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Quantifying Aircraft and Ground Operations Emissions at Lisbon Airport: A Data-Driven Approach Using ADS-B Technology

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Master in Data Science

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Department of Quantitative Methods for Management and Economics

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To the visionaries striving for a sustainable future in aviation, and to all those whose lives are enriched by the connections forged across continents

Acknowledgment

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Resumo

Este estudo analisa o impacto ambiental das operações de aeronaves no Aeroporto Humberto Delgado em Lisboa, Portugal, utilizando dados de alta precisão do Sistema de Vigilância Dependente Automática por Radiodifusão (ADS-B). A investigação examina mais de 18,4 milhões mensagens ADS-B relativas a 217.657 voos entre Janeiro e Dezembro de 2023, concentrando-se nas emissões durante o Ciclo de Aterragem e Descolagem (LTO). Uma metodologia inovadora é desenvolvida para calcular durações precisas do tempo em modo para cada fase do LTO, cruzando trajetórias geográficas extraídas das mensagens ADS-B com polígonos geográficos definidos de acordo com as fases do LTO , aumentando a precisão face às abordagens padrão feitas no cálculo de emissões. O estudo quantifica as emissões de CO_2, CO, HC, NOx e Matéria Particulada Não-Volátil (nvPM) das operações de aeronaves, bem como as atividades de transporte terrestre de passageiros, e *pushback* de aeronaves. A investigação conclui que as operações de aeronaves foram responsáveis pela emissão de 300.585,68 toneladas de CO_2 em 2023, com 486,35 toneladas adicionais provenientes das restantes operações analisadas. Estas emissões correspondem a um Custo Social do Carbono (SCC) de aproximadamente 125 milhões de dólares americanos. O estudo destaca a importância de análises específicas para aeroportos na avaliação precisa de emissões relacionadas com a aviação, e no desenvolvimento de estratégias de mitigação direcionadas. Apresenta também potenciais otimizações operacionais para reduzir o impacto ambiental, contribuindo para uma compreensão mais ampla das emissões aeroportuárias.

PALAVRAS-CHAVE: Sustentabilidade, Poluição Atmosférica, Transportes, Aviação, Ciclo LTO, Aeroporto, Lisboa

Abstract

This study analyzes the environmental impact of aircraft operations at Humberto Delgado Airport in Lisbon, Portugal, utilizing high-precision Automatic Dependent Surveillance-Broadcast (ADS-B) data. The research examines over 18.4 million data points from 217,657 flights between January and December 2023, focusing on emissions during the Landing and Take-Off (LTO) cycle. A novel methodology is developed to calculate precise time-in-mode durations for each LTO phase by cross-referencing geographical paths extracted from ADS-B messages with predefined boundary boxes, addressing limitations in standard emission calculation approaches. The study quantifies Carbon Dioxide (CO_2), Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NOx), and Non-volatile Particulate Matter (nvPM) emissions from aircraft operations, as well as ground transportation activities for passenger transfers and aircraft pushback operations. The research finds that aircraft operations generated 300,585.68 metric tonnes of CO_2 in 2023, with an additional 486.35 tonnes from ground operations. These emissions correspond to a Social Cost of Carbon of approximately 125 million United States Dollars (USD). The study highlights the importance of airport-specific analyses in accurately assessing aviation-related emissions and developing targeted mitigation strategies. It also emphasizes the potential for operational optimizations to reduce environmental impact. This research contributes to the broader understanding of airport emissions and provides a framework for future studies in aviation sustainability.

KEYWORDS: Sustainability, Air Pollution, Transportation, Aviation, LTO Cycle, Airport, Lisbon

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Glossary

CO_2: Carbon Dioxide, a colorless, odorless gas produced by natural processes like respiration and combustion, as well as human activities such as burning fossil fuels. A key greenhouse gas contributing to global warming and climate change. vii, xi, 1, 9, 15, 16, 22, 42, 50, 52, 53, 55–57, 62, 71–82

CO: Carbon Monoxide, a colorless, odorless, and toxic gas produced by the incomplete combustion of carbon-containing materials, such as fossil fuels; it can be harmful when inhaled and contributes to air pollution but is not a direct greenhouse gas. vii, 9, 42, 62, 71–73

HC: Hydrocarbons, organic compounds made up of hydrogen and carbon atoms, typically found in fuels like gasoline and natural gas; when released into the atmosphere through incomplete combustion, they contribute to air pollution and the formation of ground-level ozone (smog). vii, 9, 62

O_3: Ozone, a colorless gas with a distinct smell, found in the Earth's stratosphere, where it protects living organisms by absorbing harmful ultraviolet radiation from the sun. 9

ACARS: Aircraft Communication Addressing and Reporting System, a digital data transmission system used in aviation for the exchange of messages between aircraft and ground stations, facilitating communication of flight-related data. 72

ACI: Airports Council International, a global trade association representing the world's airports, promoting airport excellence and advocating for policies to enhance the safety, security, sustainability, and efficiency of air transportation systems. 11, 16

ADS-B: Automatic Dependent Surveillance-Broadcast, a surveillance technology in aviation that broadcasts an aircraft's Global Navigation Satellite System (GNSS)-derived position, velocity, and other relevant data for air traffic control and other aircraft to receive. vii, 2, 16, 19–24, 28, 31, 33, 35, 36, 41, 42, 44, 45, 47, 59, 63

AEDT: Aviation Environmental Design Tool, a comprehensive software tool used in aviation planning and design to assess and mitigate the environmental impact of aircraft noise, emissions, and air quality. 11

Airport Carbon Accreditation (ACA): Airport Carbon Accreditation, a global certification program that recognizes airports for their efforts to manage and reduce their carbon emissions. 11, 12, 16, 56

Airport Catchment Area (ACA): Airport Catchment Area, the geographical region from which an airport draws its passengers, encompassing the areas where people choose the airport as their primary point for air travel. 3, 6, 7, 28

AIS: Aeronautical Information Services, a service that provides critical, up-to-date information about airports, airspace, and flight operations. 30

ALQS: Airport Local Air Quality Study, a comprehensive analysis and monitoring to assess the air quality impact within and around airport regions. 11

AMDAR: Aircraft Meteorological Data Relay, a system where aircraft collect and transmit real-time atmospheric data, such as temperature, wind speed, and humidity, to ground stations to later be use in models that improve weather forecasts and aviation safety. 71

ANA: Aeroportos e Navegação Aérea, the company that operates and manages Portugal's main airports. 15, 16, 24, 46, 53, 56

API: Application Programming Interface, a set of rules and protocols that allow different software applications to communicate and interact with each other, enabling seamless data exchange and functionality integration. 23, 41, 58

ATC: Air Traffic Control, a system that manages and directs the safe movement of aircraft in the sky and on the ground to prevent collisions. 19, 38

ATD: Air Transport Demand, the level of interest and need for air travel services relative to an airport, usually measured by the number of passengers, cargo volume, or flights, driven by factors such as economic conditions, population, and tourism. 3, 6, 7

ATM: Air Traffic Management, a broader concept that encompasses the entire process of managing air traffic including ATC, ASM and ATFM . xix

ATR: Avions de Transport Régional or Aerei da Trasporto Regionale, a French-Italian aircraft manufacturer specializing in the production of regional turboprop aircraft, known for its ATR 42 and ATR 72 models commonly used for short-haul flights. 40

CSV: Comma-separated values, a simple file format used to store tabular data, where each line represents a data record and each field within the record is separated by a comma . 27

EDMS: Emissions and Dispersion Modeling System, a software tool used for simulating the release, dispersion, and impact of air pollutants from various sources in the atmosphere. 4, 11

EEA: European Environmental Agency, an EU body providing detailed and independent information on the environment and supporting sustainable development, with the goal of shaping environmental policies. 3, 10, 11

EIA: Environmental Impact Assessments, a comprehensive evaluation conducted to analyze and predict the potential environmental consequences of proposed projects or developments. 7

EMDS: Environmental Modeling System, a decision support framework that integrates environmental data, modeling, and Geographic Information System (GIS) to assist in environmental analysis and decision-making for ecosystem management. 73

EMEP: European Monitoring and Evaluation Programme, an international initiative dedicated to assessing and managing the transboundary air pollution in Europe and neighboring regions. 3, 10

EPA: Environmental Protection Agency, a governmental organization in the United States responsible for safeguarding human health and the environment by creating and enforcing regulations and policies related to environmental protection. 11

EU: European Union, a political and economic union of European countries that promotes integration, cooperation, and a single market among its member states. xix

EUROCONTROL: EUROCONTROL, an intergovernmental organization that aims to improve the efficiency of air traffic management across Europe, enhancing safety and capacity while minimizing environmental impact. 5, 20, 22, 46, 50

FAA: Federal Aviation Administration, the U.S. government agency responsible for regulating and overseeing all aspects of civil aviation, including air traffic control, aircraft safety, and pilot certification. xviii, 20

FDR: Flight Data Recorder, an onboard device that continuously records critical flight parameters and operational data to facilitate post-flight analysis and improve aviation safety and performance. 58

GHG: Greenhouse Gases, the atmospheric compounds that trap heat, contributing to the Earth's warming by allowing sunlight to enter the atmosphere but impeding the escape of infrared radiation. 71

GIS: Geographic Information System, a computer-based tool that captures, stores, analyzes, and visualizes spatial or geographic data to help understand patterns, relationships, and trends in maps and datasets. xvii

GNSS: Global Navigation Satellite System, a constellation of satellites that provides global positioning, navigation, and timing services to users worldwide. xv, xvii, 19–21

GPS: Ground Positioning System, a GNSS developed by the United States Military that provides location and time information anywhere on Earth. 19, 21

GPU: Ground Power Unit, a portable device used at airports to supply electrical power to an aircraft while it is on the ground, allowing onboard systems to operate without relying on the aircraft's engines. 29

HEX: Hexadecimal identifier, or 24-bit International Civil Aviation Organisation (ICAO) code, is a unique hexadecimal identifier assigned to every aircraft, used in aviation to distinguish individual planes in radar tracking and communication systems. 37

IATA: International Air Transport Association, a trade association representing the airline industry, facilitating global standards, operational support, and advocacy for airlines worldwide. 5, 50, 51

ICAO: International Civil Aviation Organisation, a specialized United Nations agency responsible for establishing global standards and regulations to ensure safe, secure, and efficient international aviation. xviii, 4, 5, 8–11, 15, 23, 27, 40, 42, 48, 50, 58, 59

JSON: JavaScript Object Notation, a lightweight data interchange format that is easy for humans to read and write, and easy for machines to parse and generate, primarily used for transmitting data between a server and a web application. 27, 38

LTO: Landing and Take-Off [Cycle], a part of ICAO's Environmental Framework that split a flight operation into phases: Approach, Idle, Take-off, and Climbing, encompassing aircraft maneuvers from descent to ascent, involving landing, taxiing, take-off, all below an altitude of 914 meters. vii, ix–xi, xiii, 3, 4, 8–12, 15, 16, 23, 24, 28, 29, 31–34, 36, 38–42, 47–50, 56, 58, 62, 71

MAE: Mean Absolute Error, a metric that measures the average magnitude of the absolute differences between predicted and actual values, providing a straightforward way to quantify prediction accuracy. 37, 39

MEET: Methodologies for Estimating Air Pollutant Emissions, a comprehensive framework incorporating various methods and tools to estimate air pollutant emissions from various sources, aiding in environmental assessment and regulatory compliance. 11

NAV: Navegação Aérea de Portugal, the Portuguese agency responsible for managing and controlling air traffic in Portugal's airspace. 30

NextGen: Next Generation Air Transportation System, a comprehensive modernization initiative led by the Federal Aviation Administration (FAA) to transform United

States of America's air traffic management system by leveraging advanced technologies, such as satellite-based navigation and real-time data sharing, to enhance safety, efficiency, and environmental sustainability in aviation. 20

NOx: Nitrogen Oxides, a group of highly reactive gases, including nitrogen dioxide (NO_2) and nitric oxide (NO), produced during combustion processes, especially in vehicles and power plants; NOx contributes to air pollution, the formation of ground-level ozone (smog), and acid rain, and can have harmful health effects. vii, 9, 42, 62, 71–73

NUTS II: Nomenclature of Territorial Units for Statistics Level 2, an European classification system dividing regions for statistical purposes into larger territorial units to facilitate data collection and analysis. 13

nvPM: Non-volatile Particulate Matter, solid particles, primarily composed of soot or black carbon, emitted during combustion processes such as those in aircraft engines and diesel vehicles; unlike volatile particulate matter, nvPM does not evaporate and can contribute to air pollution, climate change, and adverse health effects. vii, xx, 9, 41, 42, 50, 53, 55, 57, 58, 62

POC: Proof-of-Concept, a prototype or demonstration project created to validate the feasibility, viability, and potential of a concept or feature before investing in full-scale development. 27

PSR: Primary Surveillance Radar, a radar system that detects and measures the position of objects by transmitting radio waves and analyzing the reflected signals. 19

RAM: Random Access Memory, a type of computer memory that temporarily stores data and instructions a computer's processing unit needs while a device is running, allowing for quick access and smooth multitasking. 27

SCC: Social Cost of Carbon, an estimate of the economic damages associated with a one metric ton increase in carbon dioxide emissions, accounting for the long-term costs to human health, the environment, and the economy due to climate change impacts. 57, 62

SESAR: Single European Sky Air Traffic Management Research (SESAR), an European Union (EU) initiative aimed at modernizing and harmonizing European Air Traffic Management (ATM) to improve efficiency, safety, capacity, and environmental sustainability in the aviation sector across Europe. 20

SOx: Sulfur oxides, a group of gases composed of sulfur and oxygen, primarily including sulfur dioxide (SO_2), which can contribute to air pollution, acid rain, and respiratory problems in humans. 9, 73

SSR: Secondary Surveillance Radar, a radar system that relies on a transponder in the target object to send back a coded response, providing additional information such as identity and altitude. 19

TAP: TAP Air Portugal, the Portuguese flag-carrier airline known for its extensive hub-and-spoke network, offering flights to various destinations with a focus on Portugal, Europe, and connections to Africa, North and South America. 13

UFP: Ultrafine particles, airborne particles with a diameter less than 100 nanometers; a subset of nvPM, which are primarily solid particles emitted by combustion that do not evaporate at normal atmospheric conditions. 15, 57

USD: United States Dollar, the official currency of the United States of America represented by the symbol "$" and the code "USD".. vii, 57, 62

UTC: Coordinated Universal Time, the primary time standard used worldwide to regulate clocks and time, serving as the basis for civil time and time zones, without seasonal adjustments like daylight saving time. 24

VOCs: Volatile organic compounds, a group of organic chemicals that easily evaporate at room temperature and can contribute to air pollution and health problems, commonly found in paints, solvents, and cleaning products. 9, 73

CHAPTER 1

Introduction

Aircraft have played a pivotal role in the process of globalization, revolutionizing travel and transforming long journeys into relatively short and comfortable experiences. Recent decades have seen a substantial rise in air transport, enabling rapid global mobility while generating both benefits and drawbacks. On the positive side, air travel has undoubtedly benefited modern society by enhancing connectivity and driving economic growth. However, these advantages are accompanied by significant environmental costs, including noise pollution, air quality degradation from toxic emissions, and broader climate change impacts from combustion-related activities (Wolfe *et al.*, 2014).

The environmental impact of civil aviation is substantial, accounting for 2.4% of global energy-related Carbon Dioxide (CO_2) emissions in 2018 (Jaramillo *et al.*, 2022, p. 1086). While not directly targeted, the sector is affected by long-term climate change mitigation measures, such as the European Union's 2050 Net Zero target and the United Nations' 2030 Agenda for Sustainable Development. As critical infrastructure connecting passengers to the aviation sector, airports play a vital role in economic development and local employment. Consequently, they face heightened scrutiny for their environmental impacts on surrounding areas.

Civil aviation demand is projected to increase at an annual rate of 4.2% between 2023 and 2040 (IATA, 2023b, p. 12). This growth trajectory is anticipated to result in an increase in emissions and airport expansion, thus intensifying environmental concerns. As such, the present study addresses these challenges by examining the environmental implications of aircraft operations and associated activities at Humberto Delgado Airport in Lisbon, Portugal. As Portugal's primary international gateway, its distinctive location within a residential area proximate to the city center magnifies its environmental impact on air quality and noise levels for numerous residents. This situation exemplifies the intricate balance between operational efficiency, environmental stewardship, and community well-being.

Given this context, the present study addresses the following central research question: What is the environmental impact of aircraft operations at Humberto Delgado Airport?. The research aims to quantify emissions of key pollutants associated with aircraft operations, analyze the relationship between operational patterns and environmental impacts, and propose potential mitigation strategies. This comprehensive assessment of a major urban airport's environmental impact contributes significantly to the growing body of knowledge on aviation sustainability. The findings can inform policy decisions on airport operations and expansion plans, balancing economic benefits with environmental concerns.

Additionally, the analysis methods developed in this study are designed for adaptation to similar assessments at other urban airports globally. By examining the environmental challenges faced by Humberto Delgado Airport, this research aims to stimulate discussions on innovative, targeted solutions for sustainable aviation practices.

The research structure draws inspiration from the Cross-Industry Standard Process for Data Mining (CRISP-DM), providing a systematic framework for this data-driven study. The methodology encompasses a comprehensive literature review on airport emissions, data collection utilizing Automatic Dependent Surveillance-Broadcast (ADS-B) data, statistical analysis methods, and big-data processing tools. While the study primarily focuses on the direct environmental impacts of aircraft operations at Humberto Delgado Airport, particularly gaseous emissions, it also considers ground operations and auxiliary services. The broader indirect impacts on regional air quality and global climate change, however, fall beyond the scope of this research. It is important to note that the study's findings are constrained by the availability and accuracy of operational data, as well as the inherent uncertainties in environmental analysis.

The study is structured to provide a comprehensive exploration of the research question. Following this introduction, Chapter 2 presents a literature review and business understanding of airport operations and their environmental impacts. Chapter 3 focuses on data understanding, particularly the ADS-B data source. Chapter 4 details the data preparation techniques and methodology employed in the study. Chapter 5 presents and discusses the results of the research, highlighting the implications of these findings. Finally, Chapter 6 concludes the dissertation with recommendations and suggestions for future research.

Through this comprehensive approach, the study aims to contribute with valuable insights to the ongoing dialogue on aviation sustainability and Lisbon Humberto Delgado Airport's role in the city. By offering a data-driven perspective on these critical issues, this research aspires to inform policy decisions and contribute to the development of sustainable aviation practices in Lisbon and beyond.

CHAPTER 2

Business Understanding

Understanding an airport's operational environmental impacts is crucial for developing effective policy recommendations, implementing sustainable airport management strategies, and promoting overall sustainable development in the aviation sector. This chapter provides a comprehensive overview of airport operations and their associated environmental impacts, with a specific focus on Lisbon's Humberto Delgado Airport. The discussion begins by examining the general framework of airport operations and their environmental consequences by consulting the existing literature. Subsequently, it introduces the concepts of Airport Catchment Area (ACA) and Air Transport Demand (ATD) to deepen the analysis. Methods for quantifying emissions are then explored, serving as a foundation for discussing reduction strategies. Finally, the specific context of Lisbon Airport is examined, highlighting its unique characteristics and environmental challenges.

The environmental impact of airports has been the subject of extensive research in recent decades. Wolfe *et al.* (2014) provided a comprehensive review of near-airport environmental impacts, highlighting the complexities of measuring and mitigating these effects. Postorino (2010) examined the relationship between airport catchment areas and environmental impacts, emphasizing the importance of considering broader geographical contexts in assessing airport-related emissions. Regarding emissions quantification, ICAO (1993) established the Landing and Take-Off (LTO) cycle as a standardized method for assessing local emissions. This approach has been widely adopted and further developed by organizations such as the European Environmental Agency (EEA) and the European Monitoring and Evaluation Programme (EMEP) (Kurniawan and Khardi, 2011). More recent studies have focused on specific aspects of airport operations and their environmental impacts. For example, Pereira (2021) examined the often-overlooked environmental impact of fuel transportation to Lisbon Airport, providing valuable insights into the broader scope of aviation-related emissions. These studies collectively provide the foundation for the analysis that follows.

2.1. Literature Review

The analysis of Lisbon Airport's specific characteristics and impacts needs a preliminary examination of the broader aviation industry context. This research was guided by the central question: "What environmental impacts do airport operations have on their surroundings?" This inquiry served as the foundation for selecting appropriate databases, keywords, and criteria for article extraction and selection. By adhering to a structured approach, this study aims to provide a comprehensive and insightful examination of airport emissions, enhancing understanding of their implications for the surrounding environment.

In the initial phase of the literature research, Scopus[1] served as the primary database. Given that the research domain intersects environmental concerns and the aviation sector, an extensive body of literature exists, with numerous synonymous terms potentially serving as keywords—for instance, "emissions" and "impacts." To mitigate the risk of overlooking pertinent studies due to terminological variations, the *ALL()* query function was employed and can be consulted on Listing 2.1.

```
ALL(
    (Environment AND impact AND emission AND LTO)
    AND(Airport OR Aircraft))
```

LISTING 2.1. Query used for Scopus database search

As of January 2024, The query yielded 365 research articles, screened as they were ordered by Scopus primarily by title, followed by abstract and keywords. From these, 10 were related to specific airports or a set of airports and were chosen for in-depth review and inclusion in this document — included on Table A.1. Additionally, Google Scholar[2] was used for a similar search, returning comparable studies. During the reading of the articles mentioned, some cited articles were also included on the screening process.

With this literature review it is possible to conclude that airport and aviation industry significantly impacts various stakeholders, including travelers, local residents, and industry workers. This wide-ranging influence is reflected in the diverse array of studies found in the literature. The increasing volume of research published annually underscores the growing concern about climate change and the need to understand and address its sources. Studies in this field generally fall into two categories: those focused on quantifying emissions to assess air quality, and those examining the broader climate change impacts by modeling emission accumulation and concentration.

The majority of air quality assessment methodologies in the reviewed studies primarily utilized the International Civil Aviation Organisation (ICAO) Emissions Databank or the Emissions and Dispersion Modelling System (EDMS) model for measuring gaseous concentrations. Studies based on the ICAO Emissions Databank typically relied on flight quantity data from airport authorities and employed standard phase durations for the LTO cycle, with studies being exceptions by exploring innovative methods to enhance precision, such as incorporating meteorological data (Zhou *et al.*, 2019) or utilizing aircraft-specific communication systems (Xu *et al.*, 2020). Nevertheless, these approaches are limited by constraints in data quantity or availability.

[1]https://www.elsevier.com/products/scopus
[2]https://scholar.google.com

The subsequent sections will provide a detailed examination of each of these concepts, elucidating their distinctive features and potential limitations. This in-depth exploration will offer a nuanced understanding of the various elements at play, highlighting both their strengths and areas where caution may be warranted. As the discussion progresses, the focus will shift to an exploration of Lisbon Airport's unique characteristics. This analysis will incorporate existing literature specific to this airport, providing a contextualized perspective on its operations, challenges, and significance within the broader aviation landscape. By examining the airport through the lens of current research, this section aims to provide a well-rounded view of the aviation business and Lisbon Airport's role, focusing on its particular attributes in relation to the concepts previously discussed.

