautical Journal (2025), **129**, pp. 3602–3618
doi:10.1017/aer.2025.10058

RESEARCH ARTICLE

Benefit Potential of Continuous Climb Operations: A Case Study with Real-Flight Data

H. Aksoy and Ö. Usanmaz

Department of Air Traffic Control, Eskisehir Technical University, Eskişehir, Türkiye
Corresponding author: H. Aksoy; Email: hakkiaksoy@eskisehir.edu.tr

Received: 3 February 2025; **Revised:** 11 July 2025; **Accepted:** 16 July 2025

Keywords: air traffic management; continuous climb operations; aircraft emissions; fuel consumption; flight data analysis

Abstract

Air transportation significantly contributes to air pollution, making the reduction of fuel consumption and emissions critical for sustainable development. Continuous climb operations (CCO) have emerged as a promising approach to minimise the environmental impact of aviation, particularly during the climb phase, where fuel burn is highest. This study assesses the efficiency of vertical climb profiles using flight data from departures at Trabzon Airport. The analysis incorporates maximum thrust and maximum rate of climb constraints alongside clean configuration to design CCO profiles. These profiles are compared with actual flight data, revealing that CCO implementation could result in average savings of 5.1% in time, 8% in fuel and 7.5% in HC, 8.8% in CO and 5.8% in NO_x emissions. The study highlights challenges in CCO implementation, particularly due to speed regime changes and flight procedure constraints, emphasising the need for enhancements in air traffic management to maximise CCO benefits in complex airspace environments.

Nomenclature

ATM	air traffic management
BFFM2	Boeing fuel flow method 2
CAS	calibrated air speed
CCO	continuous climb operations
CDO	continuous descent operations
CO	carbon monoxide
FF	fuel flow
GS	ground speed
HC	unburned hydrocarbons
IC	initial climb
ICAO	International Civil Aviation Organisation
NO_x	nitrogen oxides
ROC	rate of climb
SID	standard instrument departures
TAS	true air speed
TLA	thrust lever angle
TOC	top of climb
TOD	top of descent

1.0 Introduction

Air pollution has negative impacts on the atmosphere and the health of populations. Air transportation is one of the major contributors to air pollution, and reducing fuel consumption and emissions in this sector is of utmost importance for sustainable development. In addition to improvement of aircraft design technology, advancements in engine technology, alternative fuels, etc., research is being conducted in

© The Author(s), 2025. Published by Cambridge University Press on behalf of Royal Aeronautical Society.

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

all areas of air traffic management (ATM), including flight scheduling, ground-based trajectory planning, runway configuration and trajectory optimisation with the goal of mitigation of aviation impact on climate change. Continuous climb operations (CCO) and continuous descent operations (CDO) are two promising concepts of environmentally friendly flight operations applied in terminal control areas (TMA) [1, 2]. Several studies have documented the benefits of CDOs in terms of fuel savings and emission reductions [3–7]. These studies highlight how CDOs contribute to more efficient and environmentally friendly flight operations. However, the literature on CCOs is relatively sparse despite the critical importance of the climb phase of flight, where aircraft are heavier and consume more fuel. As the aircraft are heavier and burn more fuel, this phase of flight has a critical importance to pay attention for fuel and emissions savings. For instance, McConnachie et al. [8] conducted simulations with the Piano5 tool and reported that a level-off during the climb phase resulted in 30% higher fuel savings for the B747-400 and 60% higher fuel savings for the B737-700, compared to level-offs at equivalent altitudes and durations during the descent phase. The most desired solution in the climb phase of a flight is to enable an aircraft to execute an optimal continuous climb profile from the runway to its designated cruise altitude. Nevertheless, it is not always possible to conduct CCO due to conflict between arrival and departure traffic, constraints imposed by standard instrument departures (SID), level-off segments (e.g., due to transfer of traffic from one sector to another), adverse weather conditions and inefficiencies in aircraft speed and configuration.

Various optimisation techniques have been proposed to improve the efficiency of CCOs. For instance, Kim et al. [9] developed an optimal airspace design using mixed integer linear programming to minimise altitude restrictions and enhance climb efficiency. Similarly, Mori [10] introduced a method to reduce fuel consumption by adjusting thrust near the top of the climb, showing that practical fuel savings can be achieved without compromising operational feasibility. Mitchell et al. [11] analysed the environmental trade-offs of air traffic management speed constraints during the departure phase, indicating that removing these constraints at Gothenburg Landvetter Airport could reduce carbon dioxide (CO_2) emissions by 180 kg per flight, with a slight increase in noise exposure. Klapwijk [12] further supports the potential of optimised CCOs, demonstrating significant reductions in fuel consumption and emissions at Schiphol Airport, which underscores the feasibility of adopting CCO procedures even in high-density airport environments. Tarelho Szenczuk and de Arantes Gomes [13] provide empirical evidence of the inefficiencies caused by level-offs and path stretches, quantifying potential fuel savings from optimised CCOs and highlighting significant opportunities for improving ATM. Lindner et al. [14] introduces the innovative concept of traffic flow funnels, utilising a dynamic 3D pathfinding grid and clustering algorithms to allow for more efficient, individualised climb profiles while maintaining safety in high-density terminal areas, as demonstrated at Munich Airport. These studies contribute valuable methodologies for implementing CCOs more effectively, yet they also highlight the need for further refinement to maximise their benefits. Despite the theoretical advantages, implementing CCOs in practice faces several challenges. Research by Pérez-Castán et al. [15, 16] indicates that while CCOs can improve fuel efficiency, they may also require larger separation minima due to uncertainties in aircraft performance, which could reduce airport capacity and increase air traffic control (ATC) workload, particularly in high-density traffic environments. This suggests that CCOs, while beneficial, may necessitate trade-offs in operational efficiency that must be carefully managed. The environmental benefits of CCOs are well-supported by the literature. Studies by Villegas Díaz et al. [17, 18], Rosenow et al. [19], and Hebly and Visser [20] demonstrate that optimised CCOs can lead to substantial reductions in fuel consumption – ranging from 7% to 23% and significant decreases in noise pollution. Ho Huu et al. [21] develop a two-step optimisation framework for designing and selecting aircraft departure routes and allocating flights, aiming to minimise noise annoyance and fuel burn. A case study at Amsterdam Schiphol Airport shows the framework can reduce fuel consumption by 7.3% and the number of people annoyed by up to 31% compared to the reference case. These findings underscore the potential of CCOs to enhance fuel efficiency and contribute to broader environmental sustainability goals. However, the execution of CCOs is often complicated by real-time factors such as traffic density and adverse weather conditions. Vempati [22] notes that these

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

factors can significantly decrease the likelihood of successful CCO implementation, highlighting a gap in current research that requires further investigation.

While many existing studies [11, 23, 24] rely on simulated climb profiles using aircraft performance models such as BADA, PIANO or proprietary airline tools, these methods often involve assumptions that may not fully reflect operational practices, environmental conditions or aircraft-specific variability. For instance, Senzig et al. [25] noted that although the BADA fuel consumption model performs well in cruise – with differences from airline-reported values typically around 3% – its accuracy is significantly lower in the terminal area. Their comparison of BADA-modeled and flight data recorder (FDR) - reported fuel consumption during descent and climb phases highlighted notable discrepancies, underscoring the limitations of BADA in non-cruise operations. In contrast, this study introduces a data-driven approach that leverages high-resolution FDR data from real aircraft operations. By extracting fuel flow, rate of climb, and ground speed values directly from real flights, the proposed method captures the actual aircraft behaviour under operational constraints and atmospheric conditions that are typically difficult to model precisely. This approach allows for the creation of CCO profiles based on real-world performance, offering a more realistic and practical assessment of CCO benefits without relying on theoretical or generalised models.

The objective of this study is to assess the efficiency of vertical climb profiles using real flight data, in terms of flight time, fuel consumption and emissions – including CO_2, unburned hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_x). To this end, a flight data-based CCO design method was developed and applied. The vertical profiles of actual flights were used as a reference scenario. CCO profiles were generated using performance parameters derived from real data under maximum thrust, maximum rate of climb and clean configuration constraints. These designed profiles were then compared to the actual flight trajectories to evaluate differences in fuel efficiency and emissions. The study specifically investigates how the implementation of continuous climb operations impact fuel burn and emissions relative to conventional climb procedures.

2.0 Material and methodology

In this section of the study, the features of the material used, such as the real flight data and specifics of Trabzon airport, are presented. Subsequently, the methodology used for designing CCO profiles, the determination of climb parameters (fuel flow (FF), rate of climb (ROC), ground speed (GS) and true air speed (TAS)) used for the design of the CCO profiles, and a comparison strategy between CCO profiles with the real climb profiles and emission calculations are given in detail.

