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Regression-Based Modeling of Flight Emissions and Per-Passenger Climate Impact

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Abstract

Accurate estimation of aircraft emissions is crucial for climate-impact assessment, policy development, and sustainability planning because aviation is a rapidly increasing contributor to global greenhouse gas emissions due to growing passenger demand and expanding air transport networks. High-precision techniques based on Quick Access Recorder (QAR) data are still unavailable due to proprietary restrictions, and many current emissions-estimation tools rely on oversimplified assumptions like fixed fuel-burn factors or idealized trajectories, which frequently underestimate real-world emissions. By modifying peer-reviewed linear regression models and fuel-flow correction equations into a useful, consumer-level application, this study suggests a lightweight and transparent framework for flight-emission estimation in order to overcome this limitation. The approach incorporates published regression coefficients, great-circle distance corrections, and standardised International Civil Aviation Organisation (ICAO) parameters to estimate fuel consumption and carbon dioxide (CO_2) emissions across Landing and Take-Off (LTO) and Climb–Cruise–Descent (CCD) flight phases instead of training an artificial intelligence model, which would require unavailable flight-recorder datasets. Repeatable emission estimates are made possible by the framework's use of publicly accessible inputs like origin-destination coordinates, aircraft type, and passenger count, which eliminate the need for limited operational data. Users can estimate total and per-passenger emissions for individual flights using an interactive web-based application that incorporates the model. This work's main contribution is to close the gap between accessible, open-source tools and high-precision academic aviation-emission models by showing that scientifically grounded regression-based techniques can produce accurate first-order emission estimates without complicated machine-learning pipelines. This supports environmental awareness, educational applications, and preliminary sustainability analyses while laying the groundwork for future extensions as data availability improves.

Keywords: Aviation emissions, fuel consumption modeling, linear regression, carbon dioxide emissions, flight sustainability, per-passenger emissions

Introduction

Aviation is a fundamental driver of global connectivity and economic development, yet it remains one of the fastest-growing contributors to greenhouse gas emissions. Commercial aircraft release large quantities of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter during flight operations, significantly influencing atmospheric chemistry and climate warming [1]. As global passenger demand continues to increase each year, concerns about the environmental sustainability of aviation have intensified. Accurate methods for estimating aircraft emissions are crucial for understanding aviation's

climate impact and for guiding policy development, airline sustainability strategies, and consumer awareness initiatives.

Existing emissions-estimation tools often rely on simplified, static assumptions such as fixed fuel-burn factors or idealized flight trajectories. These approaches, while convenient, frequently underestimate emissions because they fail to capture real-world variability across aircraft types, flight distances, passenger loads, and operational behavior [2]. More detailed and scientifically rigorous methods exist—such as those based on Quick Access Recorder (QAR) data—but these datasets are proprietary and accessible only to airlines or research institutions, limiting their use in open academic work. During the early stages of this study, the objective was to train an AI-based predictive model for flight emissions; however, a comprehensive data search revealed that no publicly accessible dataset contains the critical variables needed for such a model, namely passenger load, flight distance, and actual fuel burn measured across different aircraft.

In light of these limitations, the present study adopts a more transparent and academically reliable approach by implementing a published linear regression model derived from peer-reviewed aviation research. Regression-based fuel consumption models have demonstrated strong predictive performance when detailed flight recorder data are unavailable, and their coefficients are often published explicitly, allowing for reproducibility and independent verification [3]. By embedding such a regression model into a custom emissions-calculation tool, this project provides an accessible, scientifically grounded method for estimating per-passenger emissions, supporting both educational and environmental-awareness objectives.