2.2. Airport Operations and Environmental Impact

The aviation industry represents a multifaceted ecosystem characterized by diverse operational entities executing complementary functions. The ICAO assumes a central role in delineating these responsibilities, employing a comprehensive framework that encompasses the obligations of nations, regulatory bodies, and infrastructure managers. This approach ensures a cohesive and standardized structure within the global aviation landscape. ICAO, an intergovernmental agency established in 1947 as part of the United Nations, originated from the 1944 Convention on International Civil Aviation in Chicago. Initially formed with 52 participating nations, ICAO now comprises 193 signatory states with the mission to promote the development of safe and efficient international air transport while ensuring consistency in methods and operating procedures for flights between different countries. ICAO sets and reviews technical standards for aircraft operations and design, oversees crash investigations, licenses personnel, manages telecommunications and meteorology for aviation operations, and coordinates search-and-rescue missions. Additionally, it fosters regional and international aviation agreements, develops legal standards to maintain safety, and supports the advancement of international aviation law (Milde, 2008; Mingst, 2024).

Another significant stakeholder in the aviation industry is the International Air Transport Association (IATA). As a trade association for the world's main airlines, IATA encompassed approximately 80% of total air traffic in 2020, comprising 342 member airlines (IATA, 2024). Primarily focusing on promoting safe, reliable, and economical air services through commercial and technical cooperation among airlines, IATA develops industry policies, advocates for the interests of airlines, and provides global standards for airline operations, including ticketing, ground handling, and security procedures.

These stakeholders collectively contribute to the organization of a typical commercial flight operation. In 2019, 86% of flights were commercial scheduled flights, according to EUROCONTROL's 2022 market segment rules (EUROCONTROL, 2022), which comprise "Mainline", "Regional", "Low Cost", and "All-Cargo" categories. This statistic underscores that the majority of aviation operations emissions are related to the aforementioned commercial scheduled flights and their associated activities. To better understand the impacts of these operations, they must be properly identified and categorized, which will be addressed in the following section.

2.2.1. Airport Catchment Area and Air Transport Demand

The primary conceptual framework for describing airport operations involves the distinction between the "land side" and "air side" of the airport infrastructure. As indicated in Figure 2.1, the land side encompasses all areas accessible to the general public before security screening, including access roads, parking facilities, terminal entrances, check-in counters, and baggage claim areas. It involves all activities related to passenger and cargo movement up to the point of security clearance. Conversely, the air side includes all areas beyond security checkpoints, accessible only to passengers who have been previously screened and authorized personnel. This also includes departure gates, runways, taxiways, and maintenance facilities — focusing on aircraft operations, ground handling, and related services (Schmidt, 2017). This high-level overview facilitates a detailed exploration of the impacts of the next level of detail: the Airport Catchment Area (ACA), which converges with land side activities, and the ATD, which converges with air side activities.

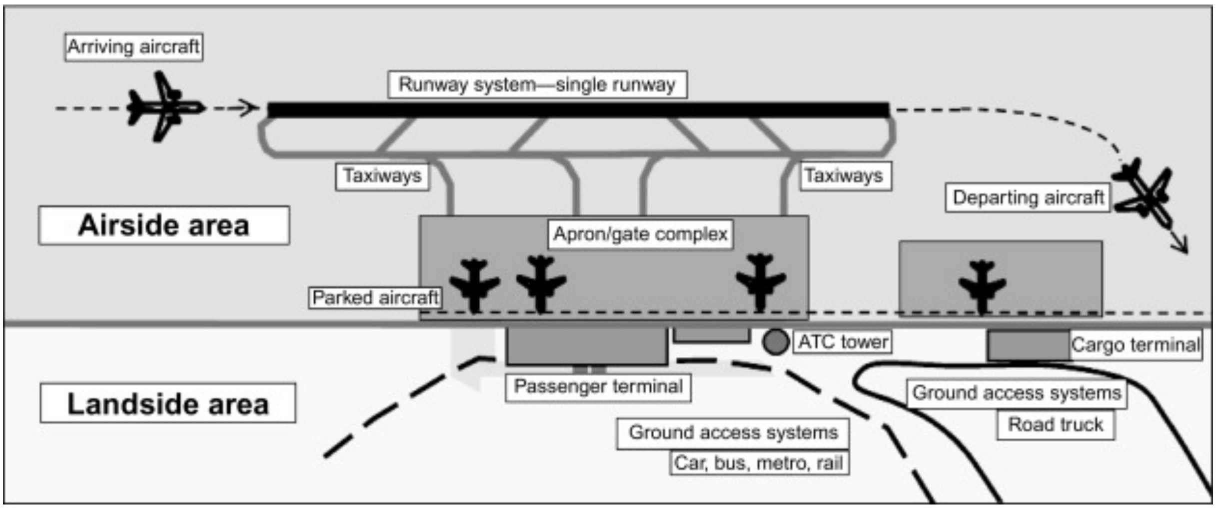


FIGURE 2.1. Generic airport with landside and airside elements (Teodorović and Janić, 2017)

The Airport Catchment Area (ACA) denotes the geographical region from which an airport attracts its passengers and freight traffic. This area is defined by various factors influencing travel behavior, including the airport's proximity to population centers, the quality of transportation infrastructure linking the airport to surrounding regions, and the socio-economic characteristics of potential users within this geographical expanse. The main environmental impacts of the activities related to the Airport Catchment Area (ACA) are generated by the way people travel to the airport and the characteristics of the overall airport infrastructure. The size and characteristics of the Airport Catchment Area

(ACA) directly influence airport operations and planning decisions related to terminal capacity, transportation access improvements, and marketing strategies designed to attract more passengers. These factors collectively affect the airport's market power and their ability and capacity of receiving users. Additionally, terminal operations, dictated by capacity requirements, demand substantial ground usage to support high-capacity mobility nodes. These operations consume significant amounts of energy and generate considerable waste, both stemming from the need to support and serve passengers. Consequently, airports have a substantial local impact, affecting land use, energy resources, and waste management systems (Postorino, 2010).

Airport infrastructure also entails indirect but significant externalities, including visual impacts, groundwater effects from impermeabilization of the ground, and waste generation, among others — typically detailed in Environmental Impact Assessments (EIA). While this study will not consider the impacts related to Lisbon's Humberto Delgado Airport Catchment Area, other studies have explored related topics, such as assessing the cost of emissions for airport access at Manchester Airport (Miyoshi and Mason, 2013) and forecasting demand based on catchment area analysis (Kroes *et al.*, 2005). Variables such as the quality and capacity of ground transportation systems, number of destinations served by air, flight frequency and scheduling, level of service, and available facilities are key indicators that define an Airport Catchment Area (ACA) (Postorino and Mantecchini, 2020). While both passenger and goods traffic are directly connected to the Airport Catchment Area (ACA), goods volumes are, most commonly, negligible compared to passenger volumes, and is expected to account for approximately 12% of the global air transport revenue in 2024, when it is expected to recover to pre-pandemic levels (Postorino, 2010; IATA, 2023a).

On the other hand, the ATD represents the volume of traffic successfully captured from the Airport Catchment Area (ACA). The emissions from the aircraft themselves, along with related activities such as ground handling, contribute to the emissions associated with the ATD (Postorino, 2010).

The primary environmental impacts of aircraft operations on their surroundings are noise and atmospheric pollution. Atmospheric pollution can be further characterized into two dimensions: impacts to the local air quality and contributions to climate change. The distribution of these impacts on airport surroundings is uneven, with significant variations in air quality effects. These effects often exhibit consistent patterns correlated with the distance from emission sources. In contrast, noise pollution analyses indicate non-circular emission contours, predominantly affecting regions aligned with runways and flight trajectories (Wolfe *et al.*, 2014).

Other important but limited environmental impacts of the air transport function include surrounding soil and groundwater and waterways contamination by aircraft de-icing products (the process of chemically removing ice or snow from the surfaces of an aircraft before take-off to ensure safe operation in cold temperatures), fuel and oil spills, herbicide use for ground management, and surface runoff from both aircraft and ground support activities — mainly tire rubber and brake dust. Air transportation also affects the environment through bird and wildlife strikes that often require mitigation measures and induce land use changes around airports (Postorino, 2010; Wolfe *et al.*, 2014).

Some of these impacts have well-established frameworks for analysis, which will be explored in the next section.

2.3. Quantifying emissions

Quantifying an airports' emission is a crucial process for evaluating the potential environmental consequences of its operations and development projects. This section explores the methods and frameworks used to quantify emissions and assess their dispersion with the goal of having knowledge to develop strategies for mitigation.

2.3.1. Aircraft Emissions

Various methods exist in the literature to quantify the environmental impacts originating directly from aircraft in the vicinity of an airport. These methods range from measuring aircraft pollutant emissions by extrapolating flight data (Chati and Balakrishnan, 2014; Tokuşlu, 2021), installing sensors on aircraft engines (Agrawal *et al.*, 2008), or utilizing atmospheric sensors for calculations (Heland and Schäfer, 1998; Schäfer *et al.*, 2003; Schäfer, 2001). Additionally, some studies focus on modeling and assessing the local and regional impact of aircraft pollutant emissions using dispersion models (Dameris *et al.*, 1998; Unal *et al.*, 2005).

These different methods share a common approach, namely, the framework used to describe the flight phases around an airport: the LTO cycle. First, in its Annex 16, Volume II (ICAO, 1993), and then in its multi-year Environmental Reports (ICAO, 2022), ICAO delineates the LTO cycle as the recommended method for determining local emissions related to aircraft operations. The LTO cycle, which encompasses an aircraft's movements from parking to runway, takeoff, landing, and return to parking, serves as the foundational framework for analyzing the environmental impact of aircraft operations at airports. Its split of operations into consistent and distinct phases makes it particularly suitable for such analysis. Furthermore, it constitutes the fundamental basis for ICAO's computation of aircraft engine emissions for certification purposes (ICAO, 2022).

The four distinct phases that constitutes the LTO cycle starts with the Approach phase, where the aircraft maneuvers towards the airport from an altitude of approximately 914 meters (3000 feet) above ground level and while the aircraft is decelerating on the runway. Subsequently, the Idle phase involves the taxiing from the runway to the final parking position, and the movement from the parking position back to the runway on the next flight. Following the Idle phase, the Take-Off section starts from the runway at departure and concludes after the aircraft leaves the ground, transitioning into the Climbing phase until it reaches the altitude of 914 meters. Above this altitude the start of the Cruise phase is triggered, which encompasses three sub-phases: Climb, Cruise, and Descent (CCD). The remaining Climb sub-phase extends from 914 meters to the initial or final cruising altitude, while the Descent phase begins as the aircraft commences its descent until reaching the altitude of 914 meters again (ICAO, 1993, 2020). To ensure consistency in LTO cycle analyses, ICAO has established standard durations for each operational mode, as illustrated in Figure 2.2.

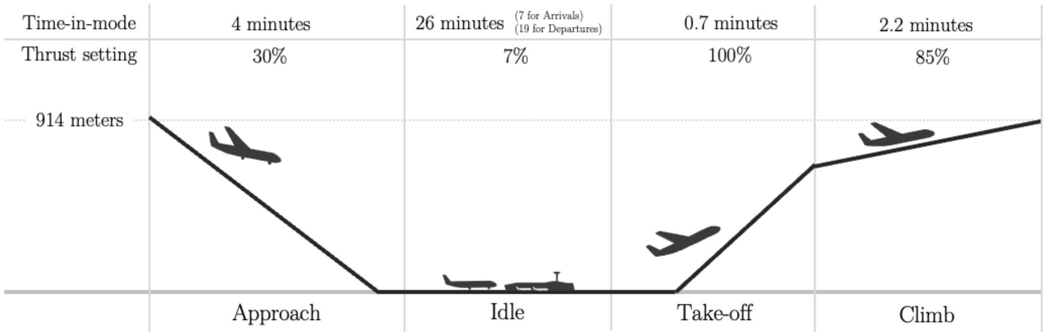


Figure 2.2. ICAO Engine Emission Certification: LTO Cycle (ICAO, 2020)

A standard commercial aircraft engine emits various substances. The complete combustion of jet fuel produces CO_2 and water vapor, with CO_2 emissions occurring at a fixed rate of 3.16 kg per kg of fuel consumed (Nojoumi *et al.*, 2009), while the emission ratios of other substances vary based on the specific mechanical characteristics of the engine. Additionally, the engine produces other pollutants in varying quantities. The incomplete combustion to which every engine is subjected at varying levels leads to emissions of Hydrocarbons (HC), Carbon Monoxide (CO), and Non-volatile Particulate Matter (nvPM) — both solid and liquid — which are small enough to be inhaled. High-temperature combustion processes cause nitrogen and oxygen in the air to form Nitrogen Oxides (NOx). Sulfur Oxides (SOx) are produced when sulfur in the fuel reacts with oxygen, contributing significantly to smog formation in the presence of heat and sunlight. Additionally, while not directly emitted, Ozone (O_3) forms in the atmosphere through the reaction of Volatile Organic Compounds (VOCs) (ICAO, 2022).

ICAO established the limits for each of these engine-dependent emissions in Annex 16 Volume II of the Convention on International Civil Aviation where stipulations for testing and analysis methods are also included (ICAO, 1993). The results obtained from these tests contribute to an engine's certification documentation and the emission data resulting from this certification process can be voluntarily submitted by the engine manufacturer to ICAO, where it becomes part of the "ICAO Aircraft Engine Emissions Databank" (ICAO, 2024). The Emission Databank provides extensive data on engines, including fuel flow and emissions observed in each LTO cycle both by kilogram of fuel burnt and by aggregating per phase (assuming the standard time-in-mode durations). By specifying the emissions generated in each mode, the Emissions Databank facilitates the calculation of emissions for an aircraft engine during every cycle.

To allow for different levels of precision depending on the available data, the EEA and the EMEP elaborated and utilize a different method of determining aircraft emissions based on LTO cycle coupled to a decision tree (Tier 1, Tier 2, and Tier 3). Both Tier 1 and Tier 2 methodologies rely on LTO data, and information on the amount of fuel sold, differing primarily in their assumption regarding the LTO cycle quantities — Tier 1 considers only the LTO cycle quantity, while Tier 2 considers LTO quantity per aircraft type. Tier 3 methodologies, on the other hand, utilize actual flight movement data, either through Origin and Destination information for Tier 3A or full flight trajectory data for Tier 3B. Unlike top-down calculations on Tiers 1 and 2 that are based on fuel consumed and inherently imprecise data, Tier 3 approaches are bottom-up and flight-based (Kurniawan and Khardi, 2011).

2.3.2. Ground Handling Operations

While the LTO cycle provides the foundation for a sizeable portion of emissions data, it is focused on aircraft processes, leaving aside numerous other tasks that are executed by stakeholders in the airport's vicinity and on the ground. When the aircraft is parked, several activities take place to prepare the aircraft for its next journey, collectively referred to as "ground handling."

As needed, passengers disembark, luggage and commercial cargo are removed, and the aircraft undergoes cleaning while flight-related waste is cleared. Crew rotations occur. If there is any required maintenance, a team is deployed to perform it. Catering vehicles deliver food and drinks, while others load new luggage and cargo. The aircraft is refueled, and passengers are subsequently boarded for the next flight (Postorino, 2010; Szabo *et al.*, 2022; Schmidt, 2017).

The emissions linked with ground handling activities vary depending on factors like the frequency of aircraft movements, flight schedules, and the size and layout of the airport's operational areas. Additionally, these emissions are also influenced by attributes specific to the vehicles involved, such as their age, fuel type, fuel efficiency, and levels of usage (Postorino, 2010). Given the diverse nature of these activities, purpose-built vehicles are tailored to each specific task, meaning that each step in this process typically involves one or more specialized vehicles to efficiently carry out the required tasks. Consequently, achieving precise calculations requires comprehensive data collection and analysis tailored to the specific context of each equipment in each specific airport (Postorino, 2010).

2.3.3. Models for Emissions Estimation and Dispersion

Beyond quantifying emissions, understanding their dispersion in the environment is crucial for determining an airport's impact on its surroundings, particularly regarding air quality. Emission dispersion can vary significantly based on geographical and meteorological conditions, resulting in diverse effects on the airport's vicinity. These variations emphasize the necessity for comprehensive studies to assess and effectively mitigate the environmental consequences of airport emissions (Wolfe *et al.*, 2014).

The EDMS was initially developed in the mid-1980s as a computer model aimed at evaluating air quality impacts related to proposed airport development projects, evolving over time to satisfy developing regulatory and precision requirements. In its latest versions, the model incorporated updated data from the ICAO Engine Exhaust Emissions Data Bank, as well as vehicle emission factors from the United States Environmental Protection Agency's (EPA) among other validated dispersion models by the EPA (Anderson *et al.*, 1997). In May 2015, the EDMS was replaced by the Aviation Environmental Design Tool (AEDT), a tool used for research and development purposes with limited access.

2.3.4. Models Comparison

A comparative analysis of various methodologies outlined in this document was conducted by Kurniawan and Khardi (2011), such as those by ICAO and EEA, alongside others such as the Methodologies for Estimating Air Pollutant Emissions (MEET) and the Airport Local Air Quality Study (ALQS). Their study concluded that ICAO's methodology, adopted by several organizations and projects, stands out as the most reliable for assessing pollutant emissions specifically within the LTO cycle. However, when assessing emissions for the entire flight duration, alternative methodologies like MEET can be more suitable.

2.4. Reduction Strategies and Frameworks

One of the main standards for measuring, managing, and reducing airports' environmental footprint is the Airports Council International (ACI) Airport Carbon Accreditation (ACA) Program. This global carbon management certification program for airports provides a common framework for active carbon management at airports, covering operational activities that contribute most to carbon emissions. The program considers various types of emissions in its calculations, categorized mainly into three scopes based on the source and control over the emissions:

Scope 1 Emissions: Direct emissions from sources that are owned or controlled by the airport. This includes emissions from airport-owned or controlled equipment and vehicles, fuel combustion on-site (e.g., from generators or boilers), and emissions from refrigerant leakage.

Scope 2 Emissions: Indirect emissions from the generation of purchased electricity, steam, heating, and cooling consumed by the airport. These are emissions that occur outside the facilities where the energy is consumed, but are accounted in the airport's carbon footprint since the airport consumes the energy.

Scope 3 Emissions: Other indirect emissions that occur as a consequence of the airport's activities but from sources not owned or directly controlled by the airport. This category is broader and can include emissions from:

- Aircraft LTO cycles;
- Emissions from ground handling services and other tenant operations at the airport;
- Passenger and staff surface access to and from the airport;
- Emissions associated with the airport's waste management and water usage;
- Emissions from the production of purchased goods and services.

On the emissions mitigation side, the Airport Carbon Accreditation (ACA) Program presents a comprehensive framework for airports to progressively enhance their carbon management practices through seven certification levels. Beginning with Level 1 (Mapping), which establishes a baseline through emission source identification and carbon footprint reporting, the program advances to Level 2 (Reduction), where airports must demonstrate effective carbon management and quantifiable emissions reductions. Level 3 (Optimization) broadens the scope to include third-party emissions and stakeholder engagement. Levels 3+ (Neutrality) and 4 (Transformation) introduce offsetting requirements and alignment with global climate goals. Level 4+ (Transition) further commits to offsetting residual emissions under airport control. The pinnacle, Level 5, demands net-zero emissions for Scopes 1 and 2, active management of Scope 3 emissions, enhanced third-party engagement, and offsetting of residual emissions through carbon removal projects. This structured approach encourages continuous improvement in airport carbon management, progressively expanding the scope and impact of environmental initiatives. This framework encourages airports to progressively reduce their carbon emissions and engage with stakeholders to achieve more sustainable operations.

2.5. Lisbon Airport Characteristics

The present section examines Lisbon's Humberto Delgado International Airport's role as an infrastructure within the broader context of environmental impact assessment. As a relevant node in the global transportation network, this infrastructure presents complexities that demand a comprehensive analysis to gauge its environmental repercussions. This investigation details the infrastructural components, operational frameworks, and associated environmental challenges pertinent to Lisbon Airport.

In the context of the escalating global climate crisis, sustainable infrastructure management has become imperative across all sectors, with Lisbon Airport presenting a unique case within aviation. Inaugurated in 1942 on the then-outskirts of Lisbon, the airport was quickly enveloped by urban expansion. By 1969, the government recognized the need to relocate the airport to accommodate the increasing global demand driven by the advent of jet-powered aircraft (Ministério das Comunicações, 1969). However, this decision has remained in deliberation for decades. Despite a formal decision on a new location in 2024, construction of Lisbon Airport's successor has not yet begun.

Lisbon, as the westernmost European capital, holds a geographical peripherality in continental terms. Lacking high-speed infrastructure for connecting traffic domestically or to its neighboring countries, Lisbon's Humberto Delgado Airport functions as a primary transportation hub, serving not only the country's mainland and island residents but also visitors arriving in or departing from Portugal. The primary airline operating in Lisbon, Transportes Aéreos Portugueses (TAP), now TAP Air Portugal, transported 13,759,000 passengers in 2022 (TAP, 2023a), constituting 48% of the 33,648,691 (ANA, 2023b, p. 133) passengers for that year, making it the biggest company operating on the airport.

For most of its existence, TAP, which was founded by intervention of Humberto Delgado, who now lends his name to Lisbon Airport, focused on point-to-point flights. Shortly after its inaugural flight in 1946 —between Lisbon and Madrid —, and drawn by Portugal's colonial territories at the time, TAP initiated flights to sub-Saharan Africa even before establishing any domestic routes. This pioneering flight from Lisbon to Luanda and Mozambique and back spanned 15 days and made 12 stops (TAP, 2023b).

TAP's evolution into a hub carrier is a recent development. Capitalizing on Brazil's significant economic growth in the mid-2000s (Maia and Menezes, 2014), TAP leveraged its extensive experience in long-haul flights to expand services to previously underserved Brazilian cities, including Belo Horizonte and Brasilia. By 2010, the airline operated 47 weekly frequencies between Lisbon and various Brazilian destinations. Simultaneously, TAP joined Star Alliance, a global airline network that enhanced collaboration among carriers. This strategic move enabled TAP to connect Brazilian and African passengers with European capitals indirectly served by the company, thus expanding its reach and reinforcing Lisbon Airport's position as a connecting hub (TAP, 2023b).

Capitalizing on Lisbon's strategic geographical location, TAP's expertise in long-haul flights, and favorable economy scenario in the mid-2000's, Lisbon Airport has evolved into a hub airport where 6,314,000 passengers — 22% of the airport's traffic volume in 2022 — comprises passengers utilizing its infrastructure for connecting flights, not as a destination (Simão and Vasconcelos, 2022). An illustrative comparison can be made with Dusseldorf, Germany: Despite Dusseldorf's NUTS II area hosting twice the population of Lisbon, in 2022, Dusseldorf's airport managed 57% of the passenger volume handled by Lisbon Airport.

Lisbon Airport's infrastructure comprises two passenger terminals, one cargo terminal, and a single runway. Terminal 1 serves as the primary facility, accommodating departures for multiple airlines, including both flag carriers and low-cost airlines, while also handling all arrivals and functioning as the hub for flight connections. The terminal's landside accessibility is extensive, featuring road connections, an underground metro station, local bus services, and diverse parking options for both short-term and long-term use. Dedicated areas are allocated for taxi pickup and ride-hailing services, with an additional very short-term parking zone for passenger drop-offs. In contrast, Terminal 2 is dedicated exclusively to low-cost carrier departures. Its landside access is limited to road transportation, prohibiting foot traffic and offering no car parking facilities. A shuttle bus service operates between Terminal 1 Departures and Terminal 2 at 12-minute intervals, with a journey time of less than 5 minutes via public roads (ANA, 2024b).