2.1 Flight data and Trabzon airport

The dataset used in this paper consisted of FDR data for 71 individual flights. This data was taken from one of the most frequently used narrow-body twin-engine commercial aircraft. All flights departed from Trabzon Airport (TZX) and arrived at Sabiha Gökçen Airport (SAW).The FDR records a range of parameters at a 1-second sampling interval from engine start to engine shut-off. These parameters include altitude, fuel flow, true airspeed, ground speed, aircraft mass, exhaust gas temperature, vertical speed (rate of climb/descent), flight phase and flap configuration. The raw data were stored in a format compatible with Microsoft Excel and were processed to exclude outliers and erroneous values using parameter-specific thresholds and visual inspection. No additional smoothing or interpolation was applied. The original cleaned dataset was then used directly to generate the figures depicting aircraft performance parameters such as FF, GS and ROC.

Trabzon Airport is located in Trabzon, on the north coast of Türkiye, and has a runway configuration of 11/29. The airport has RNAV (area navigation) GNSS (global navigation satellite systems) SID procedures for both Runway 11 and Runway 29. As shown in Fig. 1, some departing traffic took off from Runway 11, while others departed from Runway 29. Traffic departing from Runway 29 generally follows the ARLAT 1G route of the RNAV (GNSS) RWY 29 SID, while traffic departing from Runway 11

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

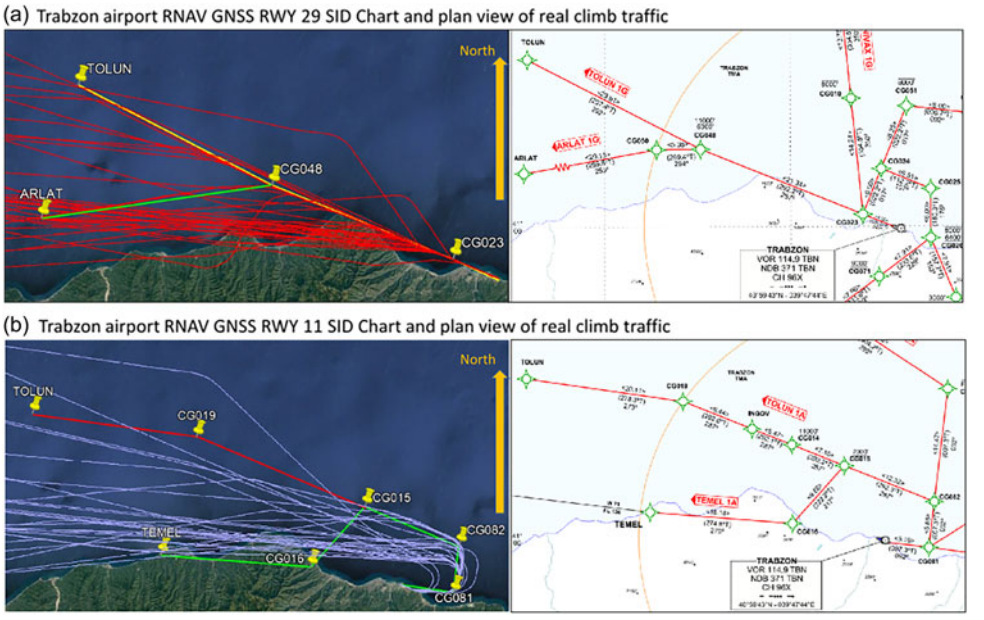


Figure 1. *Trabzon airport RNAV GNSS RWY 11/29 SID chart and plan view of real climb traffic.*

tends to follow the TEMEL 1A route of the RNAV GNSS RWY 11 SID, as published in the Aeronautical Information Publication (AIP) [26].

2.2 Design of CCO profiles

The CCO profile designed in this study represents the climb profile of an aircraft with flaps retracted, starting from the initial climb (IC) altitude – where the maximum rate of climb (ROC) and maximum or near-maximum engine thrust are employed – up to the top of the climb (TOC) altitude. This defined CCO profile represents the fastest climb profile that is closest to the fuel-economic climb profile [27]. Although explicit procedural constraints such as published SID-related speed or altitude restrictions were not modeled in the profile generation, the use of real flight data ensures that typical operational speed behaviours are inherently embedded in the dataset. Specifically, the climb regime observed in the data reflects the constant calibrated airspeed (CAS) and constant Mach number segments that characterise real-world operations, as illustrated in Fig. 6b.

The objective of the proposed CCO profile is to identify altitudes where vertical inefficiencies occur in real operations and to demonstrate the potential time, fuel and emissions savings achievable when continuous climb operations are applied. Future extensions of this work could incorporate procedural constraints more explicitly to refine the operational feasibility of the modeled profiles.

Designing the CCO profile requires three key performance parameters: FF, GS and ROC. FF is used to calculate fuel consumption, GS is needed to estimate the horizontal distance covered, and ROC determines the vertical distance gained over time. These parameters, derived from representative aircraft performance data under fastest climb conditions, are used to iteratively construct the CCO profile. The modeling process is illustrated in Fig. 2.

To demonstrate the procedure, consider a flight with an IC altitude of 1,000 ft and a TOC altitude of 39,000 ft, both extracted from actual FDR data. At the starting point ($i = 0$), the altitude is 1,000 ft, the horizontal distance covered is 0 NM, and the cumulative fuel consumed is 0 kg. The model proceeds in 1-second intervals. At each step $i + 1$, the altitude is updated using the ROC value at altitude i (e.g., $\text{Altitude}_{i+1} = \text{Altitude}_i + \text{ROC}_i \cdot \Delta t$), the horizontal distance is updated using the GS value

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

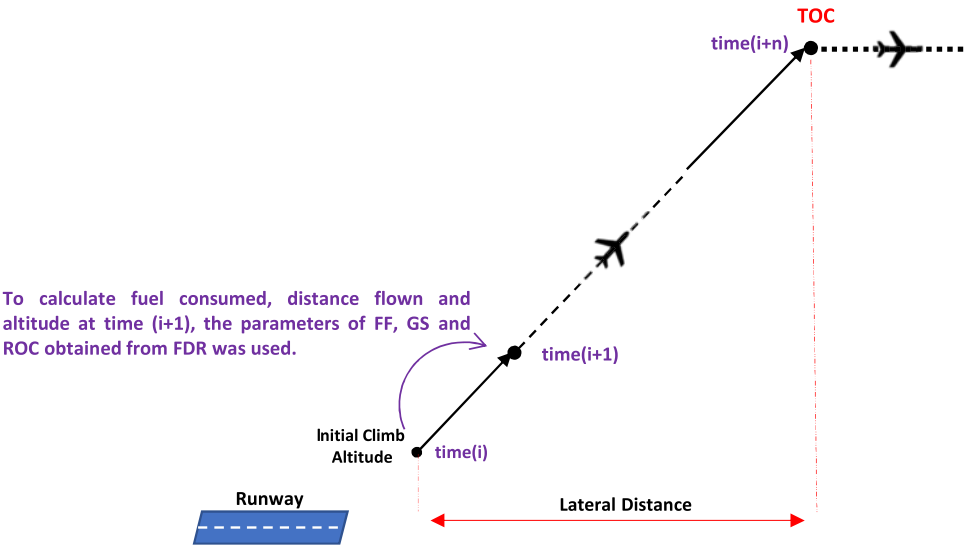


Figure 2. *Building the CCO profile from IC altitude to TOC altitude.*

(e.g., $\text{Distance}_{i+1} = \text{Distance}_i + \text{GS}_i \cdot \Delta t$), and fuel consumed is incremented by the fuel flow (e.g., $\text{Fuel}_{i+1} = \text{Fuel}_i + \text{FF}_i \cdot \Delta t$).

The values of ROC, GS and FF at each altitude are obtained from the graphs representing the GS, FF and ROC performance parameters presented in Figs. 6 and 8. These graphs reflect how these performance parameters vary with altitude and serve as the basis for modeling the continuous climb trajectory. The process continues iteratively until the modeled altitude reaches the TOC value of 39,000 ft, completing the designed CCO profile with corresponding time, distance and fuel metrics. Here, it is important to note that average values of ROC, GS and FF are used for each altitude bin when designing the CCO profiles. For instance, in the altitude bin of 1,501–2,500 ft, an average ground speed of 230 knots and a rate of climb of 2,640 ft/min are used, meaning the aircraft is assumed to climb at these values throughout this altitude range.