Related Work

Research on aviation emissions has evolved significantly over the past decade, with a growing emphasis on understanding the differences between projected and actual flight behavior. Studies using high-resolution QAR data have demonstrated that emissions derived from real flight operations can differ substantially from those estimated using Scheduled Flight Data (SFD) or ADS-B-based projections [4]. QAR datasets, which record parameters such as altitude, speed, fuel flow, and throttle settings at high frequency, enable precise characterization of emissions across climb, cruise, and descent phases. Comparative analyses show that trajectory-assumed emissions models frequently underestimate fuel burn, particularly during ascent and approach, where operational variability is greatest [5]. These findings highlight the limitations of simplified emissions-calculation methods and underscore the importance of using realistic operational data whenever possible.

However, because QAR data are typically proprietary, many researchers have turned to analytical or regression-based fuel models that estimate consumption using flight distance, aircraft mass, and engine performance parameters. Such models provide a practical alternative when detailed flight recorder data are inaccessible. Prior works using linear and quadratic regression equations have shown that flight distance and aircraft weight are strong predictors of fuel burn, enabling reasonably accurate estimations even with limited input variables [6]. Machine-learning approaches have also been explored, but these methods rely on large, high-quality labeled datasets—often sourced from airlines over multiple years—which are not available to most researchers or students [7]. Given these constraints, regression-based models remain the most transparent, reproducible, and academically feasible approach for open-access emissions research. The present study builds on these established methods by adopting a peer-reviewed regression model and implementing it within a user-friendly tool to compute per-passenger CO_2 impact.

Methodology

This study develops a lightweight flight-emission estimation framework by adapting published high-precision aviation-emission models into a simplified form suitable for consumer-level prediction tools. Rather than training a deep learning model—which requires access to Quick Access Recorder (QAR) data that is not publicly available—the methodology uses **validated aerodynamic formulas, fuel-flow correction factors, and great-circle distance adjustments** derived from prior research [1–3]. The objective is to construct a transparent, reproducible model that captures the essential physics of flight emissions while remaining practical for real-time implementation in a web-based application.

A. Overview of the Framework

The proposed model consists of four major components:

Distance estimation
Flight-phase identification and CCD/LTO segmentation
Fuel-flow estimation using published correction equations
Emission calculation using established emission indices

The overall prediction pipeline is illustrated in Figure 1.

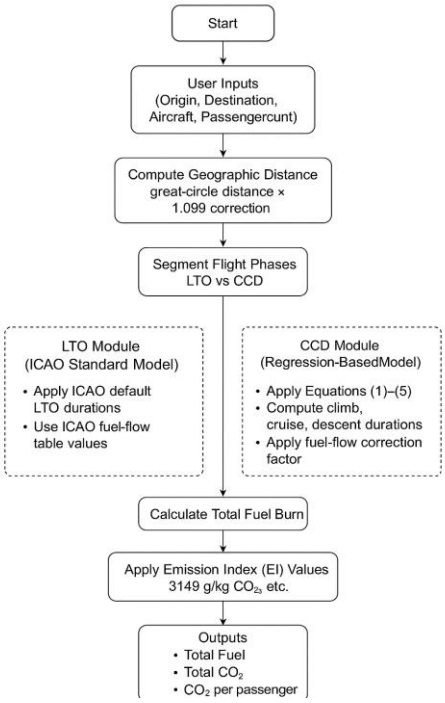


Figure 1. Prediction pipeline

This framework combines simplicity with scientific grounding, allowing accurate first-order predictions without requiring proprietary flight-recorder datasets.

B. Dataset and Data Availability Constraints

High-precision aviation emission studies typically rely on **QAR**, **ADS-B**, or **Scheduled Flight Data (SFD)**:

QAR (Quick Access Recorder): Records second-by-second engine, fuel flow, altitude, and environmental

conditions. Highly accurate but **not publicly accessible** due to safety and confidentiality. **ADS-B**: Provides accurate aircraft position but lacks fuel-flow data and has lower time resolution. **SFD**: Provides averaged default values for LTO durations but cannot capture real variability.