On the airside, Lisbon Airport features a single runway measuring 3707 meters in length and 45 meters in width, with a normal operation rate of 44 movements (take-offs and landings) per hour. The airport has 84 aircraft parking positions, of which 18 (21%) are air-bridge positions that provide direct access for passengers to disembark at Terminal 1. The remaining 66 positions are remote parking spots where passengers access the terminal using shuttle buses. Of these air-bridge positions, 11 are dedicated to flights being operated within the Schengen Area, while 7 are designated for non-Schengen flights. Additionally, when necessary, some taxiways are closed and repurposed as temporary parking spaces (NAV, 2024).

Another factor that distinguishes Lisbon Airport from other airports in the country and in Europe is its lack of a direct physical connection to aircraft fuel refineries and storage facilities. The airport has a small local storage capacity, but fuel, refined in Sines, must be completely replenished via road transport from a Fuel Logistic Center located in Aveiras (56 km by road) incurring in additional carbon emissions. This dependency on road transport became a critical issue during the truck drivers' strike in 2019, which caused significant constraints on air traffic operations due to disrupted fuel supply. Multiple projects have been announced to connect the airport to the Aveiras fuel logistics center, but these initiatives have been repeatedly delayed due to the imminent deactivation of Lisbon Airport in favor of a new airport (Pereira, 2021).

For all these operational characteristics, London Gatwick Airport serves as a pertinent comparison to Lisbon Airport, by being the busiest single-runway-operation airport in Europe. In 2023, Gatwick handled 40.9 million passengers across 253,047 aircraft movements, with a capacity of 55 aircraft movements per hour. This contrasts with Lisbon's 33.6 million passengers and 226,866 aircraft movements. Notably, Lisbon's lower average of 148 seats per flight compared to Gatwick's 161 indicates a greater proportion of large aircraft operations and, consequently, better use of resources, in the latter.

The airports' infrastructure differs significantly, with Gatwick boasting 146 parking stands, 80 of which are air-bridges (54% ratio), while Lisbon's 21% air-bridge-to-remote-stand ratio is considerably lower. These disparities underscore the need of studying physical layout in order to improve operational efficiency and environmental performance. Both airports, inaugurated in the mid-20th century (Lisbon in 1942, Gatwick in 1958), face constraints due to their older designs. Lisbon's expansion has been particularly limited by its dual runway operation until 2019, affecting terminal development possibilities.

2.5.1. Available Emission Studies and Data

Several studies and data sources provide insights into the emissions profile of Lisbon Airport, offering a foundation for understanding its environmental impact. To enhance the likelihood of identifying relevant studies, the literature review methodology was revisited and the term "Lisbon" was incorporated into the Scopus search query outlined in the Listing 2.1. This modification yielded two notable studies focused on determining airport emissions at Lisbon Airport, conducted by Correia (2009), and Sanajou and Tchepel (2024). Additionally, the search revealed several other studies that addressed more specific operational aspects of the airport such as the ones by Lopes *et al.* (2019), Pereira (2021), and Khammash *et al.* (2017). The present subsection provides a detailed examination of these studies, offering insights into their methodologies, findings, and contributions to the understanding of emissions and operations at Lisbon Airport. This comprehensive review of literature specific to Lisbon Airport serves to contextualize the current research within the existing body of knowledge and highlight the gaps that this study aims to address.

To determine the aicrafts' emissions in Lisbon airport without using generic data, Correia (2009) incorporated flight data produced by Aeroportos e Navegação Aérea (ANA) with real operational factors such as specific aircraft types, engines, and flight schedules. By analyzing various pollutants and fuel consumption based on the LTO cycle, the researchers found that actual emissions at Lisbon Airport are generally lower than those calculated using standard ICAO times calculating that, in the timeframe of a day, 788 tonnes of CO_2 were emitted.

On specific emission types, a study was conducted by Lopes *et al.* (2019) to assess the impact of Lisbon Airport on Ultrafine particles (UFP) concentrations in the surrounding urban area. UFP, which can harm respiratory health, was monitored at various sites near the airport and under flight paths over 19 non-consecutive days in 2017-2018. The study found significantly elevated UFP levels near the airport, with 18-26 times higher concentrations downwind and 4 times higher levels up to 1 km away with concentrations correlated positively with flight numbers and negatively with distance from the airport. The findings highlight airports as major sources of UFP pollution, emphasizing the need to evaluate their impact on local air quality and population health.

Complementing this broad emissions data, more specific studies have been conducted to examine particular aspects of the airport's operations. For instance, Pereira (2021) focused on quantifying the environmental impact of fuel transportation to the airport, an often-overlooked component of aviation's carbon footprint. Their research revealed that in 2019, the process of transporting fuel to Lisbon Airport alone was responsible for the emission of 2,949,923 kg of CO_2. This finding underscores the importance of considering not only direct aviation emissions but also the ancillary activities that support airport operations when assessing the overall environmental impact of air travel.

In the same line, Khammash *et al.* (2017) concluded that the introduction of an environmentally friendly taxi procedure at Lisbon Airport, utilizing a semi-robotic tractor called TaxiBot, could lead to significant environmental benefits including reduced fuel consumption and lower emissions, which would benefit both airports and airlines by reducing pollutants and operational costs. The study used a new micro-simulation approach to provide a more accurate estimation of taxi times. The findings suggest that the use of TaxiBot for aircraft towing could be a viable solution to mitigate emissions during ground operations, with potential for further research in this area.

Some technical reports are also available for analysis. Notably, ANA, the current infrastructure manager for Lisbon Airport, has adhered to the ACI Airport Carbon Accreditation (ACA) Program structure for reporting emissions since the program's inception in 2010. Lisbon Airport's journey through the ACI's Airport Carbon Accreditation (ACA) Program levels demonstrates its commitment to reducing environmental impact. Starting at Level 1 (Mapping) in 2010, the airport progressed to Level 2 (Reduction) in 2015, as recorded in the 7th Yearly Report, implementing its first emission reduction projects. The airport then achieved Level 4 (Transformation) in 2021, bypassing Level 3, and reached Level 4+ (Transition) in 2022, where ACI recorded progress towards absolute emissions reduction.

According to ANA's data, the LTO cycle emissions at Lisbon Airport resulted in the release of 273,561 tonnes of CO_2eq in 2023 (ANA, 2024a), marking a significant 14% increase from the previous year. However, it is important to note that the specific methodology used for this LTO calculation — whether it follows Tier 1, Tier 2, or Tier 3 approach — is not explicitly stated, which could affect the precision and comparability of these figures. The reason for using the CO_2 equivalent unit of measurement suggests that multiple impacts were combined in this figure, but no further clarification is given. This lack of methodological clarity underscores the need for standardized reporting practices to ensure accurate assessment and comparison of airport emissions across different facilities and time periods.

Comprehending the environmental impacts of airport operations is essential for developing sustainable practices in the aviation industry. Although significant advancements have been made in quantifying and modeling emissions, it is critical to acknowledge that many emission figures are based on average estimations and standard time-in-mode figures, which may not accurately represent all airports. This study aims to enhance the precision of these estimations by independently determining aircraft emissions for specific airports, such as Lisbon Airport, utilizing publicly available data. ADS-B messages, which provide real-time flight information, present a promising data source for this purpose. The subsequent section of this study will examine the characteristics and potential applications of ADS-B data in environmental impact assessment, with the goal of improving the accuracy and specificity of airport emission calculations.

By continually refining our methods for quantifying and analyzing airport emissions, it is possible to develop more targeted and effective strategies for reducing the environmental impact of air travel while maintaining its economic and social benefits.

CHAPTER 3

ADS-B as a Data Source

This chapter examines the ADS-B technology and its central role as a data source in the analysis of aviation operations. ADS-B represents a significant advancement in aircraft tracking and communication, facilitating real-time data transmission that enhances situational awareness and safety on flights. Initially developed to augment traditional radar systems, ADS-B has been widely adopted for various applications, including airport airside traffic control, commercial flight tracking, and research purposes. This chapter will also present the structure of the collected ADS-B data, providing a foundation for the subsequent analyses and applications discussed in this study. Through a comprehensive examination of ADS-B technology, the goal is to underscore its importance and utility in advancing the accuracy of aviation data and, consequently, the precision of environmental impact assessments.

3.1. The Technology

ADS-B is a sophisticated surveillance system that utilizes a transponder installed in aircraft, leveraging satellite navigation technologies such as Global Navigation Satellite System (GNSS) — of which Ground Positioning System (GPS) is the most widely deployed — to periodically broadcast critical information to compatible receivers, primarily Air Traffic Control (ATC) centers and proximate aircraft (Kožović *et al.*, 2023). The nomenclature ADS-B encapsulates the system's core operational principles:

Automatic: Transmission occurs at regular intervals without pilot or operator intervention;

Dependent: The broadcast information is derived from the aircraft's position and velocity data, obtained from the GNSS/Flight Management System and navigation avionics external to the broadcasting system itself;

Surveillance: Allows the determination of three-dimensional positioning and identification of aircraft, vehicles, or other assets;

Broadcast: A range of data is transmitted, including, but not limited to, identity, position, and velocity, to any entity equipped with appropriate receiving equipment.

In addition to position, it transmits data such as velocity, identification, aircraft intent, urgency, and uncertainty levels. Position data can be broadcast twice per second, while other information, such as status or intent, is transmitted based on specific events. Unlike standard radar surveillance technologies, such as Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR), which measure the range and bearing of an aircraft from a ground-based antenna, ADS-B works by having the aircraft determine their own position using GNSS and broadcast it periodically over a radio frequency to ground stations or other nearby aircraft (Schäfer *et al.*, 2014; Verbraak *et al.*, 2017; Strohmeier *et al.*, 2014).

The civil aviation sector employs ADS-B information transmitted via the established Mode S radar technology, a sophisticated system that enables two-way communication between Air Traffic Control and individual aircraft. This technology assigns a unique 24-bit address to each transponder-equipped aircraft, allowing for selective interrogation and reducing data interference. Mandatory for commercial aircraft since 1993, Mode S serves as the primary data link for air traffic management. Despite operating on a different frequency from ADS-B, which results in certain performance limitations, aviation authorities opted to enhance rather than replace the existing system due to its widespread implementation and cost-effectiveness (Schäfer *et al.*, 2014). The integration of ADS-B functionality into existing transponders typically requires only minor modifications, minimizing expenses and operational disruptions. ADS-B data is openly broadcast on the 1090 MHz frequency, which can be received by any compatible antenna within range. This accessibility has made possible the development of aircraft tracking websites like FlightRadar24.com and FlightAware.com, which utilize a global network of antennas to gather and display real-time aircraft data to users worldwide.

ADS-B technology is also in the forefront by being a tool used to address the challenges posed by expanding air traffic and to enhance the performance and safety of airspace management. Major modernization initiatives have been launched globally where the two most prominent examples are EUROCONTROL's Single European Sky Air Traffic Management Research (SESAR) in Europe and the Federal Aviation Administration (FAA)'s Next Generation Air Transportation System (NextGen) in the United States. Both of these programs have identified ADS-B as a key enabling technology for their objectives. The selection of ADS-B by these initiatives is driven by its capacity to significantly augment airspace capacity and improve safety measures in an increasingly complex and congested aviation sector. ADS-B achieves this by dramatically increasing both the quantity and accuracy of data points available for air traffic management. The integration of ADS-B into these modernization initiatives also facilitates more efficient route planning and aircraft spacing due to its increased precision, potentially leading to reduced fuel consumption and lower emissions (Strohmeier *et al.*, 2014). This aligns with the broader goals of SESAR and NextGen to not only enhance safety and capacity but also to improve the environmental sustainability of air transport.

As these programs progress, the full implementation of ADS-B is expected to play a pivotal role in enabling more dynamic and responsive air traffic management systems, capable of handling the projected growth in air traffic while maintaining or improving current safety standards. While ADS-B offers significant advantages in air traffic management, it is not without vulnerabilities and limitations. A primary concern stems from the system's dependency on the accuracy of GNSS, particularly GPS. This reliance introduces several potential risks:

GNSS Vulnerability: As noted by Kožović *et al.* (2023), GNSS is susceptible to jamming and spoofing attacks, which could corrupt, damage, or interfere with the accuracy of positioning information crucial for ADS-B operations. These vulnerabilities could potentially compromise the integrity of air traffic management systems;

Dual-Use Technology: GPS and other GNSS technologies are considered dual-use, serving both civil and military purposes. This dual nature raises concerns about potential service interruptions or degradation during times of conflict or national emergency, where military needs might take precedence over civilian applications (Ceruzzi, 2021);

Third-Party Interference: The accessibility of GNSS signals makes them vulnerable to interference by malicious third parties. Sophisticated attackers could potentially disrupt or manipulate these signals, affecting the reliability of ADS-B data (Ceruzzi, 2021); The heavy reliance on GNSS for positioning information creates a potential single point of failure in the ADS-B system. Any widespread GNSS outage could significantly impact air traffic management capabilities (Kožović *et al.*, 2023; Strohmeier *et al.*, 2014);

Self-Reporting Limitations: ADS-B relies on aircraft self-reporting their position and other data. Any malfunction or manipulation of the onboard equipment could lead to the transmission of inaccurate information. Critically, the ADS-B system itself does not inherently validate this self-reported data (Strohmeier *et al.*, 2014);

Privacy Concerns: The transmitted messages, potentially containing sensitive information such as current aircraft location, origin, and destination are broadcast in a format without any encryption or authentication methods, rendering them susceptible to interception by both authorized and unauthorized individuals. This is increasingly becoming an issue with the tracking of private jets belonging to public figures, leading to debates about the boundary between publicly accessible data and personal privacy (Mäurer *et al.*, 2022).

To mitigate these risks, aviation authorities and researchers advocate for a multi-layered approach to air traffic surveillance:

Redundancy: Maintaining traditional radar systems alongside ADS-B provides a backup in case of ADS-B failures or inaccuracies (Verbraak *et al.*, 2017; Strohmeier *et al.*, 2014);

Data Validation: Implementing cross-checking mechanisms that compare ADS-B data with other sources, such as multilateration systems or traditional radar, to detect inconsistencies;

Cryptographic Solutions: Exploring the implementation of secure broadcast authentication in ADS-B to enhance resistance against spoofing attacks.

These limitations and mitigation strategies underscore the complexity of modern air traffic management systems and the ongoing need for research and development in aviation security and reliability. As the aviation industry continues to grow, the increasing presence of aircraft in airspace brings the challenge of overcrowding due to a proportional rise in ADS-B messages. This surge presents numerous challenges for advancing ADS-B, notably the need to prevent channel congestion and message loss within the utilized frequency band, and also the capability to store and process the large amount of data (Boci and Thistlethwaite, 2015). One significant development aimed at addressing these challenges is the emergence of space-based ADS-B. This technology leverages a constellation of satellites positioned in low Earth orbit to provide comprehensive ADS-B coverage. By utilizing this satellite system, space-based ADS-B seeks to extend and enhance ADS-B coverage, offering a potential solution to the limitations posed by terrestrial infrastructure.

Despite its inherent complexities and limitations, ADS-B as a technology offers significant potential for enhancing the precision of data used in scientific research. The advanced functionalities of ADS-B systems enable the acquisition of highly accurate and reliable data, which is crucial for scientific investigations requiring precise measurements and comprehensive datasets. The effectiveness of ADS-B data in scientific research is well-established, as demonstrated by numerous studies that have utilized this technology. The subsequent section will provide a thorough review of these studies, showcasing the diverse applications of ADS-B data across various scientific domains and highlighting the technology's substantial contributions to advancing knowledge in these fields. This review will emphasize the broad utility and impact of ADS-B technology in scientific research, despite its acknowledged constraints.

3.2. Uses in Environmental Studies

ADS-B data serves as a valuable resource for analyzing aircraft operations, including performance, efficiency, and environmental impact. Over the past decade, studies across various domains have increasingly utilized ADS-B data, reflecting its growing significance with the widespread adoption of this technology in aviation. For instance, Wang *et al.* (2024) conducted an analysis focusing on aviation fuel consumption, CO_2 emissions, and emission intensity in developing countries. Their study investigated the influence of aircraft structure and flight patterns on energy efficiency, aiming to identify opportunities for emission reduction strategies, particularly through adjustments in aircraft selection and route planning.

Similarly, Schultz *et al.* (2022) explored methods to enhance standardized, collaborative decision-making processes at network-relevant airports. Leveraging data-driven approaches, such as ADS-B message analysis, their research aimed to facilitate the cost-effective integration of small and medium-sized airports into the aviation network. Their work aligned with EUROCONTROL's Airport Collaborative Decision Making framework, contributing to both the open-data initiative and the scientific community.

Furthermore, Xue *et al.* (2021) conducted a study to quantify the medium to long-term impacts of the 2019's global pandemic on China's air transport industry. By analyzing changes in flight volume, aircraft usage, fuel consumption, and emissions using ADS-B data from 2019 and 2020, they provided insights into the industry's response to the pandemic, highlighting the role of ADS-B data in understanding such disruptions.

Additionally, Filippone *et al.* (2021) integrated real-time flight data from ADS-B with a flight performance computer program. Their research aimed to predict aviation emissions at altitude, showcasing the seamless integration between databases and software systems. By filling a gap in aviation emissions inventories, their study provided granular estimates for specific routes, aircraft types, fleets, or seasons, thus contributing to a more comprehensive understanding of aviation emissions.

3.3. Details on Data Structure

The precision and high resolution of ADS-B technology offer a promising avenue to address one of the gaps identified in Chapter 2: the reliance on average and fixed durations for each phase of the LTO cycle.

To fully utilize the potential of messages received via ADS-B communication and ensure comprehensive data, a multi-layered data collection approach was adopted:

Firstly, a dedicated Raspberry Pi computer equipped with a 1090MHz receiving antenna was positioned near Lisbon Airport to capture raw ADS-B messages. This localized setup ensured the direct capture of real-time aircraft data within the airport's vicinity. Although the initial intention was to use this data for the study, maintaining the system's reliability proved to be challenging and, consequently, the data collected by this system was incomplete and used primarily to understand its structure and compare it with other sources. Despite the challenges, this customized installation was still valuable. Collaboration with widely-used aviation networks such as FlightRadar24, FlightAware.com, and OpenSky Network facilitated access to their historical data and Application Programming Interface (API). By sharing the antenna's input with these networks, access was granted to private API's containing historical data, forming the dataset's foundation. The data includes flight origins and destinations, observed departure and arrival times, operating aircraft models, and detailed aircraft paths with latitude, longitude, speed, altitude, and heading recorded every few seconds. The data structure is displayed in Tables 3.1, 3.2 and 3.3. This dual-approach data collection strategy enabled the compilation of a comprehensive and robust dataset, combining locally captured real-time data with enriched information from established aviation networks.

To enhance comprehensiveness of our dataset and to allow information crossing with the ICAO Engine Emissions Databank, additional critical information focusing on aircraft engine models was incorporated. A significant aspect of this process involved leveraging the information encoded within aircraft model numbers. These alphanumeric identifiers often contain embedded data about the characteristics of a series of aircraft, which was then utilized to infer engine models. To illustrate this inferential process, the Airbus A319 will be used as an example. This aircraft model can be equipped with one pair of two possible engine types. Specifically, Airbus A319-11 series aircraft are fitted with CFM56 engines, while the Airbus A319-13 series utilize IAE V2500 series powerplants. This level of detail is typically documented in official Aircraft Type Certificate Datasheets, such as the one published for the A320 Family by EASA (2024), which includes specifications for the A319 model. This supplementary data regarding the engines fitted into a specific aircraft model was primarily sourced from Airfleets.net, a reputable repository of aviation information. The inclusion of engine model data and the number of engines fitted per aircraft was essential for determining fuel consumption rates, which forms the fundamental basis for our emissions quantification methodology. In addition to engine data, information on typical passenger capacity for each aircraft model was also extracted from Airfleets.net and SeatGuru.com. This data is crucial for estimating the potential occupancy of flights, which in turn influences our calculations of per-passenger emissions and overall flight efficiency.

This data gathering process resulted in a Database containing information on 217,657 individual flights that arrive or depart from Lisbon Airport between the 1st of January 2023 at 00h00 Coordinated Universal Time (UTC) until the 31rd of December 2023 at 23h59 UTC. According to EUROCONTROL (2023), using internal data and data reported from ANA, the airport management company, Lisbon Airport received 226,866 flights in 2023; meaning that the dataset covers 95.9% of all recorded Lisbon Airport flight operations. For each flight, only on the LTO cycle — below 914 metres of altitude and on the 45km radius around the airport — an average of 81 ADS-B messages were recorded, translating in 18.4 million lines of flight position data.

By integrating these diverse data sources and leveraging sophisticated database management techniques, a rich, multidimensional dataset was created. This thorough approach not only enhances the accuracy of our emissions calculations but also provides a solid foundation for exploring the intricate relationships between various factors influencing aircraft emissions and overall environmental impact in the context of airport operations.

Column	Flight ID	Callsign	Phase	Aircraft	HEX	Scheduled Departure	Scheduled Arrival	Real Departure	Real Arrival
Type	String	String	String	String	String	DateTime (UTC)	DateTime (UTC)	DateTime (UTC)	DateTime (UTC)
Description	Flight's Unique ID	Flight's Number	Arrival or Departure	Aircraft Model	Aircraft Unique Broadcast ID	Departure's Scheduled Timestamp	Arrival's Scheduled Timestamp	Departure's Real Timestamp	Arrival's Real Timestamp
Example Data	2aa5bcf4	TP935	arrival	Embraer E190LR	49520F	1643451600	1643461800	1643452300	1643460500

Table 3.1. Flights Table Data Structure

Column	HEX	Squawk Code	Timestamp	Latitude	Longitude	Altitude Metres	Speed Km/h	Heading
Type	String	Integer	DateTime (UTC)	Decimal	Decimal	Integer	Decimal	Integer
Description	Aircraft Unique Broadcast ID	Number given by Air Traffic control to the Specific Flight	Observation Timestamp	Position Data	Position Data	Altitude Above Ground Level	Speed Relative to the Ground	Aircraft Heading in Degrees
Example Data	49520F	4501	1643460313	38.6666	-9.1977	617	301	23

Table 3.2. Flight Tracks Table Data Structure

Column	Aircraft	Pax Capacity	Engine	# Engines	Emission Ratio
Type	String	Integer	String	Integer	Decimal
Description	Aircraft Model	Aircraft Typical Passenger Capacity	Engine Model	Engine Quantity	Emission Ratio
Example Data	Embraer E190LR	106	CF34-10E7	2	1

TABLE 3.3. Aircraft Engines Table Data Structure

CHAPTER 4

Data Preparation

Having the knowledge from the previous sections on how airport operations are organized and how they impact their surroundings, and after collecting the relevant data, it is now possible to develop algorithms to calculate Lisbon Airport's Air Transport Demand Carbon Footprint.