2.3 Determination of climb parameters required for design of the CCO profile

The climb phase FDR data from 71 individual flights was entered into an Excel worksheet to extract the ROC, GS and FF parameters needed to construct the proposed CCO profile. This profile is intended as an alternative to the actual climb profiles of flights departing from Trabzon Airport. Filtering operations were then applied based on three specific criteria: clean configuration, maximum ROC and maximum thrust.

The first of these criteria is the clean configuration, where the flaps remain retracted during the climb. To meet this condition, flight data with flap angles of less than 5 degrees was extracted from the Excel file and stored in a separate file.

At this point, it's important to clarify the thrust constraint used in filtering the data for better understanding. The autothrottle system in B737-800 aircraft is part of the flight management system and is responsible for calculating and controlling engine thrust. This study used the thrust lever angle (TLA) as the thrust setting indicator because the thrust levers in the cockpit transmit the thrust command signal to the electronic engine control (EEC) unit via the thrust lever angle resolver. The EEC controls the engine based on these signals. For the B738 aircraft, the TLA is specified as 72 degrees in maximum climb mode [28]. Figure 3 illustrates the different TLA values observed at various altitudes during the climb and highlights the significant changes in fuel flow as TLA varies.

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

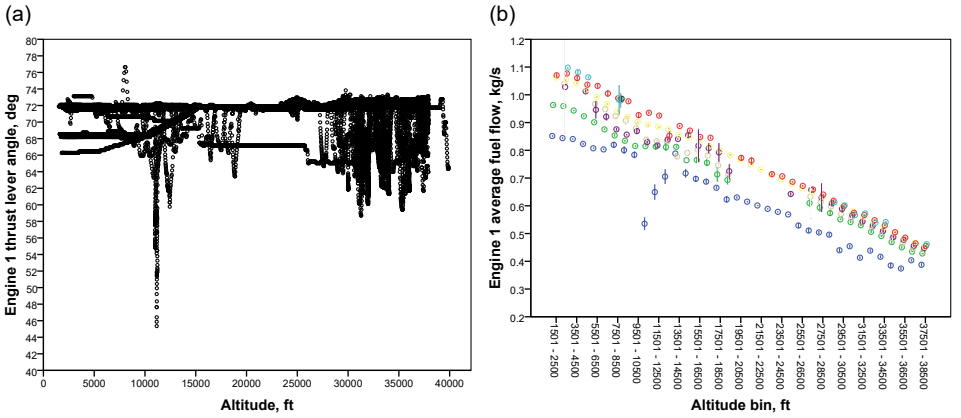


Figure 3. *(a) Variation of the TLA value of engine 1 with respect to altitude in the climb phase. (b) Variation of the fuel flow under different TLA settings.*

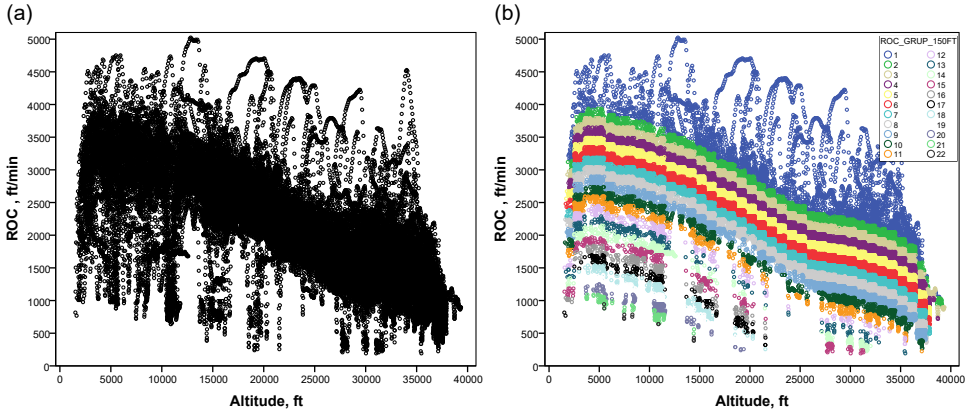


Figure 4. *(a) The altitude-dependent distribution of ROC data with TLA1 ≥ 71 and flap angle≤5 degrees. (b) ROC data grouped into intervals of 150 feet.*

Figure 3 clearly shows deviations from the maximum TLA levels during the climb phase. The variation in TLA values at different altitudes reflects different thrust levels, likely resulting from the changing thrust required to maintain the target airspeed or vertical speed. Since the CCO profile is based on maximum thrust and maximum vertical speed, only FDR data with TLA values of 71 or greater was used in the study.

The third constraint was the maximum ROC, as the climb with the highest ROC is considered the closest to the most economical climb profile [27]. Figure 4a, created using data obtained under clean configuration and maximum thrust, illustrates the distribution of ROC with respect to climb altitude. In Fig. 4b, the ROC data were grouped into 150 ft intervals to filter out outliers and select higher ROC data. Subsequently, flight data within the range of $1 < \text{ROC_group} < 10$ from the ROC groups presented in Fig. 4b were used to determine the performance parameters of FF, GS, TAS and ROC.

The three constraints mentioned above were applied to the climb data of 71 departing flights, covering the altitude range from IC to TOC. The average IC altitude in the dataset is approximately 1,500 ft; therefore, the altitude range shown in Fig. 4 spans from 1,500 ft to 40,000 ft. After applying these constraints, the remaining data was processed in the SPSS environment to generate individual graphs for FF, GS, TAS and ROC parameters. The statistics for the climb data used in analysing these parameters are presented in Fig. 5.

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

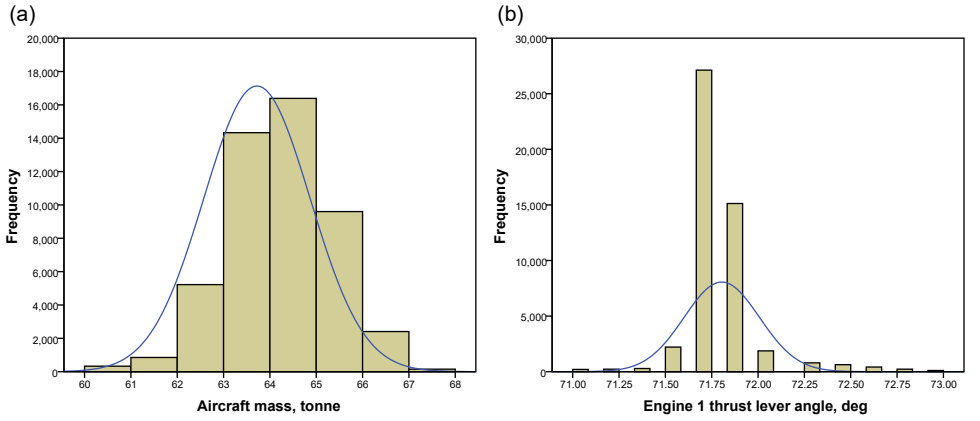


Figure 5. *Statistics regarding the data used in determining the climb phase parameters: (a) aircraft mass and (b) thrust lever angle.*

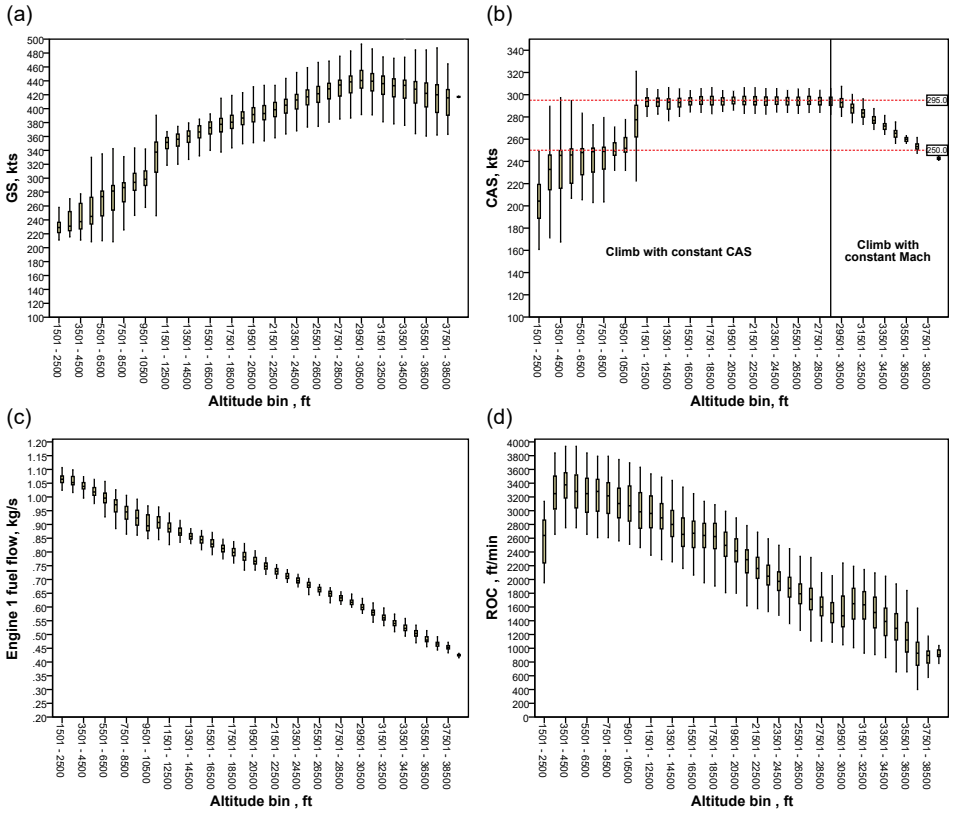


Figure 6. *The altitude-dependent variation of climb performance parameters in the conditions of maximum thrust and maximum rate of climb: (a) GS (b) CAS (c) FF (d) ROC.*