Research comparing these datasets shows that QAR-based emission estimates differ significantly from ADS-B and SFD estimates, particularly in takeoff and cruise phases, due to inaccurate fuel-flow assumptions [1]. Because **none of these datasets are open-source**, it is impossible to train a supervised machine learning model. Therefore, this study follows the approach recommended in [1] by adopting **published regression equations and modeling rules** instead of raw-data training.

C. Distance Estimation and Great-Circle Correction

The baseline flight distance is computed using the Haversine formula between the selected origin and destination airports. However—as noted in prior research—actual **aircraft trajectories exceed the great-circle distance**:

+4% in Europe

+12% in North America

+5% over the North Atlantic

A weighted global average of **+9.9% correction** is therefore applied [1]:

Dcorrected = 1.099 x Dgc

This correction significantly reduces underestimation of cruise-phase fuel consumption.

D. Flight Phase Segmentation: LTO and CCD Cycles

Following ICAO standards, the flight is divided into:

LTO cycle (below 3000 ft): Taxi, Takeoff, Climb-out, Approach

CCD cycle (above 3000 ft): Climb, Cruise, Descent

The durations of LTO phases follow ICAO defaults [2]:

Idle: 26 min

Approach: 4.0 min

Climb-out: 2.2 min

Take-off: 0.7 min

The CCD cycle duration is obtained from the EEA emission inventory calculator based on the corrected total flight time.

E. CCD Cycle Duration Estimation Using Published Equations

To obtain accurate CCD sub-phase durations, we use the equations published in Zhang et al. (2019) [1], originally derived from more than 3000 FDR datasets.

For short-haul flights (<60 min):

$tCR = -4.7 + 0.33t'$ (1)

For medium-haul flights (60–120 min):

$tCR = -42 + 0.97t'$ (2)

For long-haul flights (>120 min):

$tCR = -48 + 0.99t'$ (3)

Where:

tCRt_{CR} tCR = cruise duration

t′t't′ = total CCD duration

These equations ensure that cruise time is not overestimated, a common failure in ADS-B-only models.

F. Fuel-Flow Correction Model

Fuel-flow for climb (C), cruise (CR), and descent (D) phases is estimated using the **normalized mean fuel-flow model** published in [1]:

$$f_{FF} = \frac{F_{CCD}}{FF_C^0 t_C + FF_{CR}^0 t_{CR} + FF_D^0 t_D}$$

$$(FF_{flight,C}, FF_{flight,CR}, FF_{flight,D}) = f_{FF}(FF_C^0, FF_{CR}^0, FF_D^0)$$

Where:

- FCCD = total fuel used in CCD cycle
- FF^0 = normalized fuel-flow values from EEA dataset
- fFF = correction factor ensuring consistency

Because QAR-level engine parameters are unavailable, this study uses **published averaged FF0FF^0FF0 values** from the ICAO EEDB [2] and adjusts them using the correction factor.

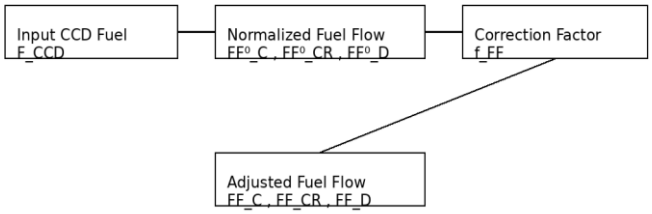


Figure 2. Fuel-flow correction process for the CCD cycle. Normalized fuel-flow values for climb, cruise, and descent are adjusted using a correction factor to ensure consistency with total CCD fuel consumption, following the methodology of Zhang et al. (2019).