Initially, the raw data, comprising JavaScript Object Notation (JSON) responses for each of the 217,657 flights stored in individual plain text files, amounted to over 18.4 million records stored in 122GB of data, necessitating advanced data processing techniques. The project began with a Proof-of-Concept (POC) phase implemented in Python, utilizing the Pandas[1] library for data loading and filtering, and the Shapely[2] library for spatial data processing. However, this approach quickly revealed its limitations due to the sheer volume of data, with single analysis steps quickly running out of Random Access Memory (RAM) and taking several hours to complete. Recognizing the need for more efficient processing, the code was adapted to leverage Apache Spark[3] distributed computing through the PySpark library — effectively replacing Pandas — and the Apache Sedona[4] for spatial data processing — replacing Shapely. In order to host this improved processing method, a Google Cloud Dataproc[5] Cluster was created in conjunction with a Google Storage Bucket. Dataproc, a cloud service specifically designed for running Apache Spark and other Big Data applications, enables decentralized processing across multiple machines, significantly accelerating data processing times. This scalable infrastructure was crucial in managing the extensive dataset efficiently.

While the main dataset, containing flight and flight track information, was processed into a Parquet file, smaller standalone datasets, such as the Engine Databank and Aircraft Specification Data presented in Table 3.3, were maintained in Comma-separated values (CSV) format for ease of access and manipulation. The integration of these datasets, particularly the cross-referencing with the ICAO's Emissions Databank, was achieved through the Engine Model as a common identifier. This linkage facilitated the association of specific emissions profiles with individual aircraft, enabling a detailed analysis and estimation of the environmental implications of aircraft operations.

In Table 4.1, a list of each element of Lisbon Airport's carbon footprint, that this study will focus on, was given, followed by a description of each processing step. The

[1] https://github.com/pandas-dev/pandas
[2] https://github.com/shapely/shapely
[3] https://github.com/apache/spark
[4] https://github.com/apache/sedona
[5] https://cloud.google.com/dataproc

selection of elements to address in this study was primarily driven by the availability and nature of the data at hand. Given that the principal source of information was ADS-B messages, the focus of the calculations was necessarily limited to those elements that could be reliably derived from this data source. This approach ensures that the study's findings are firmly grounded in empirical data, enhancing the reliability and reproducibility of the results. The decision to concentrate on ADS-B derived data has both advantages and limitations. On one hand, it provides a consistent and comprehensive dataset, resulting in a analysis grounded on precise information about aircraft movements and positions. On the other hand, it constrains the scope of the study to those aspects of emissions that can be inferred from flight trajectories and timings. This limitation underscores the importance of acknowledging the boundaries of the current research and identifying potential areas for future investigation that might incorporate additional data sources.

To provide a clear understanding of the methodological approach and its implications for the final emissions estimates, the subsequent section will offer a detailed description of the algorithms developed for each calculation. This exposition will describe the logical steps, assumptions, and data manipulations involved in transforming raw ADS-B data into meaningful emissions estimates. By presenting this information, the study aims to ensure transparency in its methods and facilitate critical evaluation of the results. Furthermore, this detailed explanation will allow readers to appreciate how the choice of algorithmic approaches and the inherent characteristics of the ADS-B data may influence the final emissions figures.

4.1. Aircraft LTO Cycle Emissions

This section focuses on the calculation of emissions directly related to the aircraft movements on Lisbon Airport, representing a core component of the airport's environmental impact. The analysis presented here is fundamentally rooted in the most elementary process of the LTO cycle: the individual flight. By centering our calculations on the flight as the primary unit of analysis, it is possible to establish a comprehensive framework for assessing the environmental implications resulting from the airports successfully drawing the Airport Catchment Area (ACA) users and generating demand for more aircrafts. This approach will then build on top of the LTO cycle for each flight, examining the emissions at each stage of the LTO cycle, from approach and landing to taxi, take-off, and initial climb. The emphasis on flight-level analysis enables a more precise quantification of emissions, accounting for variations in aircraft types, operational procedures, and specific airport characteristics. This methodology provides a robust foundation for understanding the nuanced environmental impacts associated with the diverse range of flights servicing Lisbon Airport.

4.1.1. Determining an Aircraft's Parking Position

The aircrafts' parking position is the foundation of all algorithms used for estimating the emissions in this study. Every subsequent step depends on accurately determining

Type	Activity	Calculated
Flight	LTO Cycle. Approach, Idle, Takeoff, and Climb	Yes
	Guide the aircraft to the stand The wedge of the aircraft (Follow-me Car)	No
	Setting up and connecting a Ground Power Unit (GPU) Apposition of stairs	No
	De-boarding of passengers	Yes
	Delivery of fuel vehicles	No
	Refueling Aviation Fuel	No
	Arrival of aircraft cleaning staff	No
	Cleaning the interior of the aircraft	No
	Delivery of lavatory truck	No
	Dropping of cargo pallets	No
Handling	Delivery of water truck	No
	Filling the aircraft with drinking water	No
	Delivery of waste water truck	No
	Emptying the aircraft waste water tank	No
	Delivery of a belt conveyor and a tractor with trolleys for checked baggage	No
	Unloading baggage	No
	Baggage loading	No
	Parking of a belt conveyor and a special baggage vehicle	No
	Catering vehicle delivery	No
	Loading catering	No
	Boarding of passengers	Yes
	Preparation of departure documentation	No
	Transport and inspection of documents storing + crew	No
	Parking of stairs	No
	Disconnect and park the GPU	No
	Clearance of the aircraft	No
	Rolling out of the stand (Pushback)	No

TABLE 4.1. List of Flight and Handling Activities. Adapted from (Szabo *et al.*, 2022)

this position both to determine the LTO cycle Idle Phase is complete, and to calculate emissions for related airport activities that directly serves the aircraft: the Ground Handling. This section delineates the steps undertaken to determine the parking position for each flight and outlines the criteria applied when an accurate parking position could not be established. This comprehensive examination of the process ensures a thorough and accurate foundation for all subsequent emissions calculations.

First, to make it possible to compare the aircrafts' paths with a parking position, a set of bounding boxes was created to match every parking stand in the airport. A bounding box is an area defined by coordinates that encloses an object or region of interest, in this case, the aircraft parking stands. Using data from Navegação Aérea de Portugal (NAV) Aeronautical Information Services (AIS) page for Lisbon Airport NAV (2024), along with satellite views from mapping applications (such as OpenStreet Maps[6], Google Maps[7], and Bing Maps[8]), each parking position was defined with a minimum of four latitude and longitude sets of coordinates. For irregularly shaped parking positions, additional points were used to accurately draw the bounding boxes. The coordinates were transformed in polygons by using the Shapely Python Library — later on Apache Sedona —, creating a starting point on how the positional data should be treated in the study. An illustration of the result can be seen on Figure 4.1.

(A) Terminal 1 (B) Terminal 2

FIGURE 4.1. Extract of Parking Position Bounding Boxes on Terminals 1 and 2

Having the bounding boxes created as Sedona's polygons, for each of the latitude and longitude pairs that compose an aircraft's path on the ground, it was verified if it fell inside a bounding box. This operation was made via Sedona's Spatial Join functions. The expected final result is matching a single bounding box per flight for a few seconds, with one exception: Some parking positions block others due to operational needs, as the airport may need to accommodate larger aircraft that can block multiple smaller parking positions, and vice versa. In these cases, the bounding boxes were kept individualized to avoid excluding parking positions and better reflect this operational reality. Flights

[6]https://www.openstreetmap.org
[7]https://www.google.com/maps
[8]https://www.bing.com/maps

that matched these adjacent blocking positions were considered as one in the subsequent analysis.

Having information on the flights that successfully ended or started from a known parking position bounding box, the analysis can continue to the next phase, determining the Time-In-Mode, that will be described in the next section.

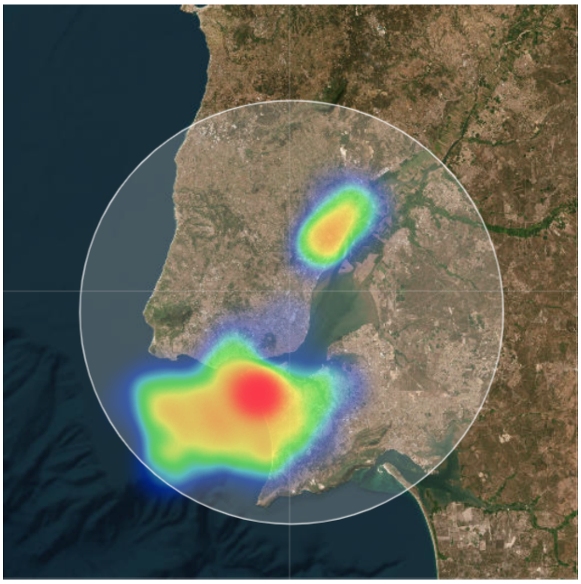
4.1.2. Determining Time-in-Mode

For the flights where a single parking position was successfully established, it is possible to proceed under the assumption that the LTO cycle is completed in its entirety. This section focuses on the calculation of aircraft emissions for each phase of individual flights. As previously introduced, the LTO cycle serves as the framework for segmenting flight operations into distinct phases, facilitating a comprehensive analysis of emissions. The subsequent examination will utilize this cycle to systematically quantify the environmental impact of aircraft operations at Lisbon Airport, providing a granular assessment of emissions across various stages of flight.

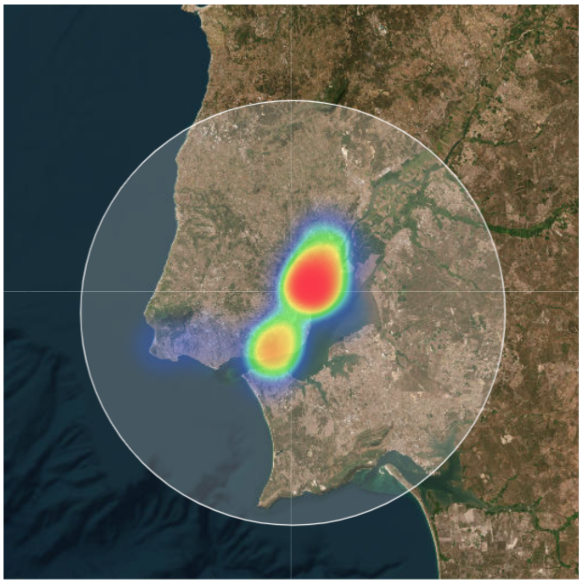
The methodology for precise time-in-mode calculations involves a multi-step process utilizing geospatial analysis and ADS-B data. Initially, the airport layout was segmented into additional bounding boxes instantiated by Apache Sedona, complementing the existing parking position demarcations. These new bounding boxes correspond to specific phases of the LTO cycle, with areas designated for taxi operations, runway activities, and regions beyond the airport perimeter where the approach and climb phases happen. First, taxi areas were delineated, encompassing all regions within the airport perimeter, covered by tarmac, excluding the runways and hangars. The runway area was subsequently defined, incorporating its entire tarmac extension. Following the ground-level demarcations, approach and climb areas were established. From a bounding box perspective, these areas are the same, defined as the region within an aproximately 45-kilometer radius from the airport, excluding the previously defined taxi and runway areas. The selection of this 45-kilometer radius was informed by heatmap analysis, as illustrated on Figure 4.2, which revealed the most frequent locations where aircraft cross the 914-meter altitude threshold marking the boundary of the LTO cycle. An arbitrary buffer zone was added to this empirically determined area to ensure comprehensive data capture. The result of the complete bounding boxes can be viewed on Figure 4.3.

It is important to note that while the 45-kilometer radius provides a generous spatial boundary, the critical factor in defining approach and climb phases remains the 914-meter altitude ceiling. This altitude threshold is consistently applied to all data and, coupled with the location of the climb and approach boundary boxes, captured the whole LTO cycle. Consequently, the precise size of the buffer zone does not significantly impact the analysis, as long as it encompasses all relevant LTO operations.

To enhance the precision of calculations for each operational phase, additional parameters were incorporated into the analysis, refining the identification and measurement of

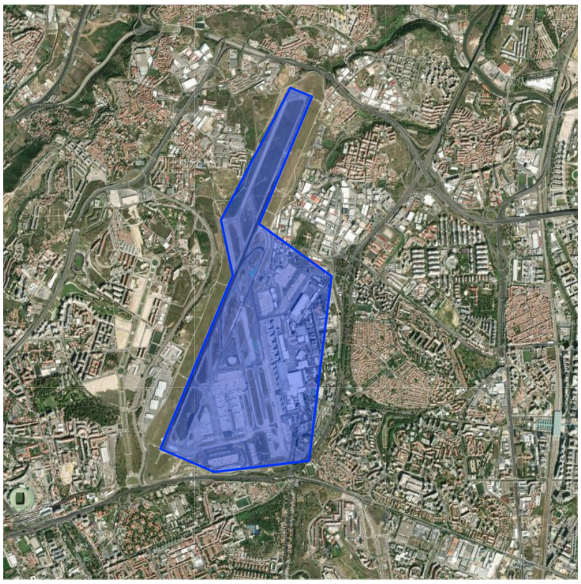


(A) Arrivals

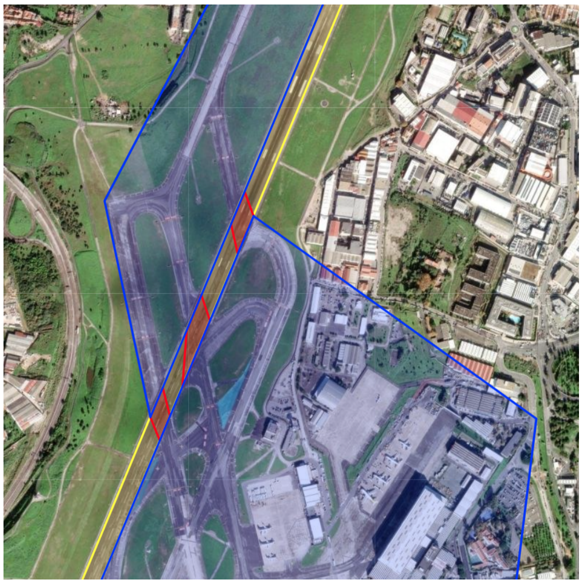


(B) Departures

FIGURE 4.2. Heatmap of the most frequent positions where the LTO threshold is crossed and the 45km radius used in this study



(A) Overview of the consolidated LTO bounding boxes



(B) Close Up of intersections, including Taxi areas (blue), Runway (yellow), and Runway Crossings (red)

FIGURE 4.3. Extract of Bounding Boxes Corresponding to LTO Cycle Phases

specific flight stages: For instance, the approach phase is exclusively associated with arriving flights, occurring at altitudes below 914 meters within the designated approach and runway bounding boxes. This phase initiates when the descending aircraft first reaches the 914-meter altitude threshold and concludes upon the aircraft's transition from the runway to the taxi area.

The taxi phase is applicable to both arriving and departing flights, confined to the predefined taxi area bounding boxes. Operations in this phase are restricted to altitudes below 110 meters, corresponding to Lisbon Airport's ground level (NAV, 2024). To ensure accurate representation of active taxiing, a velocity constraint is applied, considering only movements greater than 0 and lower than 60 kilometers per hour. This criterion effectively excludes periods when an aircraft is stationary at the end or start of the flight within a taxi bounding box, enhancing the accuracy of taxi duration calculations.

The take-off phase is exclusive to departing flights. It commences when an aircraft enters the runway bounding box and terminates upon reaching an altitude of 305 meters. This altitude coincides with the transfer of air traffic control from Lisbon Airport Tower to the Approach Control Center, marking a significant operational transition. And finally, also for departing flights, the climb phase encompasses all movements within the departure bounding box between altitudes of 305 and 914 meters.

Utilizing ADS-B data, it is then possible to track the temporal points at which aircraft enter and exit each bounding box, enabling precise determination of the duration spent in each operational phase. To mitigate potential errors in phase identification, particularly in areas where operational zones intersect, specific measures were implemented. For instance, runway crossing points, which could erroneously trigger the onset of a new phase (e.g., initiating the takeoff phase during taxi operations for departures from runway 20), were identified and marked. These crossing areas are subsequently excluded from time-in-mode calculations, ensuring the accuracy of phase duration assessments.

The subsequent stage in the analysis focuses on executing the cross-referencing between parking positional data and the aircraft's track, initially without applying any preliminary filtering. This approach is the basis for the creation of a comprehensive data processing pipeline, spanning from initial data intake to final results output. By processing the raw data through the complete pipeline without initial filtering, it is possible to observe the unaltered relationships between positional data and aircraft tracks. This unfiltered approach allows for the identification of patterns, anomalies, or inconsistencies that might be obscured or eliminated by premature data cleaning. Furthermore, it establishes a baseline against which the effects of subsequent filtering and data refinement techniques can be measured and evaluated.

The analysis of preliminary results yielded insightful findings that warranted further investigation. A thorough examination of the data for outliers revealed that while the majority of data points fell within one standard deviation of the mean, numerous outliers were detected across the dataset. This observation was particularly pronounced in the Idle Phase of the LTO cycle. The most extreme case observed in this initial analysis was an Idle Phase for a single flight lasting more than seven hours. This duration is clearly anomalous for typical aircraft operations and significantly deviates from expected norms. Such extreme outliers not only skew the overall dataset but also indicate potential issues in data collection, processing, or underlying operational factors that require careful consideration.

These identified discrepancies became the focus of a structured, iterative analysis process. The approach to addressing these anomalies was methodical, involving a series of steps or "experimentation steps." Each level was designed to systematically investigate, understand, and mitigate the observed irregularities in the data. The subsequent section of this study will present a detailed account of these experimentation steps. This structured presentation will elucidate the progressive refinement of the dataset, the methodologies employed at each stage, and the rationale behind the decisions made during the analysis process. This step-wise approach is documented to provide a transparent view of the data cleaning and validation procedures, ensuring the robustness and reliability of the final results.

4.1.3. Experimentation Steps

The analysis process underwent four iterations, as illustrated in Figure 4.4, the first one being the preliminary analysis with no modifications to the data structure and with the subsequent steps addressing issues identified in the preceding stage. It is crucial to remind that the foundation for emission calculations lies in precisely determining the time spent in each activity within the LTO cycle, as this serves as the main framework for calculating aircraft emissions. Throughout each iteration, LTO cycle phase duration outliers were scrutinized and appropriate mitigation methods were devised. On this preliminary analysis an initial challenge emerged: while the durations of approach, takeoff, and climb phases demonstrated a consistency in their duration, ground taxiing times exhibited significant variability. Empirical observations suggest that heavier aircraft tend to taxi more slowly and would be considered outliers, a phenomenon corroborated by our data as presented in Table 4.2. Moreover, as discussed in Chapter 2, the airport's geographical spread contributes to substantial variations in taxi durations, contingent upon the runway utilized and the final parking position.

Aircraft Type	**Average Time-in-Mode**	
	Arrival Idle Phase	Departure Idle Phase
Narrowbody	4.85 minutes (24.47 Km/h)	12.44 minutes (9.04 Km/h)
Widebody	5.50 minutes (17.19 Km/h)	14.77 minutes (9.16 Km/h)

Table 4.2. Time-in-Mode (Idle) and Average Speed per Aircraft Type

A multivariate approach was developed to facilitate more effective comparisons of improvements across experimentation steps. For each of the steps, a Linear Regression Machine Learning model was trained using the following features:

- Aircraft Size Categories (Narrowbody or Widebody): Narrowbody aircraft typically have a single aisle and are designed for short to medium-haul flights, whereas

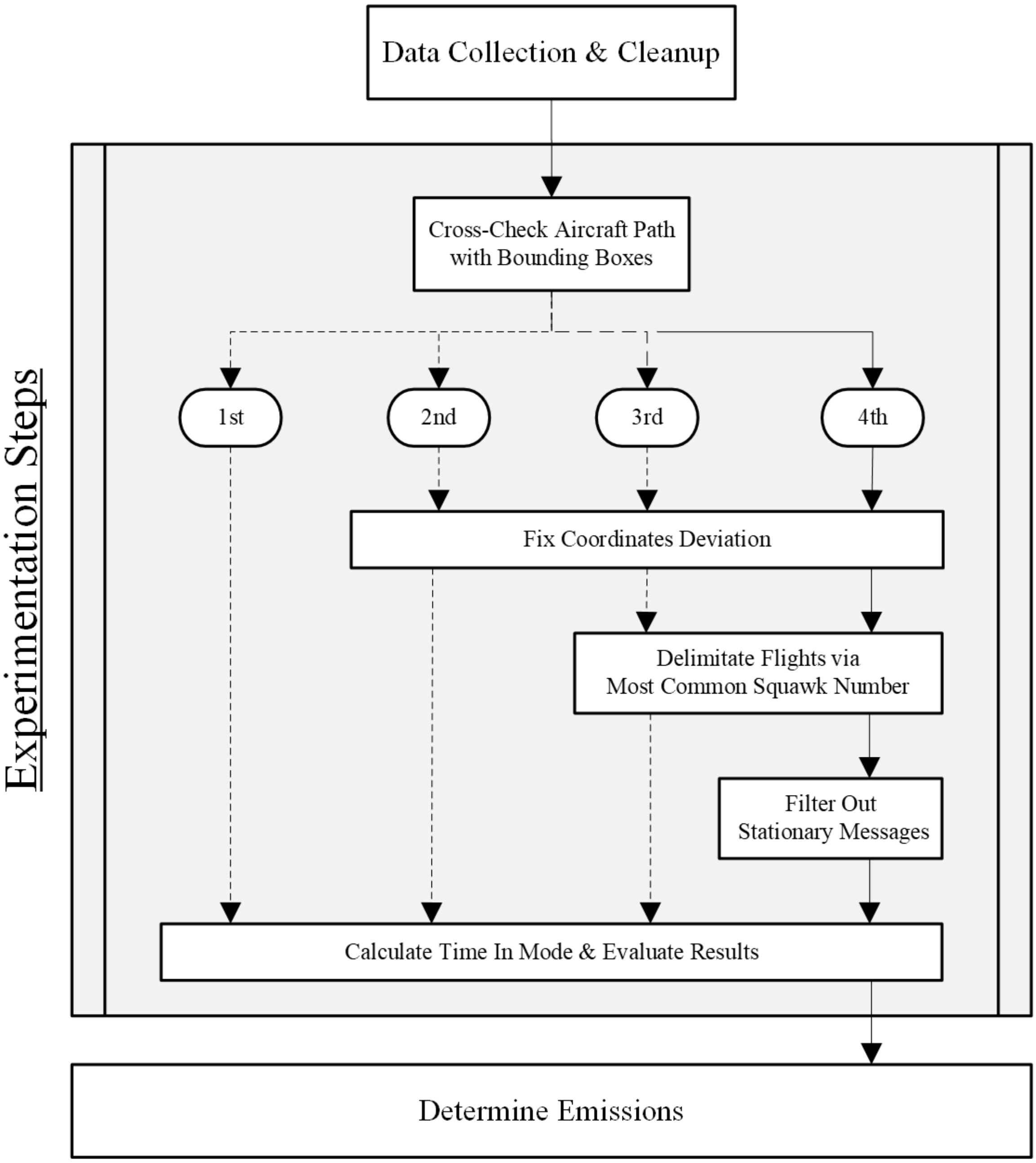


FIGURE 4.4. Data Experimentation Steps

widebody aircraft feature two aisles and are used for long-haul flights due to their larger passenger and cargo capacity;

- Taxi Distance: Calculated as the distance formed by a line created from all ADS-B messages on the ground;
- Calculated Time in Phase.