The average TLA and aircraft mass for the climb data used in designing the CCO profiles were 71.8 degrees and 63.72 tonnes, respectively. The parameters of FF, GS, CAS and ROC, which are necessary for the design of alternative CCOs, were determined based on the filtered data, with their corresponding graphs presented in Fig. 6. These parameters were derived from the data shown in Fig. 6 for calculating the CCO profiles.

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

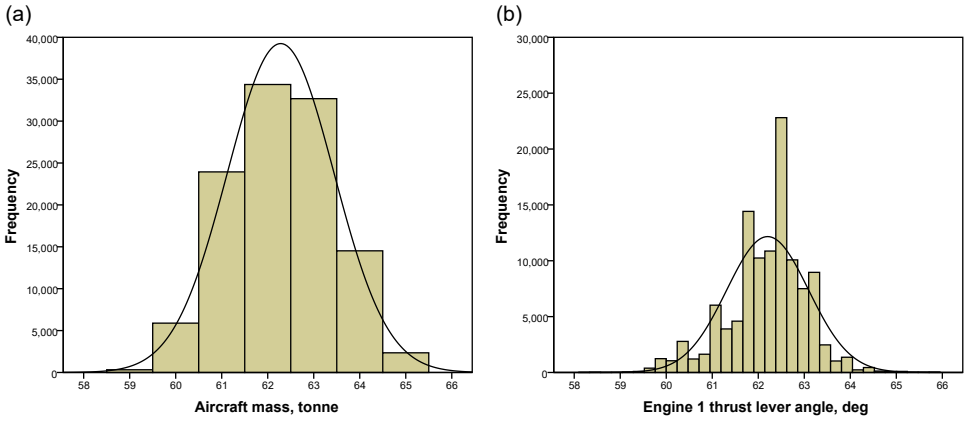


Figure 7. *Statistics regarding the data used in determining the cruise phase parameters (a) aircraft mass and (b) thrust lever angle.*

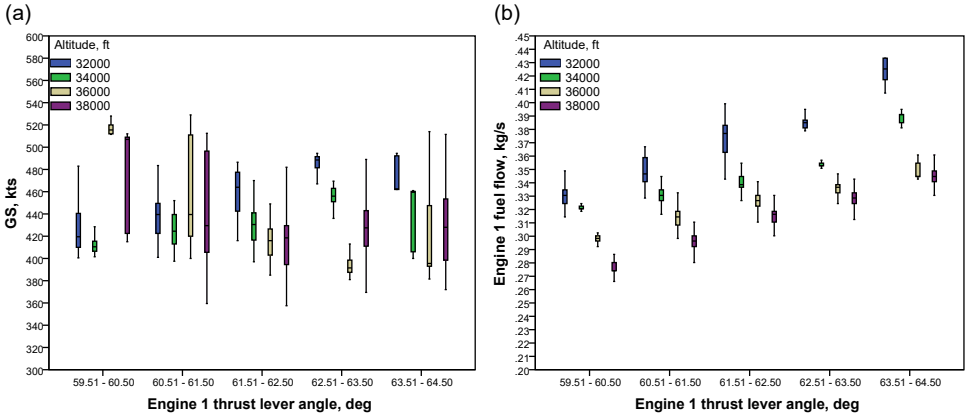


Figure 8. *Change of fuel flow and ground speed at different cruise altitudes and different thrust lever angles. (a) Ground speed (b) fuel flow.*

2.4 Determination of cruise parameters required for design of CCO profile

Using cruise phase data from actual flights departing from Trabzon Airport, the FF and GS parameters were determined to incorporate the cruise segment based on the horizontal distance between the TOC point of the designed CCO profile and the TOC point of the actual climb profile (whether ahead or behind). Cruise data between the TOC and top of descent (TOD) points for each of the 71 flights departing from TZX Airport was used to determine the FF and GS parameters. Since the cruise phase typically has an FPA value close to 0, and FPA is recorded in intervals of 0.35 in the FDR records, only cruise data with FPA values between −0.35 and +0.35 from the 71 flights were selected. The statistics for this data are presented in Fig. 7.

The FF and GS values for the cruise phase were determined by grouping the data according to altitude and TLA. Since the cruise altitudes of nearly all 71 flights were at 32,000 ft, 34,000 ft, 36,000 ft and 38,000 ft, the parameter determination was conducted for these specific altitudes. Additionally, to determine fuel flow and ground speed within each altitude group, the TLA was grouped in 1-degree intervals. The graphs showing fuel flow and ground speed for different cruising altitudes are presented in Fig. 8.

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

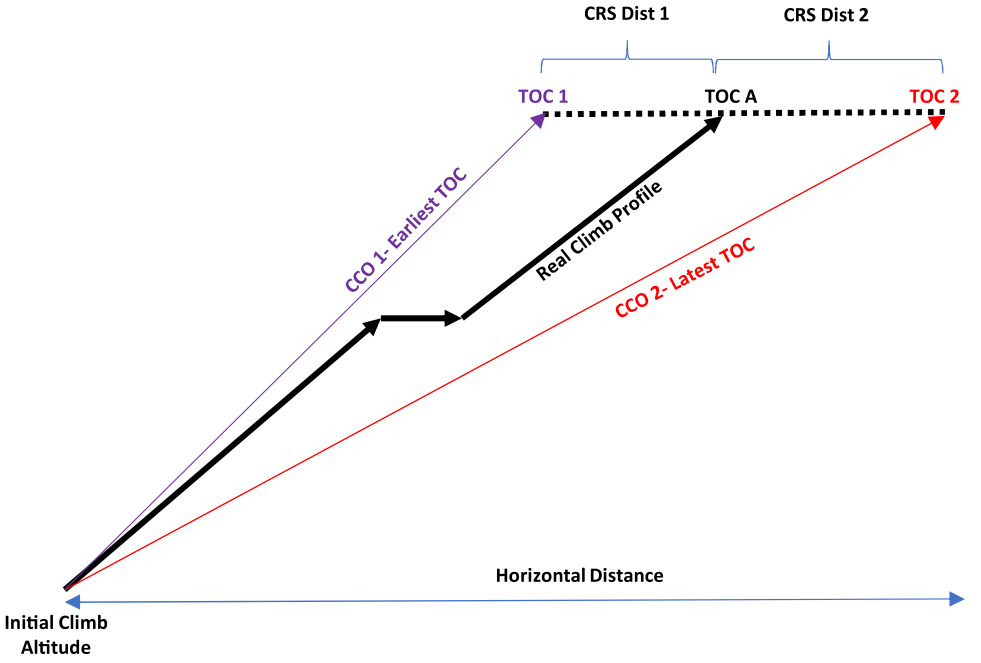


Figure 9. *The possible TOC locations of designed CCOs with respect to reference flight profiles.*

The data from the graphs provided in Fig. 8 with a thrust lever angle between 61.51 and 62.50 degrees were utilised for cruise phase calculations. This data range was selected because most cruise phase data falls within it, representing an approximate average value for the thrust lever angle.

2.5 Reference climb profiles & CCO profiles: benefit analysis strategy

This section outlines the strategy for analysing the benefits of the designed CCO profiles in comparison to the actual climb profiles of flights. The climb profiles of real flights departing from Trabzon Airport are used as the reference scenario. These real flight profiles serve as the baseline for evaluating the effectiveness of the CCO profiles, which are generated under maximum thrust and maximum ROC constraints based on actual flight data. The analysis compares fuel consumption, emissions and time savings between the reference climb profiles and the alternative CCO profiles. The possible positions of TOC locations of the designed CCO profiles, with respect to the TOC locations of the actual climb profile, are presented in Fig. 9.