G. Emission Calculation

Total emissions of pollutant iii are calculated using the ICAO formula:

$$E_i = \sum \text{Duration} \times FF \times EI_i \times N$$

Where:

- EI_i = emission index (g/kg fuel)
- N = number of engines

Standard values used in literature include [3–6]: CO_2:
3149 g/kg
H_2O: 1230 g/kg
SO_2: 0.84 g/kg
CO_2 per passenger is: Eper pax=ECO2/P

Application Design and User Interaction

To translate the proposed emission-estimation methodology into a practical and accessible tool, a web-based application was developed. The application is designed to allow non-expert users to estimate flight fuel consumption and CO_2 emissions using scientifically grounded models without requiring access to proprietary aviation datasets or specialized software.

4.1 Overall Structure of the Application

The application follows a modular and layered design architecture. At a high level, it consists of three

primary components:

1. **User Interface Layer:** This layer handles user interaction and input collection, including origin and destination selection, aircraft type, and passenger-related parameters.
2. **Computation and Modeling Layer:** This layer implements the emission-estimation methodology described in Section 2. It includes modules for distance estimation, flight-phase segmentation, fuel-flow correction, and emission calculation using published equations and emission indices.
3. **Output and Visualization Layer**: The final layer presents the computed results to the user in a clear and interpretable format, including total fuel consumption, total CO_2 emissions, and per-passenger emission contribution.

This separation ensures clarity, maintainability, and reproducibility of the application logic, while also allowing future extensions such as alternative aircraft models or additional pollutants.

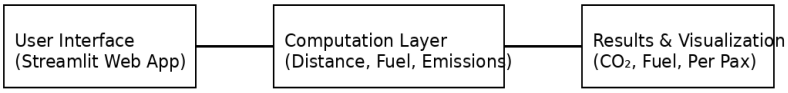


Figure 3. High-level architecture of the flight emiss

4.2 Platform and Technical Implementation

The application is implemented using **Python** and deployed as a **web-based interface** using the Streamlit framework. Streamlit was selected due to its lightweight nature, ease of deployment, and suitability for research-oriented interactive tools.

The application runs on any modern web browser and does not require local installation by the user. All computations are executed server-side using Python-based modules, ensuring consistent results across different devices and operating systems.

Key technologies used include:

- **Python** for numerical computation and modeling
- **Streamlit** for user interface and deployment
- **Geopy** for geographic distance calculations
- **Custom Python modules** implementing ICAO- and literature-based emission models

The source code is version-controlled using GitHub, with separate branches maintained to preserve application stability while enabling methodological updates.