The data were split into training and test sets (80%/20%) based on unique flight IDs, with both datasets containing an equal distribution of arrivals and departures. The PySpark Machine Learning module was employed, utilizing a Parameter Grid Builder and a Cross Validator to test multiple hyperparameters. The model's objective was to predict Time-in-Mode, from which an additional "Time Difference from the Prediction" variable was generated. This approach enabled the identification of true outliers—aircraft requiring significantly more time than typical for their size category and distance traveled. Consequently, this method allowed for the comparison of progress across steps and simplified the isolation of genuine outliers for pattern extraction. Figure 4.5 presents the statistics of this multivariate modeling. The resulting deviations are displayed in Figure 4.7 for Arrival Flights and Figure 4.8 for Departure Flights. These figures use boxplots to illustrate the deviation from expected values for each flight, highlighting outliers and their relevance.

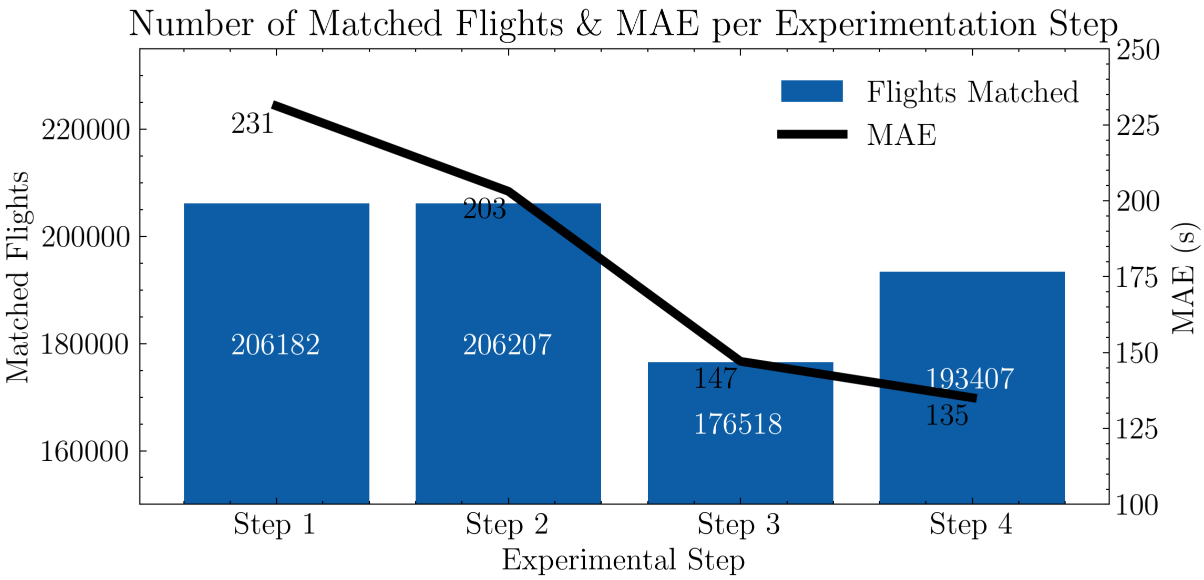
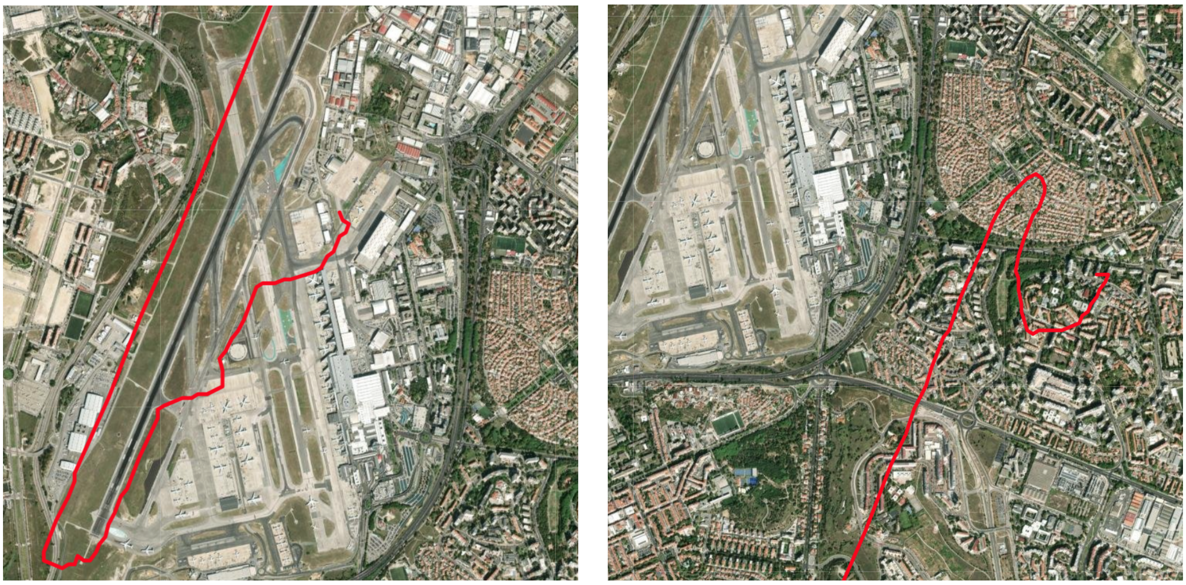


FIGURE 4.5. Experimentation Steps Model Results

4.1.3.1. *1st Experimentation Step* Composed by running a simplified pipeline without any processing steps, simply crossing ADS-B Data with the LTO cycle phase and Parking Positions Bounding Boxes, the 1st Experiment step just run the pipeline without any modification to the data. This unfiltered approach was intentionally chosen to increase the possibility of detecting edge cases and anomalies within the information. The application of this methodology yielded a 90% success rate in matching flights with a unique parking position bounding box, without the need for additional data preparation. However, further investigation into the unmatched flights, corresponding to 10% of the aircraft movements, revealed the first discernible pattern to explain this discrepancy: Some aircraft were found to have matched several parking positions remote from each other within a time frame of just a few minutes, clearly indicating an impossible situation. Closely analyzing these cases showed that the issue originated from a deviation in some aircrafts' system of reporting coordinates — imprecise data being broadcast is a known limitation of the ADS-B technology, as indicated on Chapter 3. When a sampled aircraft's track was plotted on a map, a consistently impossible set of positions was observed, such as aircraft taxiing and taking-off outside the designated taxiways and runways, respectively. Notably, this deviation occurred consistently in both Lisbon Airport and the previous or next airport, suggesting that the issue was not isolated to the data captured at Lisbon Airport and is most likely related to how the aircraft itself determines its position.

4.1.3.2. *2nd Experimentation Step* With the goal of addressing the positional discrepancy issue, it was necessary to calculate the deviation and apply the resulting delta to the entire set of coordinates. The process began by selecting positional data that fell within the Runway Bounding Box. This selection was based on the assumption that an aircraft pilot consistently attempts to maintain a position as close as possible to the runway's centerline during takeoff and landing operations, creating a straight line that could be compared to the actual flight path.



(A) Flight 3V4537 on the 22nd of May 2023 (B) Flight 3V4537 on the 17th of February 2023

FIGURE 4.6. Examples of Coordinates Deviation on the track from Aircraft HEX 4409AD (Boeing 737-4M0F Serial Number 29202/3025)

For each flight, the average delta distance in both the x and y axes was calculated between the reported positions on the runway and the runway's centerline. This calculation yielded the x and y axis coordinates discrepancy in relation to the runway for individual flights. Subsequently, all positional data for each aircraft was adjusted according to this delta, resulting in a more precise and accurate dataset. The magnitude of this adjustment was significant yet subtle. The average delta was approximately 0.0002 degrees in the decimal coordinates system, which translates to a distance of about 22.2 metres in physical space. This correction proved to be very small, slightly increased the number of aircraft matched to a single parking position by 25 flights, or 0.01%, and slightly decreasing the Mean Absolute Error (MAE). Closely examining flights that kept matching multiple parking positions showed that extracting the coordinate delta from the runway only corrected the deviation in the runway direction. Some aircrafts have extreme coordinate deltas in different directions, such as the aircraft Hexadecimal identifier (HEX)

4409AD, the most extreme case as shown in Figure 4.6, showing that this second experimentation step, while finding an unexpected indicator — aircraft with relevant deviations on their reported position —, did not produce a big impact in the final analysis.

4.1.3.3. *3rd Experimentation Step* This following step was initiated with the assumption that, although the coordinate delta mitigation process successfully eliminated a few flights matching multiple parking positions on their paths, it did not resolve the issue of unrealistically long idle phases. Consequently, flights were ordered by time-in-mode, facilitating a more detailed investigation of a representative sample of these anomalous cases. Three primary scenarios emerged:

- Aircraft being moved before or after flights and broadcasting the ground movement operation with the flight's callsign, incorrectly associating these movements with the actual flight data;
- Aircraft in resting positions occasionally broadcasting data with non-zero speeds during preparation or parking procedures, prematurely triggering or delaying the idle phase;
- Data processing errors merging parts of previous or subsequent flights into unrelated flight data, often coinciding with incomplete broadcast tracks on other flights, likely due to error in the post-processing of data.

A pattern emerged for all these cases during data analysis: Squawk codes. A Squawk code is a four-digit transponder code assigned to an aircraft by ATC before or during a flight. It is typically provided during the flight's clearance phase or at the time of departure. This code allows ATC to identify and track the aircraft on radar, ensuring safe and efficient air traffic management. Two key patterns were observed when analyzing the flights' Squawk code: each flight had a distinct Squawk code that didn't change during the LTO cycle, offering a straightforward method to correct misallocated flight data; and aircraft movements to or from parking positions outside of flight operations used different Squawk codes than those assigned for the actual flights.

Based on these insights, the dataset was split into two parts: basic flight information (including flight identification, aircraft type, aircraft hex code, airline, origin, destination, and observed departure/arrival times) and track data (comprising broadcasting hex code, timestamp, latitude, longitude, speed, and heading). A calculated field was added to the flight dataset, assigning the most frequently broadcasted Squawk code as the designated code for each flight. The analysis approach was refined by establishing new flight boundaries based on observed departure and arrival times, along with the most frequently broadcasted Squawk code. This method replaced the previous reliance on individual flight JSON data as the primary source. By utilizing these more robust and consistent parameters, the study aimed to create a more accurate representation of flight operations, potentially mitigating some of the anomalies observed in the initial dataset.

This method resolved the problem of flight records abruptly ending mid-taxi or lacking positional reports in certain LTO phase zones. Consequently, it reduced the mean average error of the time-in-mode durations, enhancing the dataset's completeness. However, an unexpected outcome was observed: the number of flights with matched parking positions decreased, particularly in the departure phase. Further investigation into the discrepancies between the second and third experimentation steps revealed an additional nuance regarding Squawk codes, triggering the fourth experimentation step.

4.1.3.4. *4^{th} Experimentation Step* At this step it was discovered that aircraft often broadcast Squawk code 0000 while parked awaiting flight approval. These broadcasts were typically recorded in the dataset at a lower resolution, possibly due to the static position of the aircraft — likely in order to reduce the data storage implications by the data provider. In some instances, the 0000 code persisted even into the initial minutes of taxiing. To mitigate this issue, a more sophisticated approach was developed:

Observing that the 0000 Squawk code could be reported well into the actual taxi operational phase, simply incorporating all 0000 Squawk code data would have negated the improvements achieved in the third step of experimentation. Therefore, the 0000 Squawk code was included in the filtering process, but with a specific condition: Taking in consideration the time intervals between broadcasts, for departures, 0000 broadcasts were only considered from the first instance where the time between broadcasts was less than 5 minutes, continuing to the end of the LTO cycle. For arrivals, the process was reversed: 0000 broadcasts were included from the beginning of the LTO cycle until the last instance where the broadcast interval was less than 5 minutes. This nuanced approach aimed to capture the relevant parking and initial taxiing data while excluding extraneous information that could skew the analysis marking the end of the analysis. With the number of flights matched closer to the unfiltered data, but with a much lower MAE on the model (42% reduction), this step was chosen as the end of the data processing and its results were used in the rest of the analysis. The next section will describe how the emissions quantity will be extracted from the resulting set of time-in-mode values.

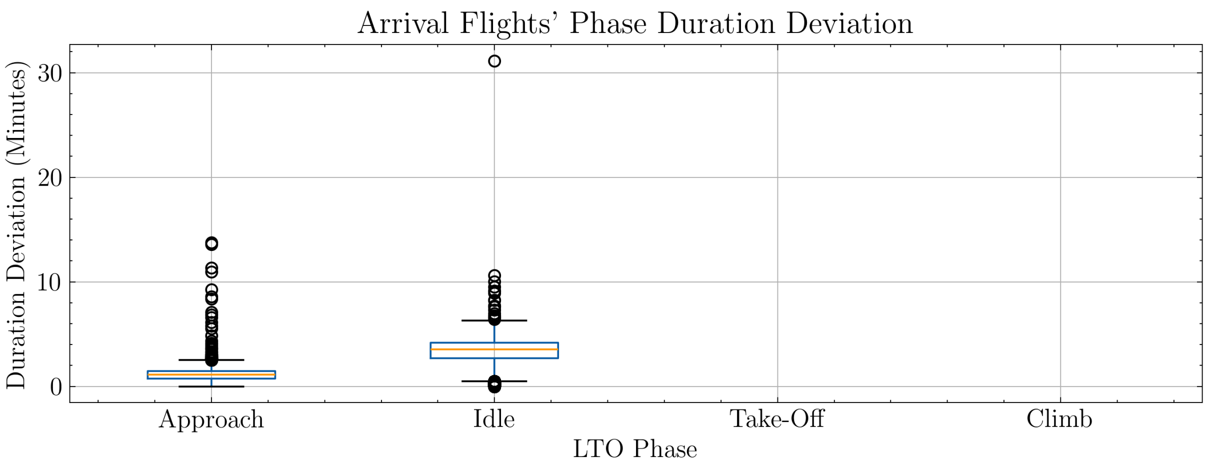


FIGURE 4.7. Calculated Arrival Time-In-Mode Deviations

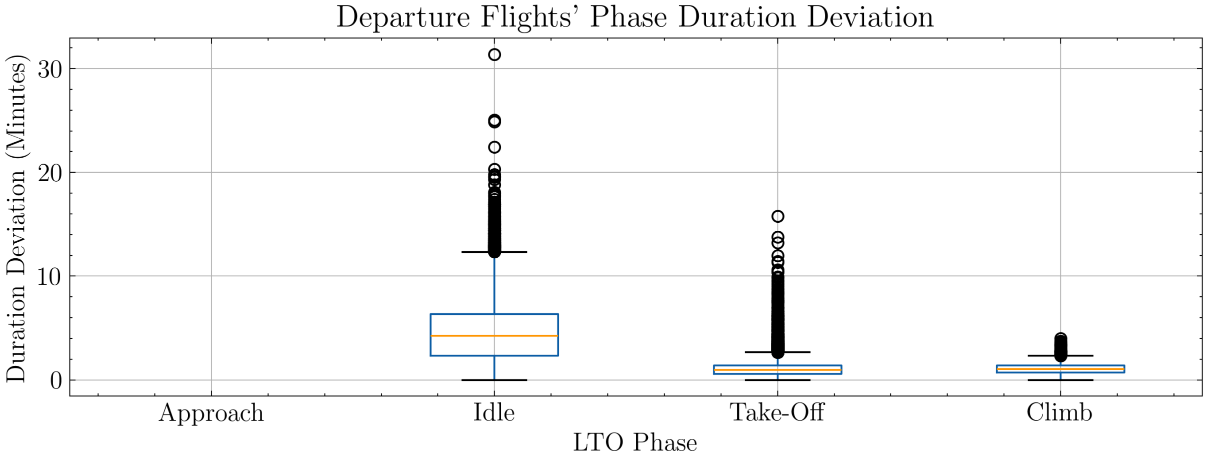


FIGURE 4.8. Calculated Departure Time-In-Mode Deviations

4.1.4. Determining the Emissions

Having determined the duration of each operational mode, the calculation of fuel consumption can proceed using the ICAO Engine Emissions Databank. This process entails extracting the fuel flow quantity by engine model per LTO phase and multiplying it by the corresponding duration and number of engines, and a variable created specifically for this study: emission factor. This methodical approach ensures a comprehensive and accurate assessment of fuel consumption across all operational modes.

For aircraft engines that are exceptions and not represented in the ICAO Engine Emissions Databank, alternative methodologies were employed. These exceptions, within the scope of this study, are: turboprop-engine aircraft — such as Avions de Transport Régional (ATR) Regional Aircraft —, business jets with individual engines producing less than 26.7 kN of thrust, military aircraft, and helicopters. For business jet flights, the relatively low engine power is the primary reason for their absence from the ICAOs Engine Database. In the case of turboprops and helicopters, beyond the lower engine power, their engines' operational characteristics differ significantly from those of regular turbofan jet engines, meaning that the standard certification environment variables may not be suitable for them and could yield imprecise results. Business jets and turboprop aircraft and helicopters amounted to 2666 flights in the dataset, making them 1% of the flights: a non-significant component of our analysis, but these exceptions were handled to keep this study's accuracy in as many situations as possible. To assign an appropriate emissions factor to these exceptions, a methodology was developed that involved applying a reduced emissions factor from a similar engine that exists in the Emissions Databank. This approach ensures that the unique characteristics of these aircraft are accurately reflected in our emissions calculations.

In the case of turboprops this study relies on marketing materials issued by ATR, a leading producer of commercial turboprop aircraft, stating a 45% reduction in fuel consumption on their newest generation of aircrafts compared to similarly sized aircraft. While marketing materials are not typically used for decision-making in scientific studies, for the purposes of this analysis, they provide a best-case scenario also serving as a conservative baseline. To operationalize this approach, a jet-powered aircraft with similar typical seat configurations to the turboprop in question and with engine information available, was selected. Then, the same fuel flow rates for each LTO cycle phase as these comparable jet aircraft was applied, but with an emission factor of 55%, effectively reducing its fuel consumption by 45% to reflect the stated efficiency advantage of turboprops.

To assign an appropriate emissions factor for business jet flights, the most common engine analyzed in the Dataset with both Gas Pollutants and nvPM emissions information was selected: the LEAP-1A3 series, a latest-generation engine used in the Airbus A321 NEO Aircraft — representing 32,526 flights — where, among all its engine variants, the one with the lowest fuel consumption was chosen. The emissions of this engine were then reduced by a factor based on the difference in power output between the LEAP-1A3 and the business jet engine (power numbers as extracted from engine specifications). This approach ensures that the emissions estimates for business jet flights are reasonable and account for the engines' lower power output.

Regarding the helicopters exception, they represent only 165 flights (0,07% of the total) and no additional processing was made. The flights were simply excluded. As for the military aircraft, it is important to note that military aircraft that freely broadcast its position and was already accounted for by the methods presented so far in our analysis, were processed as a regular flights. Any military flight with missing information was excluded and no compensation calculation was made for them. This decision is based on the unique characteristics and limitations of data availability for military operations since, due to the utilization of multiple data gathering sources, including public API's and a custom antenna setup as detailed in Chapter 3, an interesting phenomenon regarding military aircraft data was revealed. Specifically, related to its proximity to Montijo's Airbase, ADS-B track information for certain military aircraft that was not available through public API's was captured by the antenna set up on the scope of this study. This discrepancy indicates that while these aircraft were broadcasting ADS-B data, this information was intentionally omitted from public services. The deliberate exclusion of military aircraft data from public sources is justified on grounds of national security, representing an edge case in the data collection and analysis process of this study. Given the sensitive nature of military operations and the inconsistent availability of data, the decision has been made to exclude these specific cases from further analysis within the scope of this research.

This approach ensures that the analysis maintains focus on commercial and private aviation operations, for which more complete and consistent data are available. While acknowledging the presence of military and helicopter flights at Lisbon Airport and nearby facilities, their exclusion from the emissions calculations reflects both practical data limitations and respect for operational security considerations. This decision aligns with the study's commitment to producing a robust and reliable assessment of the airport's environmental impact based on the most comprehensive and verifiable data available. Finally, with the time-in-mode accurately determined and the weight of fuel used calculated based on the information contained in the ICAO Engine Emissions Databank, the study can proceed to derive the final emission values for the LTO cycle on a per-flight basis, concluding this section analysis.

Utilizing data pertaining to the aircraft engine model and the duration of each operational mode — specifically Approach, Idle, Take-off, and Climb, with Approach applicable exclusively to arrivals and Climb to departures — it is then possible to reference the fuel flow rates per second from the ICAO Engine Databank. By multiplying these rates per the number of engines and by the time spent in each mode, the results can be aggregated and the total fuel mass consumed derived. This calculation serves as the foundation for quantifying the emissions of CO_2 — by multiplying the fuel consumed by 3.16 — and other pollutants, including HC, CO, NOx, and nvPM, using ICAO Engine Emissions Databank on its June 2024 version. This methodical approach ensures a precise and comprehensive evaluation of aircraft emissions for each individual flight, contributing to a nuanced understanding of the environmental impact associated with various operational phases.

This study addresses a research gap by employing precise time-in-mode calculations derived from ADS-B location data, rather than relying on standard LTO phase durations. As previously noted in Section 2.3.1, the Engine Emissions Databank uses average LTO phase durations for its calculations, which can result in imprecise analyses due to variations in airport layouts and congestion levels. By utilizing ADS-B data, this research offers a more accurate representation of aircraft operations, accounting for the specific characteristics of Lisbon Airport and its operational dynamics. This approach enhances the precision of emissions calculations and provides a more nuanced understanding of the environmental impact associated with local aircraft movements. The next sections will describe the steps used to determine the non-aircraft related emissions.

4.2. Passenger Boarding and De-Boarding

In this section, the methodology for calculating emissions based on the distances traveled by vehicles will be presented. This approach is specifically applicable to Ground Handling operations. Lisbon Airport's operational configuration is characterized by a significant predominance of remote parking positions, with 67% of aircraft parking positions situated away from direct terminal access — without a air-bridge, like in Terminal 1 or direct foot access like in Terminal 2. This layout necessitates the extensive use of shuttle buses for passenger boarding and de-boarding processes, a factor that substantially influences the airport's ground operations and associated environmental impact.

To assess the environmental impact of remote parking stands, a comprehensive analysis of travel distances for all flights was conducted. A central location for each terminal was used as a reference point for calculating distances to and from remote aircraft positions. For departing flights, the terminal center was considered the origin, while for arriving flights, it served as the destination. The analysis was performed on a per-flight basis, using the aircraft's parking position as the key parameter. By calculating the distance traveled by ground handling vehicles and applying appropriate emission factors, it was possible to estimate the emissions generated during these operations. To ensure accuracy, precise distances between each parking position and relevant points of interest were measured using mapping applications. This approach allowed for a standardized method of distance calculation across various operational scenarios, with the aircraft parking position serving as either the origin or destination of each path.

For operations at Terminal 2, the analysis required a nuanced approach to account for its unique configuration and operational procedures. In the case of departures, a distinction was made based on the aircraft's parking location. For aircraft parked adjacent to the Terminal, in the parking positions identified by Apron 20, no shuttle bus service is required, as passengers can access the aircraft directly by walking and no distance calculations were performed for these scenarios, as they do not contribute to vehicular emissions. However, for departing flights where the aircraft is not positioned on the Terminal 2 Apron, a methodology similar to that employed for Terminal 1 was adopted. A central location within Terminal 2 was designated as the origin point, with the aircraft's remote parking position serving as the destination. It is noteworthy that Terminal 2 at Lisbon Airport does not process arriving flights. As a result, all passengers arriving on flights for companies operating on Terminal 2 are de-boarded at Terminal 1. This operational procedure aligns with the process used for airlines operating through Terminal 1 arrivals.