When compared to the actual flight's TOC point (TOC A), the TOC point of the designed CCO profile may be closer in horizontal distance to the initial climb altitude point, as in TOC1, or further, as in TOC2. In the first scenario (CCO 1 profile), where the TOC point of the actual flight shifts to TOC1, the cruise segment (CRS Dist 1) needs to be added to the CCO 1 profile for comparison with the reference actual flight profile. Conversely, in the second scenario (CCO 2 profile), where the TOC point shifts to TOC2, the cruise segment (CRS Dist 2) must be added to the actual flight profile for an accurate comparison. After determining the necessary parameters for the climb and cruise phases from the flight data, fuel consumption, time, and emissions were compared for both scenarios. The flow diagram illustrating these two scenarios is presented in Fig. 10.

2.6 Emission calculations

In this study, nearly all of the 71 flights were equipped with CFM56-7B26E engines, making this engine type the reference for our emissions calculations. For calculating CO_2 emissions resulting from the fuel consumed between the IC altitude and TOC of both the actual flights departing from Trabzon Airport

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

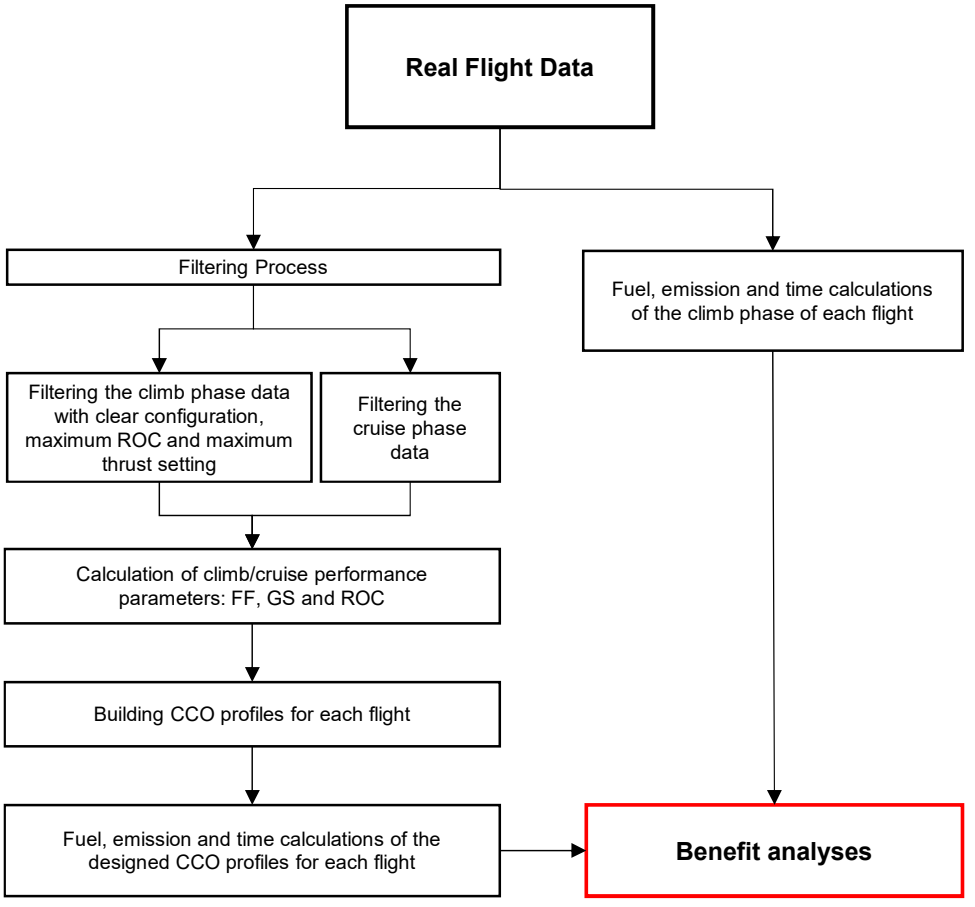


Figure 10. *Flow diagram of benefit analyses.*

and the designed CCO profiles, an emission index of 3.156 g/kg of fuel [29] was used. The calculations for HC, CO and NO_x emissions were based on data from the International Civil Aviation Organisation (ICAO) database [30]. However, the emission indices in the ICAO database can not be directly applied for calculations at any altitude. Therefore, the emission indices for CO, HC and NO_x were adjusted for altitude and ambient conditions using the Boeing Fuel Flow Method 2 (BFFM2) [31]. Emission indices for the type CFM56-7B26E engine and BFFM2 steps required are explained in detail in the paper by Aksoy et al. [32], and all calculations were performed with reference to that paper.

3.0 Results and discussion

The results and discussion are organised into three subsections. In the first subsection, the climb profiles of actual flights are analysed and compared to the CCO profiles generated under maximum thrust and maximum ROC constraints. The second subsection analyses fuel consumption and emissions at points of vertical inefficiency during the climb. The third subsection evaluates the potential changes in flight time, fuel consumption and emissions resulting from replacing the vertical profiles of actual flights with CCO profiles.

3.1 Real climb profiles & CCO profile

The CCO profile for traffic climbing from the initial climb altitude to TOC altitude, under the constraints of maximum thrust and maximum ROC, is compared to the vertical profiles of actual flights departing

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

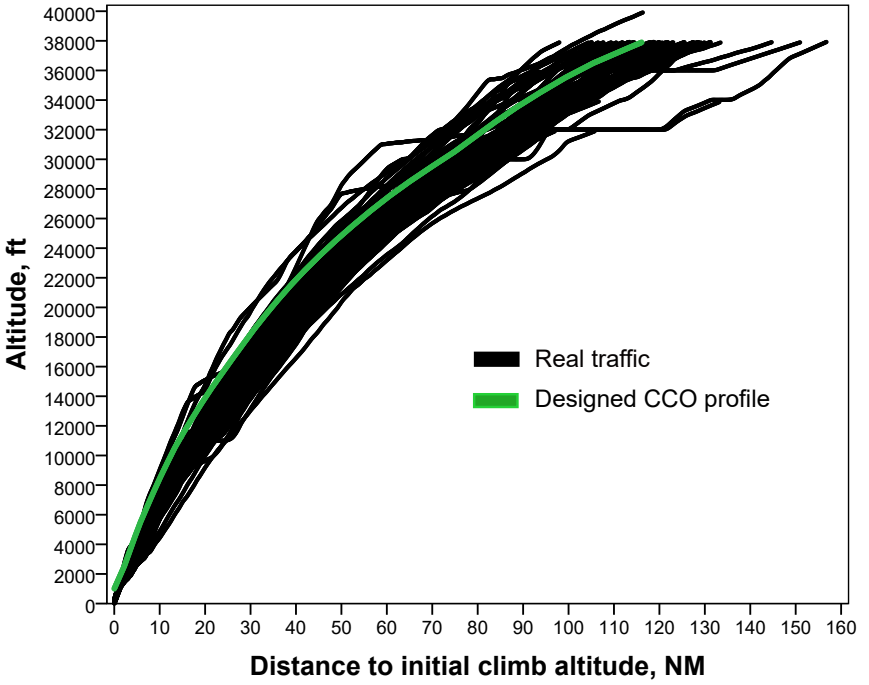


Figure 11. *Comparison of real climb profiles with the designed CCO profile.*

from Trabzon Airport in Fig. 11. As outlined in the methodology section (Section 2.2), the designed CCO profile represents the fastest climb profile. The CCO trajectory shown in Fig. 11 (green line) was generated using the average performance parameters (GS and ROC) presented in Fig. 6. This CCO profile represents a single trajectory from an IC altitude of 1,000 ft to a TOC altitude of 39,000 ft. As detailed in Section 2.2, the performance parameters (ROC, GS and FF) for each altitude bin were calculated as average values based on 71 departure flights, with the average IC altitude being approximately 1,500 ft. Due to the use of these average parameters, the designed CCO profiles exhibit very similar trajectories until reaching TOC. Therefore, this single CCO trajectory can be considered representative of the other designed CCO profiles. It is important to note that the use of averaged performance data introduces a limitation to the CCO design methodology. While the intention was to generate multiple case-specific CCO profiles reflecting variations in aircraft mass and GS, the available data was insufficient to support such differentiation. Consequently, the results do not capture the full range of variation that would occur with differing aircraft weights, which can significantly influence climb performance and emissions.