4.3 User Access and Interaction Flow

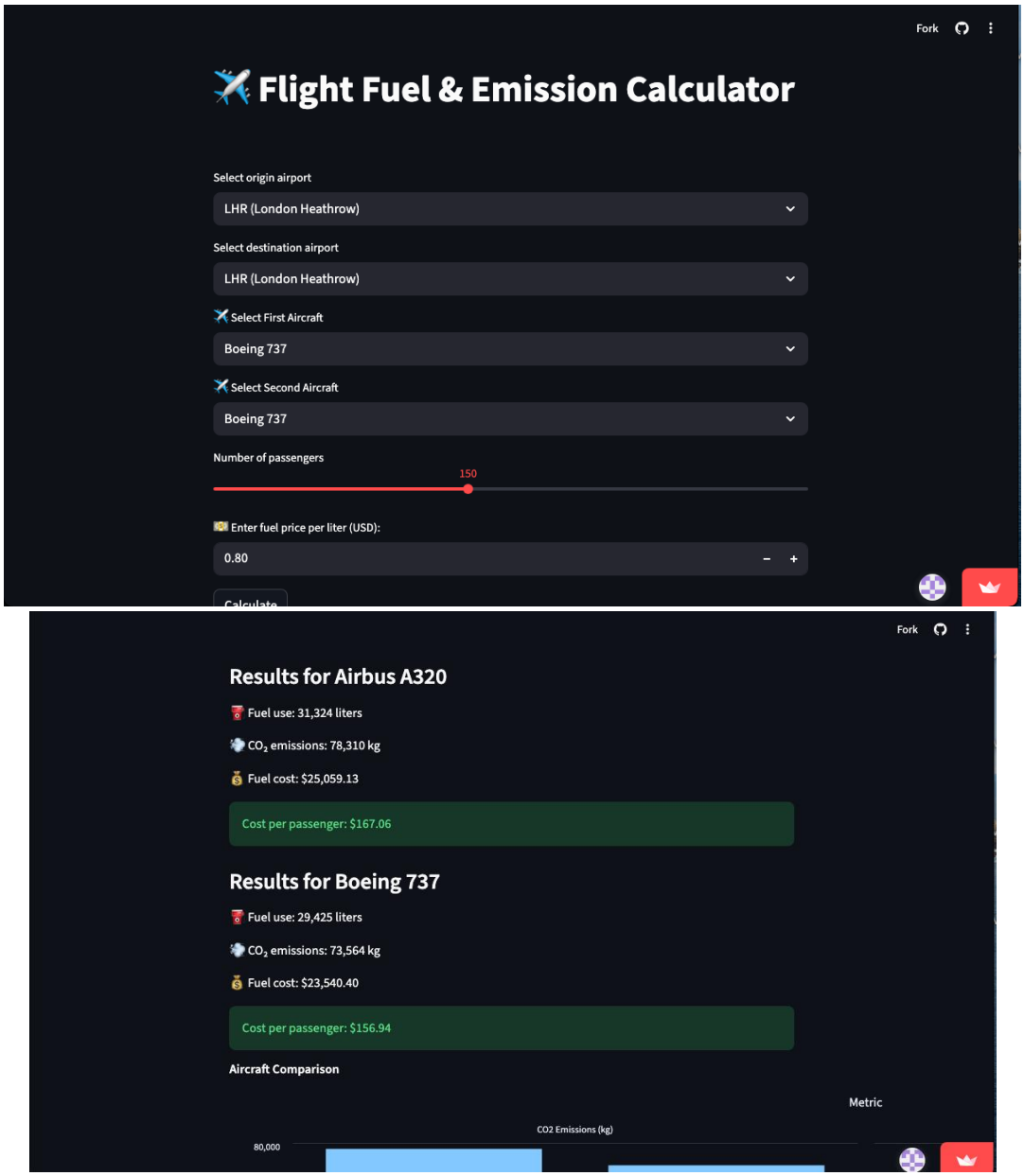
Users access the application through a publicly available web link. Upon opening the app, the user is guided through a simple, step-by-step interaction flow:

1. **Input Selection:** The user selects the departure and arrival airports. Additional inputs such as aircraft category and passenger-related parameters are provided through dropdown menus and sliders to minimize input errors.
2. **Model Execution:** After entering the required inputs, the user initiates the calculation process. The application then applies the corrected distance model, flight-phase segmentation, fuel-flow correction equations, and emission indices as described in the methodology.
3. **Result Presentation:** The output includes:

- Estimated total fuel consumption
- Total CO_2 emissions for the flight

- CO_2 emissions per passenger

4. These outputs are displayed in a concise and visually accessible format to enhance interpretability.



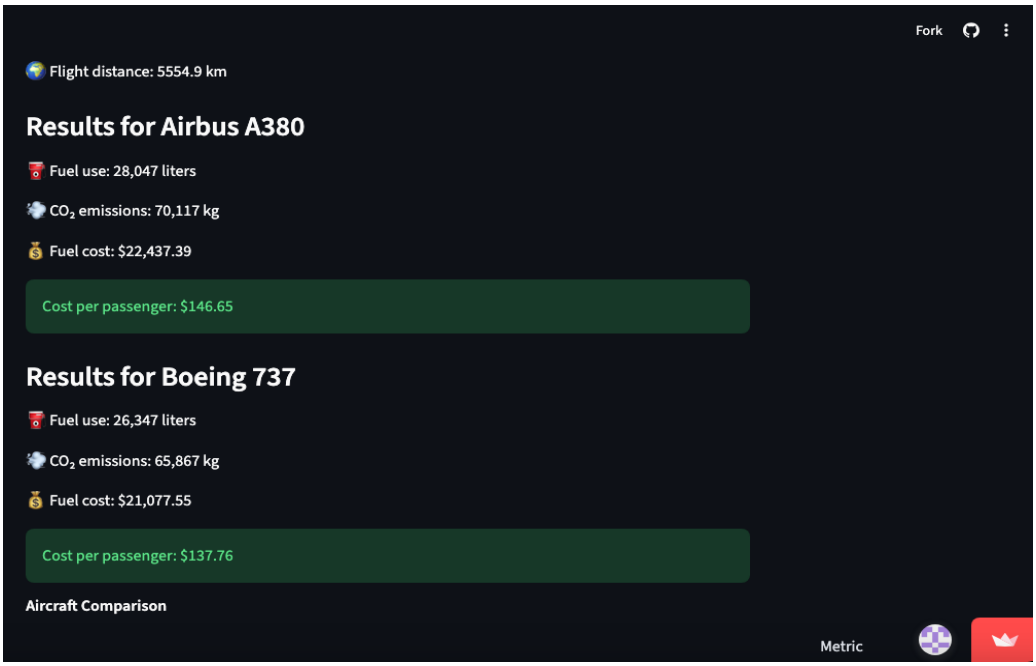
Figures 4 and 5. User interface of the flight-emission estimation application showing input parameters including origin airport, destination airport, aircraft type, and passenger count.

5. The application design emphasizes clarity and minimalism to avoid overwhelming users with excessive configuration options, while still preserving scientific rigor in the underlying calculations.

4.4 Design Rationale and Accessibility

The primary design goal of the application is accessibility. Existing aviation emission tools often target industry professionals or rely on restricted datasets, limiting their usefulness for students, educators, and environmentally conscious consumers. This application bridges that gap by combining peer-reviewed modeling approaches with an intuitive user interface.

By presenting emissions on a **per-passenger basis**, the application also helps users understand individual contribution to flight-related emissions, making abstract environmental impacts more tangible.



Figures 6 and 7. Emission estimation results displayed by the application, including total flight distance, estimated fuel consumption, total CO_2 emissions, and per-passenger carbon footprint

Conclusion

This study developed a transparent and lightweight framework for estimating aircraft fuel consumption and flight-related CO_2 emissions by adapting validated aviation-emission models into a simplified, consumer-accessible form. By integrating corrected great-circle distance estimation, ICAO-standard flight-phase segmentation, published fuel-flow correction equations, and established emission indices, the proposed model enables first-order emission predictions without reliance on proprietary flight-recorder data.

The key contribution of this work lies in **bridging the gap between high-precision aviation-emission research and practical public-facing tools**. While many existing studies depend on restricted datasets such as Quick Access Recorder (QAR) data, this research demonstrates that scientifically grounded emission estimates can still be achieved using published regression equations and standardized assumptions. The resulting web-based application further translates these methods into an intuitive interface, making aviation-emission estimation accessible to students, researchers, and environmentally conscious travelers.

The findings highlight that distance correction and proper cruise-phase modeling play a critical role in avoiding systematic underestimation of fuel consumption and emissions. Presenting emissions on a per-passenger basis also provides a clearer interpretation of individual contribution to aviation-related climate impact.

Future work could extend this research by incorporating aircraft-specific performance parameters, real-time ADS-B trajectory data, or region-specific correction factors. With access to larger and higher-resolution datasets, hybrid approaches combining regression-based models with machine learning techniques could further improve accuracy. Additional pollutants and sustainable aviation fuel (SAF) scenarios may also be integrated to broaden the environmental scope of the application.

Overall, this research contributes a reproducible, interpretable, and scalable approach to aviation-emission estimation, supporting both scientific understanding and practical decision-making related to sustainable air transport.

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