Having established the distances for passenger transfers, the next critical step in our analysis involves determining the number of buses required for boarding and de-boarding operations in each flights and their specifications. To calculate the number of buses needed, a methodology based on the typical seating configuration for the aircraft model in analysis was employed, adjusted by the average load factor for Lisbon Airport. According to data from ANA (2024a), the average load factor for all commercial flights in 2023 was 83.02%. This approach allows us to estimate the number of passengers requiring transport for each remotely parked flight, providing a realistic basis for our calculations.

Through field observations of airport traffic, the COBUS 3000 was identified as the most commonly used shuttle bus model. This vehicle was selected for this analysis not only due to its prevalence but also because it represents one of the larger models available, thereby providing a best-case scenario in terms of passenger capacity per trip. The manufacturer specifications indicate that the COBUS 3000 has a capacity of 110 passengers. However, to maintain consistency with our aircraft occupancy calculations and to account for real-world operational factors, the same flight-specific 83.02% load factor was applied to the bus capacity. This adjustment results in an average effective capacity of 90 passengers per bus, providing a more realistic estimate of actual operating conditions.

To determine the emissions per kilometer for each vehicle, figures from Carris, Lisbon's public road transport company, were used. For diesel buses, a fuel consumption rate of 55 liters per 100 km as observed in 2023 was applied (Carris, 2023). This figure accounts for the unique operational characteristics of airport shuttle buses, including frequent stops and starts and a 50km/h maximum operating speed. By utilizing this data, we ensure that the emissions calculations reflect the specific conditions under which these vehicles operate, providing a more accurate assessment of their environmental impact.

By incorporating these detailed specifications and operational factors into our analysis, we aim to provide a highly accurate assessment of the environmental impact associated with passenger ground transportation on the air side at Lisbon Airport. This approach not only quantifies current emissions but also provides a foundation for evaluating potential improvements in shuttle bus operations and their impact on the airport's overall environmental footprint.

4.3. Aircraft Pushback

This section presents the algorithm developed to calculate pushback emissions for each departing flight at Lisbon Airport. The pushback process is a critical ground operation where an aircraft is moved backwards from its parking position to access the designated taxiway that will take the aircraft to the runway. This procedure is essential at Lisbon Airport due to its parking positions' layout, which does not allow any aircraft to independently taxi forward into the taxiway.

Pushback operations are not limited to departure preparations. Although not considered in this study, they are also used when aircraft need to be relocated between parking positions, such as for long-term parking or maintenance purposes. It's worth noting that starting an aircraft's engine requires a certified pilot or maintenance engineer and, given the cost implications of having such personnel available solely for aircraft relocation, pushback (or towing) procedures are often the preferred method for these movements as well. While pushback processes can be quantified by either duration or distance, this study employs a distance-based approach, aligning with the available data ADS-B data, and reflecting the study's commitment to maximizing the accuracy of emissions calculations within the constraints of the data structure.

To determine the duration of pushback, a simple set of criteria was created and applied. First, the dataset was filtered by selecting all ADS-B reported data for departing flights where the first reported speed was 0 meters per second. This criterion ensured the inclusion of flights that began from a stationary position and would not catch any pushback operation mid-process. For each ADS-B broadcast within a specific flight, the latitude and longitude coordinates were compared to those of the previous broadcast. By analyzing two consecutive sets of coordinates and their temporal order, the bearing of the aircraft's movement was calculated. This calculated bearing of travel was then compared with the bearing reported by the aircraft via ADS-B (corresponding to the aircraft's compass bearing). When the two bearings differed by more than 35 degree absolute, it was determined that the aircraft was moving backwards and the broadcast was labelled as "Pushback." The coordinates of all broadcasts labelled as "Pushback" was then consolidated and a line was created using Apache Sedona's built-in functions, with its length in meters being the final pushback distance value.

To calculate total emissions, the pusbhack distance was multiplied by an emission factor. However, due to the great variation in pushback vehicle types and models, no reliable emission factor could be identified. As a result, the same emission factor used for passenger boarding and deboarding buses, as indicated in Section 4.2 - 55 liters of diesel fuel per 100 kilometers — was used. While not a perfect proxy, this approach allowed the incorporation of pushback activities' environmental impact into the overall assessment of the airport's operational footprint, acknowledging the limitations in data availability.

The approach to determining pushback operations, given the limitations of ADS-B tracking, aims to provide the best-case scenario while maintaining a degree of precision. Since pushback movements are not directly tracked via ADS-B signals, the methodology employs a set of carefully defined criteria to infer these operations from available data. This strategy acknowledges the inherent challenges in capturing the full spectrum of aircraft movements on the ground, particularly those that occur at low speeds or involve specialized ground equipment. By focusing on providing the best-case scenario, the research aims to establish a conservative baseline for pushback operations, which can be used as a reliable foundation for further analysis and environmental impact assessments.

4.4. Handling Exceptions

A final consideration in the methodology addresses situations where emissions calculations could not be performed due to missing flight information from the database, incomplete track data that prevented accurate parking position determination, unavailability of specific engine information, or the absence of aircraft engine emissions data. To maintain the integrity of the analysis and to avoid determining durations using partial or unreliable data, a structured approach was implemented.

First, a subset of the data, comprising only flights successfully analyzed using the previous methods, was considered. This ensured a foundation of reliable data for subsequent calculations. Using this refined dataset, a set of filtering criteria was employed to identify flights that match specific characteristics of the unresolved cases based on three key parameters when available: the airline, the aircraft model, and either the origin (for arrival flights) or the destination (for departure flights). When a match was found, the average time for each mode of operation was extracted from the matching flights and applied to the unresolved case.

In instances where no exact match was found, a step-by-step relaxation of the matching criteria was performed. This process began by removing the airline constraint, followed by the aircraft model if necessary, and finally, if still unsuccessful, by relaxing the origin/destination airport requirement. This graduated approach ensured that the most relevant data was used for each unresolved flight, even as the specificity of the match decreased.

As a last resort, in cases where no match could be found even with fully relaxed criteria, the algorithm defaulted to using the mean values calculated across all flights in the dataset. This includes the 10,027 flights not recorded in the original dataset but reported by EUROCONTROL and the airport operator, ANA. This final step ensured that every flight in the study had an assigned set of time-in-mode values, albeit with varying degrees of specificity, thereby maintaining the comprehensiveness of the analysis.

CHAPTER 5

Results & Discussion

This chapter presents the results and discussion of the analysis described in the preceding chapter, based on the examination of over 18.4 million lines of data from 217,657 flights. The results are presented as total aggregate data and broken down by relevant metrics (per flight and per seat) for each pollutant. This approach to data presentation is particularly significant as it aligns with the commonly employed LTO cycle method in similar studies, while also addressing the lack of a consistent reporting format. By providing this comprehensive breakdown, the study allows for cross-checking and comparative analysis with existing research. The twelve-month data collection window, from January to December 2023, allows for a detailed temporal granulation of the results, capturing the demand's seasonality. This level of detail offers a nuanced understanding of emission patterns, contributing to the robustness and applicability of the study's findings.

Operating a hub airport with a single runway presents significant operational constraints that impact efficiency and capacity. The primary challenge is the runway's finite capacity, requiring careful scheduling to balance arrivals and departures and minimize delays. This issue is heightened during peak traffic periods, leading to increased holding patterns and extended taxi times, which can cause unnecessary fuel consumption and emissions. Additionally, the scarcity of air-bridge parking positions necessitates optimized allocation to maximize their use and minimize disruptions to flight schedules. When air-bridge positions are unavailable, airlines must use remote parking positions, which require shuttle buses for passenger boarding and de-boarding. This not only increases the airport's carbon footprint but also potentially affects passenger satisfaction and operational timeliness. The operational efficiency of an airport is greatly influenced by its infrastructure, particularly the number and utilization of air-bridge parking positions. At airports like Lisbon Airport, with a limited number of these positions, resource management becomes critical.

This study developed and analyzed a comprehensive database to determine the environmental impact of aircraft operations at Humberto Delgado Airport. The availability of high-precision data in the form of ADS-B messages enabled a focused analysis on the airport's activities that are tracked by this technology. This approach allowed for a detailed examination of aircraft movements, providing a robust foundation for assessing environmental impacts. The study employs an element-by-element approach to present its findings, ensuring a thorough and systematic evaluation of the various components contributing to the airport's environmental footprint, including flights and their related activities such as ground handling procedures. This methodological structure allows for a granular analysis of different operational aspects, facilitating a more nuanced understanding of their respective environmental implications. The subsequent sections of this study will present the results for each element identified in this approach, offering a comprehensive overview of the environmental impact associated with aircraft operations at Humberto Delgado Airport.

5.1. Time-in-Mode: LTO Cycle

The algorithmically defined LTO cycle mode durations were analyzed. The average observed durations for the Approach, Take-Off, and Climb phases as well as the standard values for each LTO phase as proposed by ICAO are displayed on Table 5.1.

The analysis of LTO cycle durations provides valuable insights into both the accuracy of the calculation methods employed and the unique operational characteristics of Lisbon Airport. The close alignment between the durations calculated in this study and the standard durations for the approach phase, as well as for the combined take-off and climb phases, lends significant credibility to the overall methodology. Notably, while the individual results for take-off and climb phases do not closely match the standard durations, their combined duration aligns with remarkable precision. This discrepancy suggests that the boundary between take-off and climb phases in this study differs from that used in standard duration calculations, without compromising the aggregate accuracy. The difference likely stems from the study's definition of the take-off phase transition to climb at approximately 300 meters above ground level, coinciding with the transfer of aircraft control from Tower to Approach Control. In contrast, standard durations may only consider the time an aircraft spends on the runway.

The concordance observed in these phases is particularly significant because approach, take-off, and climb are generally consistent across different airport environments due to their standardized and procedural nature. This consistency makes these phases excellent benchmarks for assessing the robustness of the algorithmic approach utilized in this study, further validating the methodology's effectiveness in capturing and analyzing LTO cycle dynamics at Lisbon Airport.

<table>
<tr><th rowspan="3">Operation</th><th rowspan="3">Aircraft Type</th><th colspan="8">Average Time-in-Mode</th></tr>
<tr><th colspan="8">Observed (Expected)</th></tr>
<tr><th colspan="2">Approach</th><th colspan="2">Idle</th><th colspan="2">Takeoff</th><th colspan="2">Climb</th></tr>
<tr><td rowspan="2">Arrival</td><td>Narrowbody</td><td>4.39</td><td rowspan="2">(4.00)</td><td>4.85</td><td rowspan="2">(7.00)</td><td colspan="2" rowspan="2">-</td><td colspan="2" rowspan="2">-</td></tr>
<tr><td>Widebody</td><td>4.38</td><td>5.50</td></tr>
<tr><td rowspan="2">Departure</td><td>Narrowbody</td><td colspan="2" rowspan="2">-</td><td>12.44</td><td rowspan="2">(19.00)</td><td>1.79</td><td rowspan="2">(0.70)</td><td>0.86</td><td rowspan="2">(2.20)</td></tr>
<tr><td>Widebody</td><td>14.77</td><td>3.23</td><td>1.14</td></tr>
</table>

Table 5.1. Average Time-in-Mode Observed (and Expected) per Flight Phase and Aircraft Type

However, the marked deviation from standard durations observed in the taxi phase highlights the importance of airport-specific analyses. The significantly shorter average taxi duration at Lisbon Airport compared to the standard LTO cycle assumptions is a crucial finding. This discrepancy underscores the potential for overestimation of emissions in studies that rely on standard durations when assessing Lisbon Airport's environmental impact. The implication is clear: generic, one-size-fits-all approaches to airport emissions calculations may lead to inaccurate assessments, particularly in airports with unique operational characteristics or layouts, as indicated on Chapter 2.

Further analysis revealed that runway usage impacted taxi durations. Flights utilizing runway 02 consistently demonstrated shorter taxi times compared to those using runway 20. For arrivals, runway 02 flights averaged 5.07 minutes of taxi time versus 4.43 minutes for runway 20. Similarly, departures from runway 02 required 12.08 minutes of taxi time on average, while runway 20 departures took, on average, 14.2 minutes. These observed variations in taxi durations provide valuable insights into the operational dynamics of Lisbon Airport. The shorter taxi times recorded for both arrivals and departures using runway 02, compared to those using the other end, runway 20, reflect the airport's physical layout. The concentration of parking positions in the southern section of the airport, along with the point where the aircraft enters the taxi phase — closer to runway 02 on departures or runway 20 on arrivals — explains this operational efficiency. This spatial relationship between runway configuration and taxi durations has several implications. Firstly, it demonstrates the direct impact of airport design on operational efficiency and, consequently, on emissions. Secondly, it suggests potential strategies for emissions reduction through optimized use of runways and thoughtful planning of aircraft parking positions. Lastly, it highlights the complexity of airport operations and the need for nuanced, data-driven approaches to emissions reduction strategies.

Finally, the analysis of taxi durations revealed that the runway used does not account for the observed differences between arrival and departure phases. Further examination, as presented in Table 5.1 and complemented by Table 4.2, provides additional insights into taxi times, specifically regarding average speeds. Consistently, the data shows lower average speeds during departure taxi compared to arrival taxi. This discrepancy suggests that aircraft frequently experience delays in departure queues while awaiting takeoff clearance. In contrast, arriving aircraft typically proceed directly to their designated parking positions, resulting in more efficient taxi operations, highlighting the distinctive operational characteristics and potential bottlenecks associated with departure and arrival procedures at the airport.

The delicate balance of resource allocation and geography characteristics is exacerbated by the cascading effects of flight delays. Any deviation from scheduled arrival or departure times for aircraft assigned to air-bridge positions can have far-reaching consequences on subsequent operations. Such delays necessitate an even more granular and dynamic approach to resource management, requiring real-time decision-making capabilities and robust contingency planning. Airport operators must employ sophisticated scheduling algorithms and maintain flexibility in their operations to mitigate the impact of these disruptions. This scenario underscores the intricate relationship between airport infrastructure, operational efficiency, and environmental impact, highlighting the need for innovative solutions that can optimize resource utilization while minimizing the ecological footprint of airport operations.

With the LTO Time-In-Modes foundation set, and the complete results presented on Table A.2, the next sections will present and discuss the aircraft and passenger transport emissions: these constitute the predominant source of emissions at Lisbon Airport, which aligns with the airport's primary function as a hub for air travel.

5.2. Aircraft Emissions

Emissions data were derived from the LTO cycle durations in conjunction with information on each flight's operating aircraft engine and the ICAO Engine Emissions Databank in its June of 2024 version. The total emissions for the analysis period (1st of January 2023 to 31st of December 2023) amounted to 300,585.68 metric tonnes of CO_2 from 95,122.05 metric tonnes of fuel burnt. To facilitate comparisons with other locations, timeframes, and flight characteristics, multiple averages were calculated and presented in Table 5.2, as well as the value that would be reached if the standard emissions from the ICAO Engine Emissions Databank were used (titled chCO2 Databank).

Aggregation	CO_2 Databank	CO_2	CO	HC	NOX	nvPM
Total (Tonne)	422804.01	300585.68	637.86	57.52	1922.37	1.94
Average Per Flight (Tonne)	1.85	1.32	0.002	0.0003	0.0085	0.00
Average Per Seat (Tonne)	0.0168	0.012	0.00003	0.00	0.00006	0.00

Table 5.2. Aircraft Aggregate Emissions from LTO Cycle

The table provides two key metrics: average emissions per flight and average emissions per seat. The per-flight average is particularly useful for projecting emissions at Lisbon airport across different timeframes, as it captures the mix of aircraft characteristics specific to this airport. Alternatively, the per-seat average allows for more generalized comparisons with different airports, as it normalizes the data relative to the seating capacity offered, making the study more agnostic to fleet characteristics.

The analysis reveals a strong correlation between emission quantities and flight numbers at Humberto Delgado Airport, underscoring the direct impact of air traffic volume on environmental outcomes. Figure 5.1 provides a visual representation of this correlation, illustrating the number of flights and corresponding emissions on a weekly basis, while also highlighting the discrepancy in total flights reported by EUROCONTROL compared to this study's database. Much of the finer variation in emissions can be attributed to differences in LTO cycle durations and aircraft mix, ranging from larger, more polluting aircraft to smaller, less polluting ones.

The graph clearly depicts increased emissions during the high season, corresponding to IATA's Summer Season, with a subsequent decrease during IATA's Winter Season. IATA

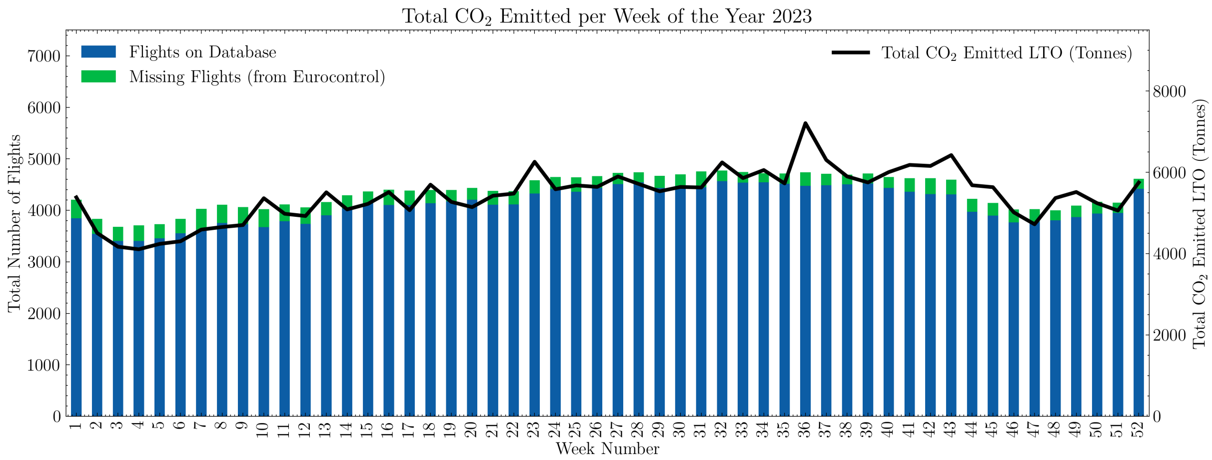


FIGURE 5.1. Weekly Flights and Emissions Quantity

summer and winter seasons are used in the aviation industry to define scheduling periods. The IATA summer season runs from the last Sunday in March to the last Saturday in October, while the winter season spans from the last Sunday in October to the last Saturday in March. These seasons guide airlines in setting flight schedules to accommodate changes in demand and daylight hours (Dobruszkes *et al.*, 2022). Notably, the low season values in the second semester exceed those of the first semester (equivalent to the previous winter), indicating rising demand reflected in increased flight numbers, as corroborated by IATA's Sustainability Report ANA (2024a). This graphical depiction offers a clear temporal perspective on the airport's operational intensity and its associated environmental impact, with parallel trends in flight frequency and emission levels demonstrating the intrinsic link between aviation activity and environmental consequences.

Considering the environmental impact of geographical inefficiencies at airports, such as extended taxi distances to parking positions and prolonged queues during departures, the implementation of electric taxiing systems emerges as a promising mitigation strategy. As proposed by Lukic *et al.* (2019) and Re (2017), these systems offer a potential solution to reduce unnecessary emissions during ground operations. The primary advantage of electric taxiing lies in its ability to optimize engine operating time, allowing aircraft to activate their main engines only when operationally necessary. This approach could significantly reduce fuel consumption and emissions during the taxi phase of both arrivals and departures. By enabling aircraft to move independently on the ground using electric power, the system could mitigate the environmental impact of long taxi routes and waiting times in departure queues. Furthermore, this technology aligns with broader industry efforts to enhance operational efficiency and reduce the carbon footprint of airport operations. The adoption of such systems could represent a significant step towards more sustainable airport ground operations, addressing the specific challenges identified in the analysis of Lisbon Airport's taxiing patterns and their associated emissions.

Another avenue to be explored in the mitigation would be using bigger aircraft to increase the overall efficiencies of the airport, reducing emissions. The concept of utilizing

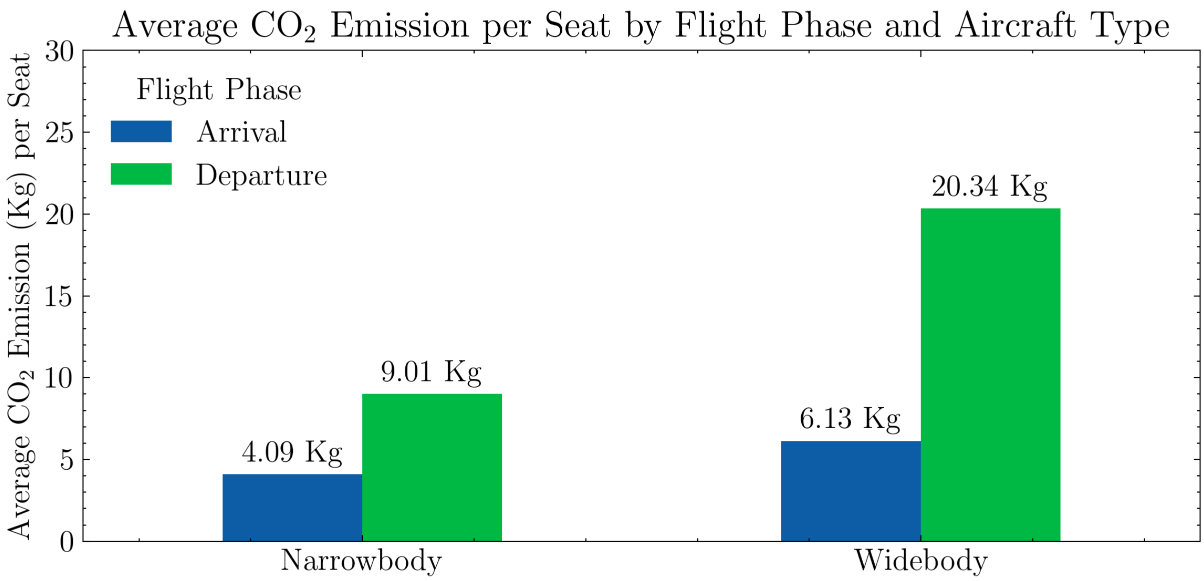


FIGURE 5.2. Average CO_2 Emission per Seat by Flight Phase and Aircraft Type

aircraft with higher seating capacities as a potential mitigation measure for emissions is complex and not as straightforward as it might initially appear. While larger aircraft could theoretically improve efficiency in terms of resource utilization, with airport services and resources being allocated to fewer aircraft, the emissions profile presents a more nuanced picture. As illustrated in Figure 5.2, widebody aircraft, despite consuming less fuel per seat, paradoxically emit more CO_2 during ground operations. This counterintuitive result is primarily attributed to their slower taxi speeds. The impact of taxi speed on emissions is further evidenced by the discrepancy in emissions per seat between arrival and departure operations, where the primary differentiating factor is the taxi speed. This observation underscores the importance of considering multiple operational factors when assessing the environmental impact of aircraft size and type. It suggests that while larger aircraft may offer benefits in terms of passenger capacity and fuel efficiency during flight, their ground operations could potentially offset these advantages in terms of CO_2 emissions. This finding highlights the need for a detailed approach to emissions reduction strategies, considering not only aircraft design and capacity but also ground operations and airport infrastructure optimization.