When comparing the vertical climb profiles of actual flights with the designed CCO profile, it is evident that some TOC locations of the real traffic occur later than the TOC points of the CCO profile, while others occur earlier. Notably, below 30,000 ft in the real climb profiles, prolonged level flight segments are absent. However, above 30,000 ft, prolonged level segments are observed in some instances before reaching cruise altitude. The locations and causes of these vertical inefficiencies in the climb profiles of actual flights are analysed separately to provide a better understanding.

3.2 Vertical inefficiencies: locations and causes

Comparing the ROC values between the real flights and the designed CCO profile at various altitudes helps identify the specific points where the actual flights diverged from the continuous climb profiles (Fig. 12a). The figure shows that the average ROC of the actual flights consistently falls below that of the designed CCO profile across different altitudes, with the difference becoming particularly pronounced

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

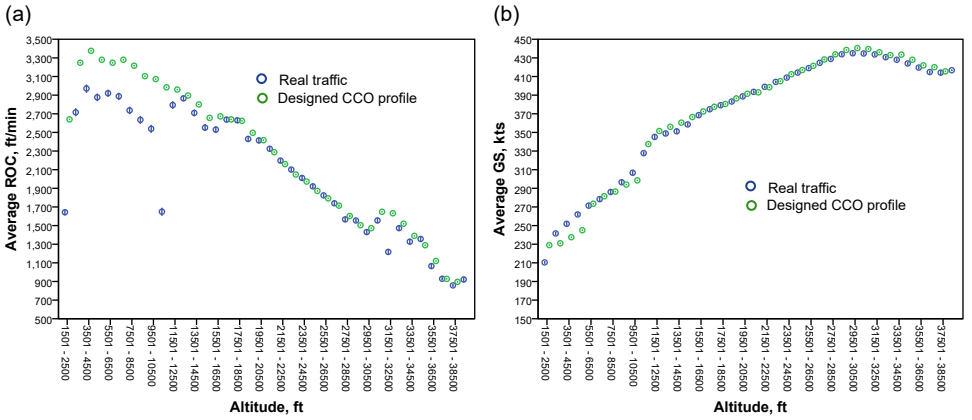


Figure 12. *Comparison of the average rate of climb and ground speed values of real traffic with the average values of the designed CCO profiles: (a) rate of climb and (b) ground speed.*

below 10,000 feet. Additionally, a sudden and significant drop in ROC is observed around 11,000 feet. This may be due to the change in speed regime during the climb phase, where the aircraft uses energy that would otherwise go toward vertical climb for acceleration, resulting in a decrease in ROC. The ground speed data in Fig. 12b supports this, which shows a notable increase in ground speed of around 11,000 feet.

The other probable reason for the sharp decrease in the average ROC of real traffic at 11,000 feet altitude is the altitude restrictions specified in the SIDs for departure traffic. It was indicated in the material section (Section 2.1) that departure traffic from Runway 29 follows the ARLAT 1G or TOLUN 1G routes. There is an altitude constraint of 11,000 feet at the CG048 waypoint, approximately 24 NM from the runway threshold, for traffic following the ARLAT 1G and TOLUN 1G routes. When examining Fig. 11, it can be seen that the segments of level flight are around 20–25 NM, which aligns with the distance from the CG048 waypoint to Runway 29. If the aircraft reaches the CG048 waypoint early, it must maintain its altitude until passing the waypoint.

The average fuel and emission values of real climb profiles have been compared with those of the designed CCO profiles to assess the impact of inefficient vertical profiles on fuel and emissions. Figure 13 below shows how the average HC, CO, NO_x emissions and fuel flow values vary during the climb for both real traffic and the designed CCO profiles (for Engine 1 only). At each altitude, emission values in g/s were calculated by multiplying the fuel flow (in kg/s) by the corresponding emission indices (in g/kg).

Fuel flow is a key parameter in emissions analysis, as aircraft emissions are directly dependent on the amount of fuel burned. Therefore, analysing FF trends offers valuable insight into the environmental impact of different climb profiles. When comparing the FF trends of the designed CCO and real climb profiles, a notable difference is observed up to approximately 10,000 ft. The CCO profile exhibits significantly higher average FF values in this range, likely due to the design constraints imposed – specifically, the use of maximum thrust and the maximum rate of climb. Additionally, the lower FF values at low altitudes in the real climb profiles may reflect operational considerations such as noise abatement departure procedures.

Following the analysis of fuel flow trends, the focus now shifts to emission trends to further evaluate the environmental impact of the climb profiles. Although the CO_2 trend is not shown in the Fig. 13, it closely follows the fuel flow trend since CO_2 emissions are directly proportional to fuel consumption. NO_x emissions follow a similar trend to fuel flow values and CO_2 emissions. However, HC and CO emissions exhibit opposite trends compared to NO_x and CO_2. As fuel flow increases, HC and CO emission

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

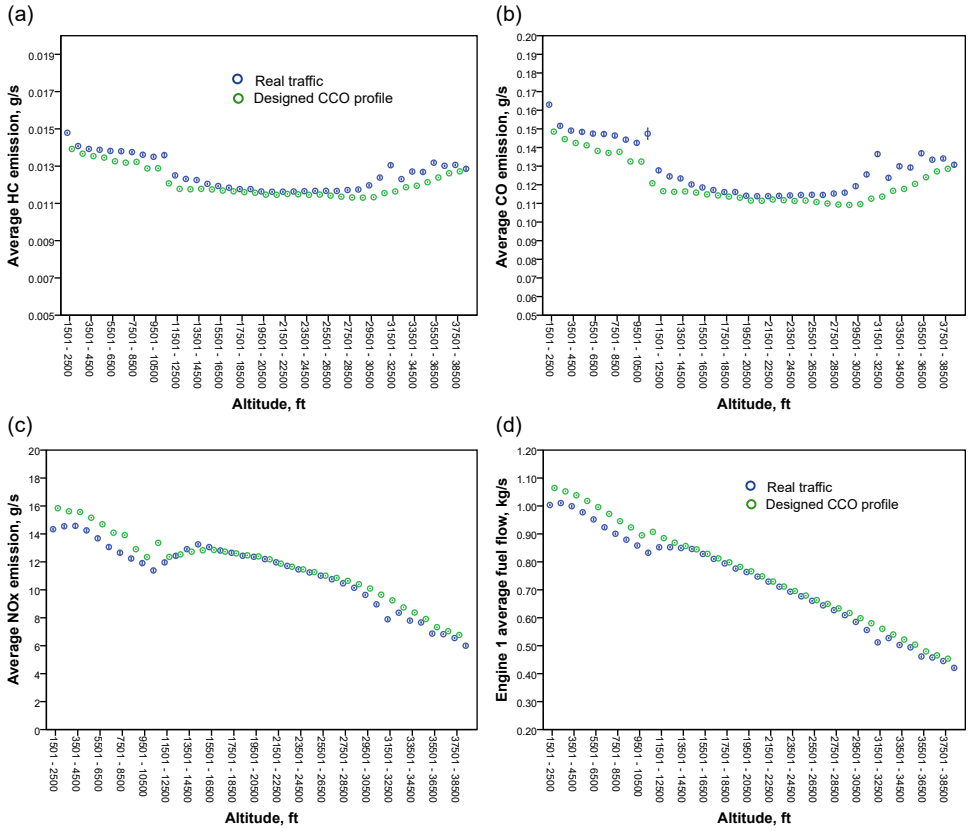


Figure 13. *Comparison of the average emission values of real traffic with the average values of the designed CCO profiles: (a) HC (b) CO (c)* NO_x *(d) fuel flow.*

indices decrease, resulting in higher HC and CO emissions in the designed CCO profiles at altitudes where average fuel flow values are lower.

3.3 Time, fuel and emission benefits of designed CCO profiles

The comparison of total fuel consumption, time spent, and emissions released during the climb phase – from IC altitude to TOC altitude – for each flight departing from Trabzon Airport is conducted against the designed CCO profiles. The findings are illustrated in Fig. 14.

In Fig. 14, the savings resulting from implementing the CCO profile, designed as an alternative to actual flight profiles, are depicted. Figure 14a presents four distinct regions, labeled 1-2-3-4, that define the savings values. In Region 1, applying the CCO profile yields time savings at the expense of increased fuel consumption. Region 2 indicates an increase in both time and fuel consumption. Conversely, in Region 3, time increases while fuel consumption decreases. Finally, Region 4 represents savings in both time and fuel consumption. The optimal scenario in all graphs of Fig. 14 is characterised by data points clustered around the origin, indicating that the departure traffic closely adhered to the designed CCO profile during the climb, representing the most favourable outcome.