5.3. Passenger Transport & Pushback Emissions

The study's scope extended beyond aircraft operations to encompass the emissions generated by ground transportation activities, specifically focusing on the movement of passengers between remotely parked aircraft and terminal buildings, and the aircraft pushback processes. This additional layer of analysis provides a more comprehensive understanding of the airport's overall environmental impact.

5.3.1. Passenger Shuttle Transport

A significant proportion of flights, accounting for 54.8% of the total, or 86,576 from the flights that were successfully matched to a parking position, utilized remote parking positions. This operational configuration necessitated the use of ground transportation to ferry passengers between the aircraft and terminal facilities. The analysis of this ground transportation activity revealed substantial environmental implications. The results are displayed on Table 5.3.

Aggregation	CO_2	CO	HC	NOx	nvPM
Total (Kg)	448140.29	245.32	24.53	1297.14	25.49
Average Per Flight (Kg)	80.18	0.16	0.01	0.50	0.00
Average Per Seat (Kg)	0.01	0.00	0.00	0.00	0.00

Table 5.3. Airside Shuttle Buses Aggregate Emissions

Over the course of the study period, these passenger transfer operations resulted in the emission of 448.14 metric tonnes of CO_2. This considerable carbon footprint was generated from an estimated 306 651 kilometers of cumulative travel distance. On average, each flight utilizing remote parking positions required two bus trips to facilitate passenger movement, highlighting the frequency and scale of these ground transportation requirements.

The analysis of shuttle bus usage frequency per airline reveals noteworthy patterns when normalized to account for varying flight volumes across carriers. The metric "Airlines Rate of Bus Shuttles per 100 Flights" was developed to facilitate equitable comparison. Table 5.4 presents the top 10 and bottom 10 airlines according to this metric, yielding intriguing insights. The top 10 positions are predominantly occupied by charter airlines, a phenomenon potentially attributable to ANA's pricing structure, which imposes higher fees for air bridge parking compared to remote parking positions (ANA, 2023a). This financial incentive may influence operational decisions, particularly for charter operators, since low cost operators operates from Terminal 2 and does not have access to Air-Bridge parking positions. Conversely, the bottom of the list predominantly features airlines operating flights outside the Schengen area.

Figure 5.3 illustrates the average number of individual flights per day per air-bridged position, reflecting the extended rotation times typically associated with larger aircraft serving long-haul, non-Schengen routes. However, this pattern may also indicate an oversupply of non-Schengen air bridge positions, potentially explaining why airlines with lower shuttle bus utilization rates are those eligible to use these parking positions. This analysis underscores the complex interplay between operational decisions, infrastructure allocation, and economic factors in shaping airport ground operations and their subsequent environmental impact.

The analysis of Lisbon Airport's ground operations reveals three primary issues affecting environmental performance and operational efficiency. First, the airport has a lower

Airline	Passenger Shuttles per 100 Flights
Fly2Sky	98.775
Swiftair	92.968
World2Fly	88.888
Capital Airlines	85.806
White	79.545
Wamos Air	79.310
Bulgaria Air	76.414
Hi Fly	75.000
British Airways	73.044
TAAG Angola Airlines	69.696
⋮	⋮
Turkish Airlines	23.939
Air Europa	23.021
Etihad Airways	22.085
SAS	21.666
Air Algerie	9.756
Cabo Verde Airlines	9.589
Delta Air Lines	9.417
AirSERBIA	5.405
Emirates	1.963
El Al	1.486

TABLE 5.4. Top and Bottom 10 Airside Shuttle Buses per Airline per 100 Flights

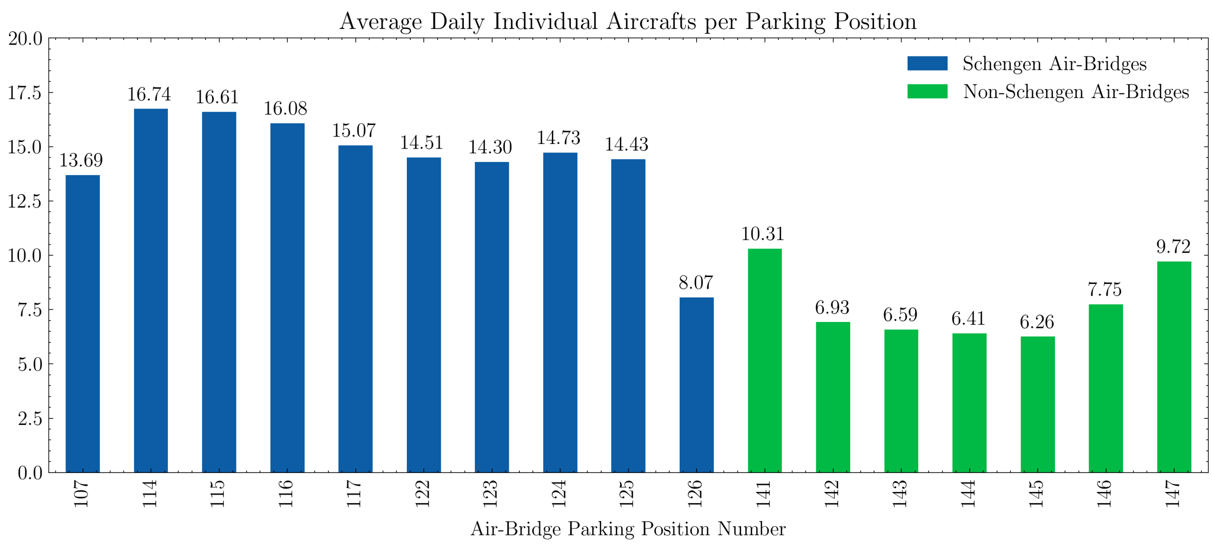


FIGURE 5.3. Average Daily Flights per Air-Bridge Parking Position

ratio of air-bridge positions compared to similar airports, resulting in more aircraft parking at remote positions and necessitating road transport to shuttle passengers between aircraft and terminals. Second, there is an imbalance in the ratio of Schengen to non-Schengen air-bridges, favoring non-Schengen flights despite their lower frequency. Third, the current use of internal combustion engine vehicles for ground transport contributes to unnecessary emissions.

To address these challenges, several mitigation solutions can be considered. The creation of new air-bridge parking positions, as proposed in the airport expansion plan, could alleviate the first issue. However, this solution faces a significant drawback given the decision to replace the airport in the future, making substantial infrastructure investments potentially uneconomical. Rebalancing Schengen and non-Schengen air-bridges could optimize usage, but this option may be constrained by the terminal's existing layout, potentially requiring extensive and costly internal reorganization.

The most feasible and immediately implementable solution appears to be the adoption of zero tailpipe emission vehicles for airport shuttle transfers. This solution addresses the emissions issue directly without requiring major infrastructure changes, aligning with current sustainability trends in airport operations. It offers a pragmatic approach to reducing ground operation emissions while the longer-term plans for the airport's future are developed and implemented. This strategy not only mitigates current environmental impacts but also demonstrates the airport's commitment to sustainability, potentially serving as a model for other airports facing similar challenges.

5.3.2. Pushback

As per the CO_2 emissions related to the pushback activities, presented on Table 5.5, were of 38.2 metric tonnes, related to 26,143 kilometers executed, and only calculated for Departure Flights.

Aggregation	CO_2	CO	HC	NOx	nvPM
Total (Kg)	38205.59	20.91	2.09	110.59	2.17
Average Per Flight (Kg)	0.16	0.00	0.00	0.00	0.00
Average Per Seat (Kg)	0.00	0.00	0.00	0.00	0.00

Table 5.5. Pushback Operations Aggregate Emissions

Pushback operations, while constituting a relatively minor component of overall flight operations, nonetheless present a significant opportunity for targeted emissions reduction. The annual emission of 38 tonnes from these activities, though small in comparison to total airport emissions, represents a tangible and addressable source of pollution. The implementation of zero-emission vehicles for pushback operations, as proposed by Baaren and Roling (2019), offers a feasible and effective solution to mitigate this environmental impact.

Notably, Lisbon Airport has already taken steps in this direction. Portway, one of the airport's handling companies, has been utilizing equipment capable of performing pushback operations for narrowbody aircraft using zero-emission technology since 2021[1]. This early adoption demonstrates the airport's commitment to integrating more sustainable

[1]https://www.publituris.pt/2021/08/17/portway-com-primeiro-reboque-totalmente-eletrico

ground handling practices and serves as a practical example of how such technologies can be successfully implemented in operational settings.

The introduction of these zero-emission pushback vehicles not only directly reduces the airport's carbon footprint but also contributes to improved air quality in the immediate airport environment. Furthermore, as this technology becomes more widespread and refined, it has the potential to be extended to larger aircraft types, further amplifying its environmental benefits. This initiative aligns with broader industry trends towards sustainable airport operations and illustrates how targeted interventions in specific operational areas can contribute to overall emissions reduction goals, even when the individual contribution might seem modest in isolation.

5.4. Comparing the Global Results

To facilitate a detailed comparison between our findings and those presented in official reports and related studies, relevant reports and studies were selected. Lisbon Airport, as a participant in the Airport Carbon Accreditation (ACA) program, as elaborated upon in Chapter 2, is obligated to provide carbon emission calculations through its managing authority to maintain its Accreditation Level. These calculations serve as a valuable benchmark for our comparative analysis. According to ANA (2024a, p. 67), the aircraft operations at Lisbon Airport, specifically those within the LTO cycle, generated 273,561 metric tonnes of CO_2 in 2023. This figure demonstrates a notable concordance with our study's results, exhibiting only a 9% discrepancy. However, it is pertinent to note that the Sustainability Report does not elucidate the methodological approach employed to derive this figure, thereby precluding a precise explanation of the observed variance.

A comparison between the study by Correia (2009) and the present research reveals intriguing similarities and differences in daily CO_2 emissions at Lisbon Airport. Correia (2009) reported daily emissions of 788 tonnes of CO_2, which aligns closely with this study's findings of 774 tonnes. However, the age of Correia (2009)'s study (2009) raises important questions about the comparability of these figures, given the significant changes in airport traffic over time. The oldest available report from ANA, dating from 2013 (ANA, 2014), indicates that the number of aircraft movements that year was 142,333, which means that 2023 figures represents a 60% increase. This substantial growth in traffic suggests that the similarity in emissions between the two studies, despite the time gap, might be attributed to improvements in aircraft efficiency and operational processes. However, this hypothesis cannot be definitively validated without per-aircraft emission values, which are not provided in the earlier study.

This lack of methodological transparency across different airports and studies highlights a significant impediment to standardized comparisons and emphasizes the need for a more uniform approach to carbon emission reporting in the aviation industry. Such standardization would greatly enhance the reliability and comparability of inter-airport environmental performance assessments.

In broadening our comparative scope to include other international airports, we revisited London Gatwick Airport, which was previously compared with Lisbon Airport in Chapter 2. London Gatwick reports CO_2 emissions of 400,109 tonnes in 2023, a figure that is 33% higher than that of Lisbon Airport, despite only having 13% more flight volume. The methodology underpinning this calculation is similarly unspecified, underscoring one of the principal challenges in conducting cross-scenario comparisons within the aviation sector.

To contextualize the environmental impact of these emissions, we can apply the concept of the Social Cost of Carbon (SCC). The SCC is an economic metric that quantifies the long-term damage done by a metric tonne of CO_2 emissions in a given year. It encompasses factors such as changes in agricultural productivity, human health impacts, property damage from increased flood risk, and changes in energy system costs. Using an SCC value of $417 United States Dollars (USD) per emitted metric tonne of CO_2 (Ricke *et al.*, 2018), it is possible to estimate the broader societal impact of Lisbon Airport's emissions. Based on this SCC figure, the calculated impact of the airport's and ground handling emissions on its surroundings during the analyzed timeframe and activities amounts to 125,546,751.51 USD. It is crucial to note that this substantial figure only accounts for CO_2 emissions and does not factor in other greenhouse gases or pollutants that may be released during airport operations and that the $417 USD is currently under debate, with studies stating that it is probably an underestimation and that the true figure is closer to $1,065 USD per tonne of CO_2 (Bilal and Känzig, 2024). This underscores the significant environmental and economic implications of airport emissions and highlights the potential benefits of implementing more efficient operational practices and cleaner technologies in the aviation sector.

While the discussion of the environmental impact of airports covers primarily on CO_2 emissions and their implications for climate change, it is also important to address the growing concern regarding nvPM emissions in airport environments. Although nvPM does not significantly contribute to global warming, its impact on human health is a matter of increasing scientific and public health interest. The health implications of nvPM exposure are particularly alarming due to the nature of these particles. Their small size allows them to be absorbed directly into the bloodstream, bypassing many of the body's natural defense mechanisms. This direct absorption has been linked to a range of serious health conditions, including hypertension, diabetes, and dementia. The scale of this issue is highlighted by the study conducted by van Seters *et al.* (2024), which estimated that approximately 52 million European citizens living in close proximity to airports are exposed to unhealthy levels of nvPM. Lisbon Airport is not exempt from this. As indicated by Lopes *et al.* (2019), the areas surrounding the Airport have UFP concentration levels 20 times above the recommended. This figure emphasizes the widespread nature of the problem and the potential for significant public health impacts in Lisbon and across

Europe. The association between nvPM exposure and these chronic diseases underscores the urgency of addressing this form of pollution in airport vicinity.

As a vital infrastructure, an airport inherently generates environmental impacts, which, though unavoidable, can be quantified to inform decisions aimed at reducing emissions or mitigating their effects. By assessing these impacts, stakeholders can develop strategies to manage and minimize the environmental footprint of airport operations. The following section will discuss the results of this study, comparing them with findings from other airports and industries. This comparative analysis will provide context for Lisbon Airport's operations, particularly given its unique challenge of concentrating emissions within a densely populated urban center. By situating Lisbon Airport within a broader framework, this discussion will highlight both the challenges and opportunities for improving environmental management in similar contexts.

5.5. Research Gaps

This research, while comprehensive, acknowledges several important limitations that could impact the interpretation and generalizability of its findings. These limitations stem from the nature of the data sources, the methodological approach, and the complexity of aircraft operations.

Firstly, the study relies on data from API's that pre-process information to add context or make it suitable for commercial use, such as website display. This pre-processing may introduce unknown nuances or biases into the data, potentially adding a layer of uncertainty to the results. The extent and nature of these pre-processing steps are not fully transparent, which could affect the accuracy and reliability of the analyses based on this data.

Secondly, the study attempts to establish strict boundaries for the LTO mode, primarily based on geographical criteria, but also incorporating factors such as aircraft speed, altitude, and heading. While this approach provides a standardized framework for analysis, it may not fully capture the complexity and variability of aircraft operations. Rare events such as go-arounds — where an aircraft aborts a landing attempt and circles for another approach — or aborted take-offs may not be adequately represented within these strict boundaries. These edge cases, although infrequent, could have significant implications for emissions calculations and operational analysis.

Additionally, certain aspects of the study, particularly the emissions data from ground handling equipment, are based on informed estimations rather than real-world measurements of equipment in operation at Lisbon Airport. While these estimations provide a basis for analysis, they may not accurately reflect the specific equipment, operational procedures, or maintenance practices employed at the airport. This limitation introduces a degree of uncertainty into the calculations of ground-based emissions and their environmental impact.

Finally, comparing real-world engine performance measured by Flight Data Recorder (FDR) to the ICAO Engine Database, Chati and Balakrishnan (2014) found that the latter tends to underestimate emissions across the primary chemicals by approximately 5%. This discrepancy highlights the potential for differences between laboratory-based data and actual in-flight performance and is a considerable gap on this study by its heavy reliance on the ICAO Engine Emissions Databank.

These gaps in the research highlight the challenges inherent in conducting detailed studies of complex airport operations and their environmental impacts. They underscore the need for continued refinement of data collection methods, more granular and transparent data sources, and the development of flexible analytical frameworks that can account for the full spectrum of operational scenarios. Future research could address these limitations by incorporating more diverse data sources — including raw ADS-B data —, developing more nuanced boundary definitions for flight phases, and conducting on-site measurements of ground equipment emissions to enhance the accuracy and applicability of the findings.

CHAPTER 6

Conclusions & Future Work

Lisbon Airport, like any major infrastructure, exerts a significant environmental impact on its surroundings. Being an important transportation hub for the country, its role extends far beyond its role in facilitating air travel. Its importance is multifaceted, serving vital social, economic, and cultural functions. The airport plays a central role in maintaining connections between mainland Portugal and its autonomous regions of Madeira and the Azores, ensuring cohesion and accessibility for these geographically distant communities. Furthermore, it serves as a critical link for the Portuguese diaspora, facilitating connections with their homeland and preserving cultural ties across borders. Economically, the airport's contribution is substantial, particularly in its role as a gateway for international tourism. The tourism sector has experienced consistent growth over the past decade, becoming a cornerstone of Portugal's economy. Given the country's limited high-speed rail connections with other nations, Lisbon Airport stands as the primary point of entry for international visitors. This position not only drives tourism growth but also generates significant revenue, contributing to local and national economic development. The airport's dual function in supporting both domestic connectivity and international tourism underscores its indispensable role in Portugal's transportation infrastructure and economic landscape.

Conversely, it brings a few drawbacks. Its location in the city center amplifies this effect, placing additional pressure on the local population. This situation is further complicated by the fact that 22% of passengers utilizing the airport are only in transit, connecting to other destinations. This scenario creates a unique dynamic where a substantial portion of the airport's environmental burden is imposed on the local community but without directly serving their travel needs. This proximity to residential and commercial zones means that the noxious gases produced by aircraft operations and associated ground activities are not readily dispersed before reaching populated areas. Consequently, the concentration of harmful pollutants in the surrounding atmosphere is intensified, potentially leading to elevated levels of air pollution in nearby neighborhoods. This situation poses substantial health risks to the local population, as prolonged exposure to these pollutants has been associated with various respiratory and cardiovascular issues. This juxtaposition of the airport's economic benefits against its environmental and health implications underscores the need for careful balancing of urban planning, public health considerations, and economic development in managing and mitigating the airport's impact on the surrounding community.

The research question "What is the environmental impact of aircraft operations at Humberto Delgado Airport?" guided this study towards a comprehensive assessment of emissions at Lisbon Airport. The findings reveal a significant environmental footprint, with conservative estimates indicating that aircraft operations at the airport contribute 301,072.02 tonnes of CO_2 to the atmosphere annually. This substantial figure underscores the considerable impact of aviation activities on greenhouse gas emissions and, by extension, on climate change. Moreover, the study identified emissions of other pollutants, including CO, HC, NOx, and nvPM, which have direct implications for both environmental quality and public health.

The SCC figure calculated in this study, 125,546,751.51 USD related to the emissions from flight operations and selected ground handling activities in 2023, although being a very conservative value, provides a valuable indicator for policymakers and stakeholders to consider when planning the timeline for the airport's potential deactivation and replacement. This economic metric offers a tangible representation of the long-term environmental and societal costs associated with the airport's continued operation in its current location, balancing these against the economic benefits it provides.

The complexity of airport operations was mirrored in the intricacy of this analysis. Beyond the sheer volume of data processed, the study had to account for significant operational variations between flights, necessitating complex calculations to accurately model emissions. This level of detail underscores the importance of nuanced, airport-specific studies in precisely assessing and managing aviation-related emissions. This study's findings collectively emphasize the critical nature of tailored research approaches in the aviation sector. Generic models or standardized calculations, such as using standard time-in-mode durations for the LTO cycle, may fail to capture the unique characteristics of individual airports, potentially leading to over or underestimation of emissions. This study demonstrates that airport-specific analyses are essential for developing accurate emissions profiles and, consequently, for formulating effective mitigation strategies.

The results indicate that operational optimizations could serve as effective tools in emissions reduction efforts. Strategies such as the strategic positioning of aircraft to minimize taxi times and the deployment of zero-emission ground vehicles have the potential to significantly reduce an airport's carbon footprint. These operational adjustments represent readily implementable measures in the broader effort to mitigate aviation's environmental impact.

Looking ahead, several avenues for future research emerge from this study.

First, there is potential to apply these methodologies and findings to other airports, allowing for comparative analyses and the identification of best practices across different airport configurations.

Second, investigation on the potential for apron layout modifications or operational adjustments to improve air-bridge utilization and minimize taxi times, thereby reducing associated emissions.

Lastly, a comprehensive understanding of airport emissions would benefit from collecting and analyzing data related to activities not tracked by ADS-B systems, such as ground handling operations. These activities, while often overlooked in broader emissions studies, contribute to the overall environmental impact of airport operations and warrant closer examination.

In conclusion, this study not only provides valuable insights into the specific emissions profile of Lisbon Airport but also establishes a framework for more accurate and nuanced assessments of airport emissions globally. By highlighting the importance of airport-specific analyses and identifying potential areas for operational optimization, this research contributes to the ongoing effort to reconcile the economic benefits of air travel with the imperative of environmental sustainability.