Examining Fig. 14a, which illustrates fuel and time savings, it is evident that most data points cluster within region 4. This clustering indicates inefficiency during the climb phase, a trend also apparent in the vertical profile comparison graph depicted in Fig. 11. In Fig. 14b and Fig. 14c, the HC and CO change graphs tend to cluster around region 4, accompanied by higher savings in emission amounts.

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

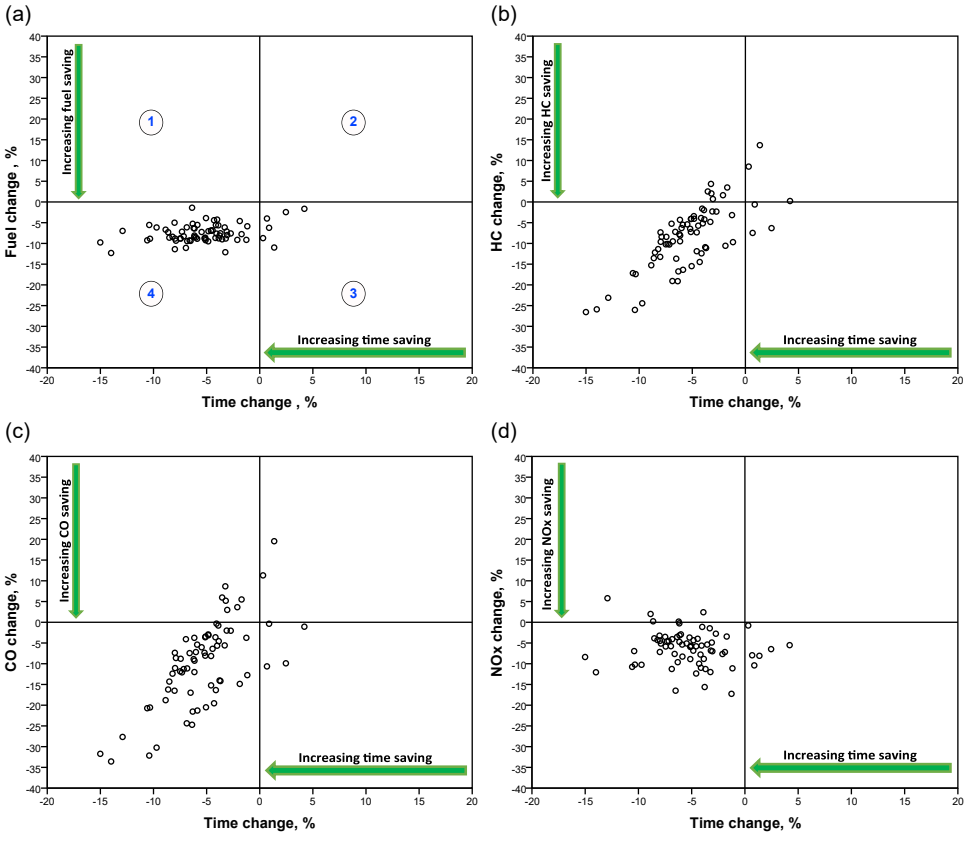


Figure 14. *Changes in time, fuel, and emissions in case of CCO implementation (a) fuel (b) HC (c) CO (d)* NO_x.

This observation is likely attributable to the higher fuel flow parameter of the designed CCO profile, which results in lower HC and CO emission indices, which are particularly noticeable below the altitude of 10,000 feet, as previously mentioned.

The NO_x emission holds particular significance among the emissions examined in this study. This is because the power setting is near maximum during the climb phase, and the NO_x emission index demonstrates an almost linear relationship with the power setting, reaching its peak. When we look at the NO_x change graph in Fig. 14d, almost all of the designed CCO profiles resulted in NO_x saving. This might prompt the question: 'How is it possible that the fuel flow parameter of the designed CCO profile, especially below 10,000 feet, is higher but resulted in lower total NO_x emission?' This case can be clarified by examining the graph illustrating the average ROC values of both the CCO and actual climb profiles. Since the average ROC value of the designed CCO profile significantly surpasses that of the actual climb profiles, the designed CCO profile ascends to cruise altitude more quickly. Consequently, this could lead to lower total NO_x emissions in the designed CCO profiles owing to reduced fuel flow during the cruise phase in comparison to the climb phase, resulting in lower fuel flow values and hence a diminished NO_x emission index.

Figure 15 shows the average saving values for the departure traffic from Trabzon airport if the CCO profile, designed as an alternative to each real climbing flight, were implemented. Median values are utilised in this figure to minimise the influence of outliers. The average savings percentages for time, fuel, HC, CO and NO_x with implementing CCO profiles are 5.1%, 8%, 7.5%, 8.8% and 5.8%, respectively.

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

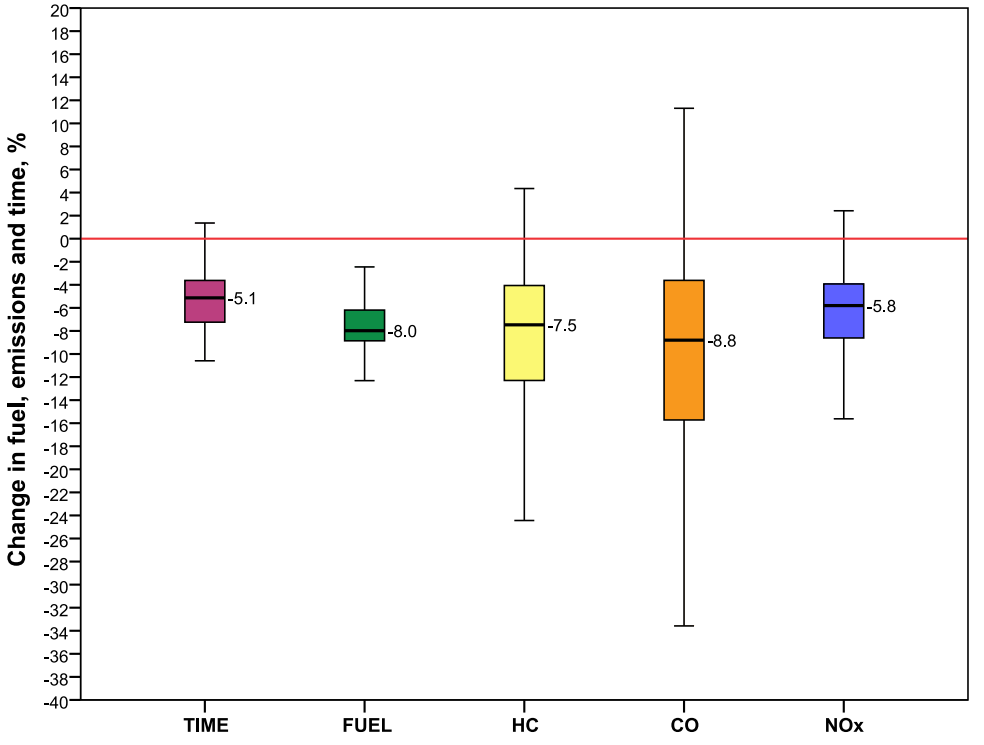


Figure 15. *Average changes in time, fuel and emissions in case of CCO implementation.*

4.0 Summary and conclusion

This study analyses the vertical profile efficiency of departure traffic at Trabzon Airport, focusing on time, fuel consumption and emissions of HC, CO, NO_x and CO_2, while evaluating the benefits of continuous climb operations. Unlike theoretical or model-based approaches, our analysis was based entirely on real flight data. Real climb profiles served as the reference scenario, while CCO profiles were constructed under maximum thrust, maximum ROC and clean configuration constraints.

To ensure a fair comparison, the cruise segments between the TOC locations of the real and CCO profiles were considered. Including the cruise segment was important to ensure an accurate comparison of total fuel consumption and time between the real and CCO profiles, as omitting it could lead to misleading conclusions. The analysis revealed variations in TOC locations between real flights and the designed profiles. While the number of level-offs during climb was relatively low, deviations from the designed CCO trajectory – particularly around 11,000 feet – were observed, largely due to aircraft acceleration resulting from speed regime transitions and SID constraints. Sector transitions may also contribute to level segments in this phase.

Our results demonstrate the potential for time, fuel and emissions savings through CCO implementation. However, the practical feasibility of CCO in terminal areas remains a challenge. Constraints such as SID restrictions, controller and pilot workload, route structure and the requirement for increased separation limit the applicability of uninterrupted climbs. Concepts like performance-based navigation (PBN), RNAV and required navigation performance (RNP) offer potential solutions by supporting more flexible route design and separation management.