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APPENDIX A

Tables

Document	Airport Location	Timeframe	Research Goals	Data & Methods	Results
Tokuşlu (2021)	Batumi International Airport, Georgia	2018	Estimate aircraft emissions during the LTO Cycle	Data provided by the airport's managing company + ICAO Engine Emissions Databank	The 2018 emissions in tonnes for NOx, CO, and HC
Song and Shon (2012)	Four major airports, South Korea	2009 and 2010	Estimate aircraft emissions during the LTO Cycle	Data provided by the airport's managing company + EDMS	The range of yearly emissions of GHGs (CO_2, N_2O, CH_4, and H_2O) individually for each airport
Zhou *et al.* (2019)	204 Airports in Mainland China	2015	Accurately estimate aircraft emissions during the LTO Cycle	Real-time data from Aircraft Meteorological Data Relay (AMDAR)	The total emissions from LTO cycles in 2015 for NOx, CO, SO_2, HC and PM

Document	Airport Location	Timeframe	Research Goals	Data & Methods	Results
İlker Yılmaz (2017)	Kayseri Airport, Turkey	2010	Estimate pollutant gas emissions from aircraft during LTO cycles	Data provided by the airport's managing company + ICAO Engine Emissions Databank	HC: 8.39 tonnes CO: 66.89 tonnes NOx: 102.62 tonnes
Dissanayaka *et al.* (2020)	Bandaranaike International Airport, Sri-Lanka	Between January and March 2018	Evaluate the flight delays and CO_2 emission at the taxing phase for both arrivals and departures	Data provided by the airport's ATC + ICAO Wake Turbulence Category	The estimated CO_2 emissions due to delays varied between 600 and 800 tonnes per month.
Özgür Zeydan and Yıldız Şekertekin (2022)	46 Airports in Turkey	2015	Determine the air pollution caused by emissions arising from domestic flights of Turkey	Data provided by the airport's managing company + EEA/EMEP Emission Inventory Guidebook	The total emissions (LTO + Cruise) were calculated as 1.67 million tons CO_2, 6472.23 tons NOx, 2839.03 tons CO, and 80.52 tons PM for the year 2015.
Xu *et al.* (2020)	Shanghai Hongqiao International Airport, Shanghai, China	2017	Analyze operation times, fuel and emission parameters of 8 aircraft models during taxi phase and compare to ICAO standard values	ACARS data + ICAO Engine Emissions Databank	The taxi-out times at are generally overestimated by ICAO (up to 35.3%). Fuel flows and Emission Indices are overvalued by ICAO at values as high as 28.3%

Document	**Airport Location**	**Timeframe**	**Research Goals**	**Data & Methods**	**Results**
Simonetti *et al.* (2015)	Amerigo Vespucci airport, Florence, Italy	2011	Analyze the emissions from an Airport that is inserted in an urban context, with a simulation of future growth	Data provided by the airport's managing company + Environmental Modeling System (EMDS)	Emission Indices for both scenarios (Current and Future) for CO_2 NOx, VOCs, SOx, and PM. Also a comparison with closer emitters such as highways
nan Wang *et al.* (2023)	Beijing Daxing International Airport, China	July 2020 to June 2021	Evaluate the Airport's Environmental Impact	Real Flight Data + ICAO Engine Emissions Databank	The emissions from the timeframe are as follows: CO: 1.15 $\times 10^3$ | NOx: 1.76 $\times 10^3$ | HC: 1.38 $\times 10^2$ | SO_2: $\times 10^2$ | PM: 3.53 $\times 10^1$ | CO_2: 3.75 $\times 10^5$ tonnes
Kuzu (2018)	Atatürk International Airport, Istanbul, Turkey	2015	Quantify emission from LTO Operations.	Flight Radar Sample + Ground Based Environment Monitoring Stations + AEDT Methods using Standard LTO Phase Durations	The emissions from the timeframe are as follows: CO: 2153 | NOx: 4249 | HC: 181 tonnes

Table A.1. Literature Review Results

Flight Phase	Aircraft Category	Runway	Quantity	Mean Time-in-Mode (minutes)				CO_2 Emissions (kg)	
				Approach	Idle	Take-Off	Climb	Average	Total
Arrival	Narrowbody	02	67478	4.477	5.016	-	-	675.931	45610506.217
		20	22826	4.136	4.348	-	-	613.282	13998786.038
		Undetermined	591	4.060	4.640	-	-	560.533	331275.533
	Widebody	02	7495	4.447	5.624	-	-	1760.233	13192949.837
		20	2217	4.208	5.307	-	-	1672.207	3707283.915
		Undetermined	28	3.907	5.140	-	-	1592.163	44580.571
Departure	Narrowbody	02	61988	-	11.888	1.703	0.886	1410.983	87464059.841
		20	20841	-	13.912	2.034	0.801	1599.091	33326658.324
		Undetermined	953	-	13.497	2.263	0.724	1572.511	1498603.564
	Widebody	02	6794	-	13.902	1.824	1.147	4206.688	28580241.721
		20	2169	-	17.573	7.869	1.130	10932.398	23712373.122
		Undetermined	27	-	17.246	6.470	0.722	9733.327	262799.835

Table A.2. Detailed flight results for aircraft that matched a parking position

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Narrow	Airbus A320-214	CFM56-5B4/P	40180	4.415	8.395	1.690	0.982	1.126	45261.089
Narrow	Airbus A321-251NX	LEAP-1A3X	21513	4.405	8.683	2.203	0.849	1.141	24555.889
Narrow	Airbus A320-251N	LEAP-1A26/26E1	19640	4.412	8.491	1.669	0.792	0.876	17204.546
Narrow	Boeing 737-8AS	CFM56-7B26	16464	4.016	8.855	1.640	0.804	1.139	18744.854
Narrow	Embraer E190LR	CF34-10E7	12940	4.575	8.512	1.683	0.741	0.862	11157.278
Wide	Airbus A330-941	Trent7000-72	10622	4.318	9.947	3.333	1.381	3.604	38278.198
Narrow	Airbus A321-251N	LEAP-1A3X	8764	4.373	8.515	1.919	0.782	1.067	9349.448
Narrow	Airbus A319-111	CFM56-5B5/3	5717	4.479	8.385	1.804	0.870	0.944	5395.722
Narrow	Embraer E195AR	CF34-10E7	5210	4.367	8.558	1.938	0.843	0.910	4740.099
Narrow	Airbus A321-271NX	PW1133G-JM	4894	4.539	9.593	1.984	0.891	1.124	5502.682
Narrow	Airbus A321-231	V2533-A5	4594	4.358	8.987	1.841	0.971	1.493	6859.648
Narrow	Airbus A320-232	V2527-A5	4368	4.458	9.011	1.657	1.009	1.200	5241.896
Narrow	Boeing 737-8K2	CFM56-7B27	4299	4.253	8.518	1.730	0.790	1.191	5119.569
Narrow	Airbus A321-211	CFM56-5B3/P	4141	4.280	8.375	1.937	1.076	1.417	5866.166
Narrow	Embraer E195LR	CF34-10E5A1	3909	4.328	8.564	1.973	0.840	0.914	3573.412
Narrow	Embraer E190AR	CF34-10E6	3827	4.541	8.592	1.692	0.741	0.808	3091.949
Narrow	Boeing 737 MAX 8-200	LEAP-1B27	3739	4.027	9.503	1.617	0.807	0.991	3704.104
Narrow	Airbus A319-112	CFM56-5B6/P	3312	4.464	8.299	1.723	0.832	0.978	3237.496
Narrow	Embraer E190STD	CF34-10E5	2856	4.497	7.644	1.513	0.823	0.759	2166.972
Narrow	Boeing 737-85P	CFM56-7B26	2507	4.258	8.831	1.740	0.927	1.197	3001.956
Narrow	Airbus A320-271N	PW1127G-JM	2005	4.547	8.764	1.636	0.786	0.815	1633.873
Narrow	Airbus A220-300	PW1524G	1632	4.493	8.437	1.848	0.653	0.809	1319.600
Wide	Airbus A330-202	CF6-80E1A4	1563	4.387	9.901	3.562	1.295	3.998	6249.245

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Narrow	ATR 72-600	CF34-8E5	1497	4.798	8.123	1.872	1.209	0.391	585.611
Wide	Airbus A330-343	Trent 772	1299	4.583	10.794	3.519	1.026	4.340	5638.127
Narrow	Airbus A321-212	CFM56-5B1/3	1294	4.531	8.553	1.939	0.872	1.311	1695.830
Wide	Boeing 777-31H(ER)	GE90-115B	1255	4.243	10.539	3.534	0.776	5.831	7317.394
Narrow	Airbus A321-253NX	LEAP-1A3X	1214	4.542	8.906	1.706	0.815	1.053	1277.896
Wide	Boeing 767-332(ER)	PW4060	1107	4.405	10.596	3.101	0.513	3.112	3444.511
Narrow	Airbus A320-216	CFM56-5B6/2	868	4.418	8.678	1.687	1.006	1.003	870.260
Narrow	Boeing 737-8JP	CFM56-7B26	781	4.281	8.941	1.766	0.868	1.180	921.924
Narrow	Airbus A321-253N	LEAP-1A3X	749	4.679	8.784	1.716	0.823	1.059	793.272
Narrow	ATR 72-500	CF34-8E5	744	4.762	7.559	1.987	1.244	0.393	292.383
Wide	Boeing 767-34P(ER)	PW4056	721	4.421	9.992	2.490	0.555	2.541	1831.852
Wide	Airbus A330-243	Trent 772	622	4.680	10.331	3.145	1.067	4.163	2589.243
Narrow	Airbus A320-233	V2527E-A5	597	4.450	8.805	1.801	0.983	1.218	727.020
Narrow	Boeing 737-86N	CFM56-7B26	593	4.235	9.300	1.715	0.732	1.167	692.224
Wide	Boeing 787-10 Dreamliner	GEnx-1B76/P2	553	4.225	10.635	3.525	0.953	3.683	2036.789
Wide	Boeing 787-9 Dreamliner	GEnx-1B67	545	4.284	10.168	3.168	0.695	2.966	1616.495
Wide	Boeing 767-25E(BDSF)	CF6-80C2B2F	452	4.607	9.707	2.457	0.314	2.233	1009.327
Narrow	Boeing 737-7K2	CFM56-7B22	442	4.556	8.701	1.684	0.717	1.012	447.209
Narrow	Boeing 737-86J	CFM56-7B27	408	4.299	8.984	1.862	0.777	1.221	498.361
Narrow	Boeing 737-9K2	CFM56-7B26	386	4.059	7.993	1.912	0.833	1.174	453.154
Narrow	Boeing 737 MAX 8	LEAP-1X/2X	378	4.123	9.659	1.766	0.867	1.076	406.573
Narrow	Boeing 737-7M2	CFM56-7B24	370	4.438	9.168	1.753	0.784	1.112	411.566
Wide	Boeing 777-3M2(ER)	GE90-115B	362	4.428	11.271	3.105	0.931	5.696	2061.952

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Wide	Boeing 767-424(ER)	CF6-80C2B7F	360	4.354	10.146	3.147	0.993	3.193	1149.658
Narrow	Airbus A319-131	V2522-A5	341	4.640	9.375	1.646	0.876	1.130	385.396
Wide	Airbus A330-203	CF6-80E1A3	337	4.693	9.933	3.550	1.031	3.732	1257.652
Narrow	Boeing 737-8B6	CFM56-7B26	325	4.178	9.241	1.529	0.559	1.092	354.966
Narrow	Boeing 737-8GJ	CFM56-7B24	301	4.296	8.841	1.788	0.792	1.070	322.131
Narrow	Boeing 737-4Q8(SF)	CFM56-5B5/3	290	4.676	8.282	1.483	0.623	0.839	243.327
Narrow	Boeing 737-958(ER)	CFM56-7B20E	288	4.269	9.194	2.479	0.659	1.059	304.966
Wide	Airbus A340-313	CFM56-5C4	287	4.941	10.270	2.997	1.113	3.374	968.339
Narrow	Airbus A321-131	V2530-A5	269	4.414	9.126	2.369	0.954	1.585	426.303
Narrow	Boeing 737-84P	CFM56-7B26	245	4.314	8.945	1.777	0.772	1.148	281.244
Narrow	Boeing 737-8GP	CFM56-7B26E	223	4.324	8.785	1.694	0.893	1.186	264.579
Narrow	Boeing 757-224	RB211-535E4B	223	4.430	10.282	2.789	0.830	2.536	565.425
Wide	Boeing 777-36N(ER)	GE90-115B	203	4.444	10.312	2.760	0.797	5.174	1050.309
Wide	Airbus A350-941	Trent XWB-84	203	4.405	10.122	3.451	0.771	3.900	791.782
Wide	Boeing 787-8 Dreamliner	GEnx-1B64	197	4.540	10.016	3.536	0.600	2.685	528.949
Narrow	Boeing 737-490(SF)	CFM56-5B5/3	192	4.656	8.564	1.546	0.608	0.862	165.417
Narrow	Airbus A321-111	CFM56-5B1	184	4.361	8.501	1.715	0.756	1.206	221.947
Wide	Boeing 777-243(ER)	GE90-94B	172	4.665	9.965	2.433	0.706	3.819	656.839
Narrow	Boeing 737-8Q8	CFM56-7B27	167	4.101	9.644	1.804	0.744	1.256	209.827
Narrow	Boeing 737-82R	CFM56-7B26	157	4.301	8.942	1.961	0.789	1.220	191.617
Narrow	Airbus A220-100	PW1524G	150	4.578	8.338	1.672	0.595	0.776	116.450
Narrow	Boeing 737-8K5	CFM56-7B27	145	4.246	8.918	1.719	0.884	1.218	176.659
Narrow	Airbus A319-132	V2522-A5	143	4.696	8.460	1.719	0.870	1.080	154.406

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Narrow	Boeing 737-6D6	CFM56-7B18	128	4.639	8.939	1.444	0.538	0.839	107.410
Narrow	Boeing 737-8AL	CFM56-7B24	120	4.392	9.037	1.606	0.742	1.043	125.132
Wide	Airbus A300B4-622R(F)	PW4158	119	4.553	8.950	2.582	0.532	2.603	309.816
Narrow	Boeing 757-2Q8(PCF)	PW2040	118	4.950	14.276	2.850	0.606	3.072	362.515
Narrow	Boeing 737-7C9	CFM56-7B22	110	4.626	8.823	1.710	0.748	1.030	113.293
Wide	Airbus A340-312	CFM56-5C3	94	5.039	10.540	3.796	1.211	3.711	348.808
Narrow	Boeing 737-8KN	CFM56-7B26	92	4.133	8.813	1.707	1.037	1.199	110.335
Narrow	Boeing 737-8HX	CFM56-7B26	73	4.433	9.229	1.906	0.769	1.198	87.432
Wide	Boeing 767-432(ER)	CF6-80C2B7F	68	4.597	10.043	2.972	0.568	2.968	201.836
Narrow	Boeing 737-8BK	CFM56-7B27	54	4.240	8.972	1.993	0.708	1.266	68.390
Narrow	Bombardier Challenger 350	AS907-2-1A	51	4.611	7.998	1.169	0.244	0.336	17.115
Narrow	ATR 72-500(F)	CF34-8E5	49	4.960	6.923	2.090	0.990	0.380	18.643
Narrow	Mitsubishi CRJ-900ER	CF34-8C5	48	4.649	8.517	1.583	0.489	0.582	27.943
Narrow	Boeing 737-7D6C	CFM56-7B22	42	4.311	9.213	1.453	0.575	0.951	39.940
Narrow	Bombardier Challenger 604	CF34-3B/-3B1	37	4.774	7.675	1.264	0.357	0.362	13.397
Narrow	Boeing 737-4Y0(SF)	CFM56-5B5/3	36	4.441	7.162	1.492	0.554	0.743	26.738
Narrow	Boeing 737-49R(SF)	CFM56-5B5/3	36	4.493	5.968	1.525	0.625	0.672	24.174
Narrow	Boeing 737-46J(SF)	CFM56-5B5/3	35	5.180	5.268	1.663	0.442	0.722	25.259
Narrow	Airbus A321-213	CFM56-5B2/3	34	4.297	8.819	1.450	0.979	1.249	42.466
Narrow	Embraer E195-E2	PW1921G	33	4.181	8.304	1.765	0.828	0.722	23.829
Narrow	Airbus A318-111	CFM56-5B8/P	33	5.021	7.996	1.773	0.866	0.943	31.126
Narrow	Boeing 757-28A(PCF)	RB211-535E4	33	nan	14.967	2.537	0.580	3.121	103.002
Narrow	Boeing 737-86Q	CFM56-7B27	32	4.165	8.897	1.750	0.740	1.195	38.232

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Narrow	Boeing 737-8Z9	CFM56-7B27	28	4.177	8.529	2.583	0.737	1.391	38.951
Narrow	Boeing 737-8D6	CFM56-7B27	26	4.393	8.634	1.315	0.483	1.056	27.449
Narrow	Gulfstream G200 Galaxy	PW307A	26	3.872	8.878	1.170	0.397	0.316	8.216
Wide	Boeing 767-219(BDSF)	CF6-80A	24	4.761	9.546	2.597	0.491	2.321	55.713
Narrow	Boeing 737-476(SF)	CFM56-5B5/3	23	4.412	8.152	1.745	0.550	0.859	19.748
Narrow	Boeing 737-4Z9(SF)	CFM56-5B5/3	23	4.687	8.004	1.472	0.693	0.836	19.239
Narrow	Boeing 757-28A(SF)	RB211-535E4	21	nan	13.494	2.295	0.492	2.811	59.032
Narrow	Boeing 737-448(SF)	CFM56-5B5/3	21	4.492	7.452	1.283	0.578	0.731	15.347
Narrow	Boeing 757-23N(SF)	RB211-535E4	20	nan	14.713	2.958	0.492	3.359	67.182
Narrow	Boeing 737-43Q(SF)	CFM56-5B5/3	20	4.684	5.450	0.967	0.417	0.658	13.158
Narrow	Boeing 737-8CX(SF)	CFM56-7B26	19	4.947	8.550	1.573	0.527	1.079	20.507
Wide	Boeing 767-204(BDSF)	CF6-80A	18	4.874	9.023	4.193	0.588	2.987	53.764
Narrow	Boeing 737-8FE	CFM56-7B26	18	4.088	9.704	1.814	0.965	1.248	22.465
Narrow	Mitsubishi CRJ-1000	CF34-8C5A2	17	4.400	9.655	1.770	0.724	0.717	12.183
Narrow	Boeing 737-8FZ	CFM56-7B26	17	4.055	10.196	1.959	0.956	1.363	23.172
Wide	Boeing 767-324(ER)	CF6-80C2B1	16	4.848	9.545	1.651	0.536	2.005	32.082
Narrow	Boeing 737-81Q	CFM56-7B26	16	4.117	9.117	1.903	0.992	1.251	20.018
Narrow	Boeing 737-301(SF)	CFM56-5B5/3	16	4.898	7.094	1.327	0.475	0.761	12.178
Narrow	Embraer ERJ-135ER	AE3007A1	15	4.974	7.067	1.861	0.464	0.365	5.469
Narrow	Boeing 737-8FN	CFM56-7B26	15	3.877	10.160	1.619	0.774	1.264	18.955
Narrow	Bombardier Global Express	BR700-710A2-20	14	4.881	7.843	1.347	0.433	0.684	9.583
Narrow	Boeing 737-809	CFM56-7B26	13	4.158	9.004	2.402	0.998	1.401	18.208
Narrow	Boeing 737-3Y5(SF)	CFM56-5B5/3	13	4.867	7.147	1.428	0.444	0.774	10.063

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Narrow	Boeing 737-8F2	CFM56-7B26	12	4.317	10.057	1.358	0.821	1.146	13.753
Narrow	Boeing 737-8C9	CFM56-7B20E	12	4.003	8.786	1.729	0.821	0.926	11.117
Narrow	Bombardier Global 6000	BR700-710A2-20	12	4.840	7.264	1.642	0.521	0.694	8.332
Narrow	Boeing 737-85F(SF)	CFM56-7B27	11	4.577	6.114	1.133	0.550	0.865	9.517
Wide	Boeing 777-212(ER)	Trent 892	10	4.714	9.162	3.878	0.500	4.650	46.496
Narrow	Boeing 737-86N(SF)	CFM56-7B26	10	4.233	5.931	nan	nan	0.774	7.743
Wide	Boeing 777-258(ER)	Trent 970-84	10	4.420	11.047	1.953	0.873	2.993	29.935
Narrow	Boeing 737-9F2(ER)	CFM56-7B27	8	4.350	10.427	3.008	0.721	1.580	12.642
Narrow	Boeing 737-858	CFM56-7B27	8	4.279	10.075	1.613	0.733	1.229	9.829
Narrow	Boeing 737-405(SF)	CFM56-5B5/3	7	4.961	5.353	nan	nan	0.683	4.784
Narrow	Boeing 737-81M	CFM56-7B26E	7	3.971	9.024	1.822	1.083	1.187	8.310
Narrow	Boeing 737-430	CFM56-5B5/3	6	4.167	8.992	1.700	0.658	0.903	5.419
Narrow	Boeing 737-83N(BCF)	CFM56-7B27	6	4.606	7.736	1.294	0.767	1.083	6.495
Narrow	Boeing 737-4M0(SF)	CFM56-5B5/3	6	5.933	6.872	5.872	0.628	1.621	9.723
Narrow	Embraer E190SR	CF34-10E2A1	6	4.106	10.086	1.183	0.750	0.758	4.546
Narrow	Boeing 737-732	CFM56-7B22	4	4.275	8.704	3.700	0.683	1.375	5.499
Narrow	Boeing 757-223(PCF)	RB211-535E4	4	5.058	9.575	1.467	0.442	1.792	7.169
Wide	Boeing 767-322(ER)	PW4060	4	4.125	10.850	5.883	0.825	4.574	18.295
Narrow	Bombardier Global 7500	Passport20-19BB1A	4	5.008	11.225	4.792	0.750	1.371	5.485
Narrow	Cessna 680A Citation Latitude	PW306A	4	5.283	6.767	1.150	0.367	0.298	1.194
Narrow	Airbus A320-211	CFM56-5-A1	4	5.550	7.133	2.183	1.100	1.195	4.778
Narrow	Learjet 45	TFE731-2-2B	4	4.383	7.592	1.750	0.658	0.214	0.858
Narrow	Boeing 737-8CX	CFM56-7B26	3	4.700	9.411	1.717	1.017	1.358	4.073

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Narrow	Boeing 737-429(SF)	CFM56-5B5/3	3	4.550	8.800	1.917	0.517	0.876	2.627
Narrow	Boeing 737-8AS(BCF)	CFM56-7B24	3	4.525	7.217	1.717	0.533	0.930	2.791
Narrow	Dassault Falcon 50	TFE731-2-2B	3	5.358	6.006	1.867	0.900	0.320	0.961
Narrow	Boeing 737-8FH	CFM56-7B24	3	3.750	9.489	1.683	0.733	1.145	3.434
Wide	Boeing 777-21H(LR)	GE90-110B1	2	4.017	12.775	1.600	0.450	3.972	7.943
Wide	Airbus A330-303	CF6-80E1A3	2	4.333	13.925	1.767	1.133	3.333	6.666
Wide	Airbus A330-302	CF6-80E1A4	2	3.983	6.592	nan	nan	1.691	3.382
Wide	Airbus A330-223	PW4168A	2	4.133	20.025	1.700	0.750	3.549	7.097
Wide	Airbus A300F4-622R	PW4158	2	4.400	7.208	nan	nan	1.715	3.429
Narrow	Boeing 757-236(PCF)	RB211-535E4	2	nan	11.075	1.458	0.483	2.054	4.108
Narrow	Boeing 737-48E(SF)	CFM56-5B5/3	2	4.233	8.417	1.400	0.650	0.834	1.669
Narrow	Boeing 737-35B(SF)	CFM56-5B5/3	2	5.075	4.592	nan	nan	0.668	1.336
Narrow	Cessna S550 Citation S/II	JT15D-4 series	2	6.250	5.525	2.067	0.683	0.210	0.419
Narrow	Boeing 737-809(SF)	CFM56-7B26	1	4.033	5.500	nan	nan	0.731	0.731
Narrow	Boeing 737-522	CFM56-5B5/3	1	4.783	4.250	nan	nan	0.627	0.627
Wide	Boeing 777-333(ER)	GE90-115B	1	nan	21.783	1.600	0.500	6.284	6.284
Narrow	Cessna 525B Citation CJ3	LEAP-1A3X	1	6.633	3.783	nan	nan	0.075	0.075
Wide	Boeing 777-224(ER)	GE90-110B1	1	nan	12.000	1.817	0.933	3.897	3.897
Narrow	Boeing 737-83N	CFM56-7B27	1	4.050	6.217	nan	nan	0.786	0.786
Narrow	Boeing 737-85R(SF)	CFM56-7B26	1	4.550	5.833	nan	nan	0.810	0.810
Narrow	Boeing 737-8ME	CFM56-7B18	1	4.350	4.267	nan	nan	0.571	0.571
Narrow	Hawker 850XP	TFE731-3	1	5.167	3.533	nan	nan	0.176	0.176
Narrow	Gulfstream G650ER	BR700-725A1-12	1	4.167	4.367	nan	nan	0.490	0.490

Aircraft Information				Mean Time-in-Mode (minutes)				CO_2 Emissions (t)	
Category	**Model**	**Engine**	**Quantity**	**Approach**	**Idle**	**Take-Off**	**Climb**	**Average**	**Total**
Narrow	Bombardier Challenger 650	CF34-3B/-3B1	1	4.600	4.367	nan	nan	0.283	0.283
Narrow	Bombardier Global 5000	BR700-710A2-20	1	4.017	2.333	nan	nan	0.405	0.405
Narrow	Boeing 757-256(PCF)	RB211-535E4	1	nan	15.250	7.067	0.217	6.122	6.122

Table A.3. Detailed aircraft results for aircraft that matched a parking position