This study has several limitations. First, while the FDR dataset includes realistic flight behaviour, aircraft mass and thrust values were averaged for cruise phase analysis, which may introduce inaccuracies when evaluating total fuel, emission and time during climb. Additionally, the analysis does not account

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

for transient flight dynamics such as acceleration or inertia. The CCO profiles represent a performance-based ideal trajectory rather than an optimised or dynamically simulated path. Also, air traffic control feasibility and real-time operational constraints were not explicitly modeled, which limits the direct operational applicability of the results.

Future research could enhance this work by incorporating aircraft mass variability, transient dynamics and trajectory optimisation or machine learning approaches to explore more adaptive and operationally feasible climb profiles. Moreover, while this study focused on a trajectory closest to the most economical climb profile, evaluating trade-offs using different cost indices could provide deeper insights. Finally, since level-offs often occurred near speed transition altitudes, a future research question could be whether allowing descending aircraft to maintain continuous descent while climb traffic levels off at these points may reduce conflict and improve overall system efficiency.

Acknowledgements. This study was supported by the Eskisehir Technical University Scientific Research Project Commissions under grant no:20DRP030. The authors would like to thank the Pegasus Airlines for providing flight data records.

Declaration of use of artificial intelligence (AI) tools in the writing process. During the preparation of this work, the author(s) used ChatGPT in order to improve language and readability with caution. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

[1] ICAO. Doc 9931: Continuous Descent Operations (CDO) Manual, 1st ed., 2010.
[2] ICAO. Doc 9993: Continuous Climb Operations (CCO) Manual, 1st ed., 2013.
[3] Aksoy, H., Turgut, E.T. and Usanmaz, Ö. The design and analysis of optimal descent profiles using real flight data, *Transp. Res. Part D: Transport Environ.*, 2021, **100**, p 103028.
[4] Inaad, M. Fuel and emission benefits for continuous descent approaches at Schiphol, Master's Thesis, Delft University of Technology, 2016.
[5] Jin, L., Cao, Y. and Sun, D. Investigation of potential fuel savings due to continuous-descent approach, *J. Aircr.*, 2013, **50**, (3), pp 807–816.
[6] Wilson, I. and Hafner, F. Benefit assessment of using continuous descent approaches at Atlanta, *24th Digital Avionics Syst. Conf.*, 2005, **1**, pp 2.B.2–2.1.
[7] Clarke, J-P., Ho, N.T., Ren, L., Brown, J.A., Elmer, K.R., Tong, K-O. and Wat, J.K. Continuous descent approach: design and flight test for Louisville International airport, *J. Aircr.*, 2004, **41**, (5), pp 1054–1066.
[8] McConnachie, D., Bonnefoy, P. and Belle, A. Investigating benefits from continuous climb operating concepts in the national airspace system, in *11th USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)*, FAA & EUROCONTROL, June 23–26, 2015.
[9] Kim, E., Hong, S. and Lee, K. Optimal airspace design for continuous climb operation, in *15th AIAA Aviation Technology, Integration, and Operations Conference* (Paper No. AIAA 2015-2432). Dallas, TX, USA, June 22–26, 2015. doi: 10.2514/6.2015-2432
[10] Mori, R. Fuel-saving climb procedure by reduced thrust near top of climb, *J. Aircr.*, 2020, **57**, (5), pp 800–806.
[11] Mitchell, D., Ekstrand, H., Prats, X. and Grönstedt, T. An environmental assessment of air traffic speed constraints in the departure phase of flight: a case study at Gothenburg Landvetter Airport, Sweden, *Transp. Res. Part D: Transport Environ.*, 2012, **17**, (8), pp 610–618.
[12] Klapwijk, J. Potential fuel benefits of optimized continuous climb operations at Schiphol, Master's Thesis, Delft University of Technology, 2018.
[13] Tarelho Szenczuk, J.B. and de Arantes Gomes, R. Level-offs in terminal areas and path stretches: empirically estimating extra fuel burn rates in commercial aviation, *J. Air Transport Manag.*, 2022, **105**, p 102276.
[14] Lindner, M., Zeh, T., Braßel, H., Rosenow, J. and Fricke, H. Traffic flow funnels based on aircraft performance for optimized departure procedures, *Future Transp.*, 2022, **2**, (3), pp 711–733.
[15] Pérez-Castán, J.A., Gómez Comendador, F., Rodríguez-Sanz, A., Barragán Montes, R., Arnaldo Valdés, R. and Pérez Sanz, L. Impact of continuous climb operations on airport capacity, *Transp. Res. Part C: Emerg. Technol.*, 2018, **96**, pp 231–250.
[16] Pérez-Castán, J.A., Asensio, B., Rodríguez-Sanz, Á., Ho-Huu, V., Pérez Sanz, L., Gómez Comendador, F. and Arnaldo Valdés, R.M. Impact of continuous climb operations in ATC workload: case study Palma airport, *J. Air Transport Manag.*, 2020, **89**, p 101890.
[17] Villegas Díaz, M., Gómez Comendador, F., García-Heras Carretero, J., María, R. and Valdés, A. Enhancing operational efficiency of terminal maneuvering areas through continuous climb operations, in *8th European Conference for Aeronautics and Space Sciences*, 2019. doi: 10.13009/EUCASS2019-867
[18] Villegas Díaz, M., Gómez Comendador, V.F., García-Heras Carretero, J. and Arnaldo Valdés, R.M. Environmental benefits in terms of fuel efficiency and noise when introducing continuous climb operations as part of terminal airspace operation, *Int. J. Sustain. Transport.*, 2020, **14**, (12), pp 903–913. doi: 10.1080/15568318.2019.1651924

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press

[19] Rosenow, J., Förster, S. and Fricke, H. Continuous climb operations with minimum fuel burn, *Sixth SESAR Innov. Days*, 2016.
[20] Hebly, S.J. and Visser, H.G. Advanced noise abatement departure procedures: custom-optimised departure profiles, *Aeronaut. J.*, 2015, **119**, (1215), pp 647–661.
[21] Ho-Huu, V., Hartjes, S., Visser, H.G. and Curran, R. An optimization framework for route design and allocation of aircraft to multiple departure routes, *Transport. Res. Part D: Transport Environ.*, 2019, **76**, pp 273–288.
[22] Vempati, L. Observed impact of traffic and weather on continuous descent and continuous climb operations, in *2015 IEEE/AIAA 34th Digital Avionics Systems Conference (DASC)*, 2015. doi: 10.1109/DASC.2015.7311343
[23] Alam, S., Tang, J., Lokan, C.J. and Abbass, H.A. An assessment of BADA fuel flow methodologies for in-trail procedure evaluation, *Def. Secur. Appl. Res. Centre, Univ. New South Wales, Austr. Def. Force Acad.*, 2009.
[24] Edwards, H.A., Dixon-Hardy, D. and Wadud, Z. Aircraft cost index and the future of carbon emissions from air travel, *Appl. Energy*, 2016, **164**, pp 553–562. doi: 10.1016/j.apenergy.2015.11.058
[25] Senzig, D.A., Fleming, G.G. and Iovinelli, R.J. Modeling of terminal-area airplane fuel consumption, *J. Aircr.*, 2009, **46**, (4), pp 1089–1093. doi: 10.2514/1.42025
[26] AIP Turkey. *Aeronautical Information Publication* [Internet]. 2015. https://dhmi.gov.tr/Sayfalar/aipturkey.aspx
[27] Hale, F.J. *Introduction to Aircraft Performance, Selection, and Design*. New York: Wiley, 1984.
[28] Boeing. B737-600/700/800 Aircraft Maintenance Manual, 2013.
[29] Masiol, M. and Harrison, R.M. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: a review, *Atmos. Environ.*, 2014, **95**, pp 409–455.
[30] ICAO. ICAO Aircraft Engine Emissions Databank. https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank
[31] DuBois, D. and Paynter, G.C. 'Boeing Fuel Flow Method 2' for estimating aircraft emissions, *SAE Technical Paper 2006-01-1987*, 2006.
[32] Aksoy, H., Usanmaz, Ö. and Turgut, E.T. Effect of vertical profile inefficiency during descent on fuel burn, emissions, and flight time, *Aeronaut. J.*, 2018, **122**, (1252), pp 913–932.

Cite this article: Aksoy H. and Usanmaz Ö. (2025). Benefit Potential of Continuous Climb Operations: A Case Study with Real-Flight Data. *The Aeronautical Journal*, **129**, 3602–3618. https://doi.org/10.1017/aer.2025.10058

https://doi.org/10.1017/aer.2025.10058 Published online by Cambridge University Press