

# THE ENVIRONMENTAL IMPACT OF EQUIVALENT CO<sub>2</sub> IN EXECUTIVE JETS

Case Study

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Provas destinada à obtenção de grau de:

**Mestre em Operações de Transporte Aéreo**

NOVEMBER 2024

ISEC LISBOA | INSTITUTO SUPERIOR DE EDUCAÇÃO E CIÊNCIAS

Escola de Gestão, Engenharia e Aeronáutica

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November 2024

## **ACKNOWLEDGEMENTS**

I am grateful to my family, especially my parents, for their support and positive reinforcement, allowing me to believe I could do this research and the master's in general. My parents have provided me with the "can-do" attitude and framework that I have leveraged many times in my life in many situations.

Thank you to those friends, some closer than others, who also believed in me achieving this deadline and understood when I had to close myself from the outdoors and dedicate extensive time to research and writing.

Thank you also to those in the academic world who guided, supported, and encouraged me, notably Professor Eurico de Brito, Professor Maria Baltazar, and all the remaining professors at the ISEC, for their collaboration and integration during these two years of graduate studies.

## RESUMO

Esta investigação tem como objetivo explicar os diferentes impactos ambientais da aviação executiva e comercial, centrando-se nas suas emissões equivalentes de CO<sub>2</sub> (eCO<sub>2</sub>), abordando assim um aspeto fundamental da contribuição da aviação para o aquecimento global.

O estudo adota uma abordagem de métodos mistos, combinando dados primários de medições diretas de emissões com informações secundárias da literatura e das bases de dados existentes. Esta estratégia abrangente foi concebida para quantificar e comparar com precisão as emissões dos jatos executivos e comerciais, utilizando técnicas analíticas avançadas para garantir a fiabilidade e a validade dos resultados.

Esta investigação revelou disparidades distintas nos perfis de emissões dos jatos executivos e comerciais. Esta investigação oferece novas perspetivas sobre os impactos ambientais de diferentes práticas de aviação, abordando explicitamente a lacuna na análise comparativa das emissões entre tipos de jatos no sector da aviação. Ao dissecar as características específicas das emissões de cada tipo de jato, o estudo visa identificar as áreas em que os esforços de redução das emissões podem ser aplicados ou atenuados de forma mais eficaz. Demonstrou-se que a consideração do eCO<sub>2</sub> refletiu que a aviação de negócios está mais próxima da aviação comercial no que respeita ao impacto ambiental total. Além disso, este estudo sublinha a importância de uma investigação setorial diferenciada no contexto mais vasto de mitigação das mudanças climáticas. Estas conclusões melhoram a compreensão da pegada ambiental da aviação.

Nota aos leitores: A análise apresentada neste artigo baseia-se em dados de um projeto (Concerto Working Group) gerido por duas empresas privadas. Embora tenha sido concedida autorização para utilizar os dados agregados, o acesso e publicação ao conjunto completo de dados brutos não foi autorizado.

## Palavras-chave

Emissões da Aviação, CO<sub>2</sub> Equivalente (eCO<sub>2</sub>), Jatos Executivos & Comerciais, Impacto Ambiental e Rastos de Condensação

## **ABSTRACT**

This research aims to explain the differential environmental impacts of executive and commercial aviation by focusing on their equivalent CO<sub>2</sub> (eCO<sub>2</sub>) emissions, thereby addressing a pivotal aspect of aviation's contribution to global warming.

The study adopts a mixed-methods approach, blending primary data from direct emissions measurements with secondary information from existing literature and databases. This comprehensive strategy is designed to accurately quantify and compare the emissions from both executive and commercial jets, leveraging advanced analytical techniques to ensure the reliability and validity of findings.

This research will unveil distinct disparities in executive and commercial jets' emission profiles. Such findings are expected to enhance our understanding of aviation's environmental impact. By dissecting the specific emission characteristics of each jet type, the study aims to pinpoint areas where emission reduction efforts could be most effectively applied or mitigated. This investigation offers novel insights into the environmental impacts of different aviation practices by explicitly addressing the gap in comparative emission analysis between jet types within the aviation sector. It is expected to demonstrate that considering eCO<sub>2</sub> will reflect that business aviation is closer to commercial aviation regarding total environmental impact. Furthermore, this study underscores the importance of nuanced, sector-specific research in the broader context of climate change mitigation.

Note to readers: This paper's analysis is based on data from a project managed by two private companies (Concerto Working Group). While permission was granted to use the aggregated data, access and sharing to the complete raw dataset was not authorized.

## **Keywords**

Aviation Emissions, Equivalent CO<sub>2</sub> (eCO<sub>2</sub>), Executive & Commercial Jets, Environmental Impact and Contrails.

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## **ABBREVIATIONS AND ACRONYMS**

The following abbreviations and acronyms are used throughout this study to facilitate understanding and avoid redundancy:

**CO<sub>2</sub>** – Carbon Dioxide

**eCO<sub>2</sub>** - Equivalent CO<sub>2</sub>

**NO<sub>x</sub>** - Nitrogen Oxides

**SO<sub>x</sub>** - Sulfur Oxides

**GHGs** - Greenhouse Gases

**GWP** - Global Warming Potential

**ICAO** - International Civil Aviation Organization

**EPA** - Environmental Protection Agency

**IPCC** - Intergovernmental Panel on Climate Change

**FAA** - Federal Aviation Administration

**EU ETS** - European Union Emissions Trading Scheme

**NGO** - Non-Governmental Organization

**UNFCCC** - United Nations Framework Convention on Climate Change

**LTO** - Landing and Takeoff Cycle

**OEM** - Original Equipment Manufacturer

**R&D** - Research and Development

**SAR** - Specific Absorption Rate (used in discussions of radiative forcing)

**VOCs** - Volatile Organic Compounds

**CORSIA** - Carbon Offsetting and Reduction Scheme for International Aviation

**SAF** - Sustainable Aviation Fuel

**CLEEN** - Continuous Lower Energy, Emissions, and Noise

**ADS-B** - Automatic Dependent Surveillance-Broadcast

**HEFA** - Hydroprocessed Esters and Fatty Acids

**ATJ** - Alcohol-to-Jet

**GTF** - Geared Turbofan

**CMC** - Ceramic Matrix Composite

**GDPR** - General Data Protection Regulation

**IATA** - International Air Transport Association

**CAAC** - Civil Aviation Administration of China

## DEFINITIONS

**Aviation Emissions** - Refers to the gases and particles released into the atmosphere by aircraft engines during flight operations. These emissions include but are not limited to, carbon dioxide (CO<sub>2</sub>), water vapour, nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), and particulate matter.

**Equivalent CO<sub>2</sub> (eCO<sub>2</sub>)** is a measure that expresses the global warming potential of all the different greenhouse gases and climate-forcing agents associated with aviation emissions in terms of the amount of CO<sub>2</sub> that would have the same warming effect over a specific period. This measure includes CO<sub>2</sub>, NO<sub>x</sub>, water vapour, contrails, and other substances that affect climate.

**Executive Jets** - An aircraft category designed for transporting small groups of people, often used by business executives, high-net-worth individuals, or government officials. These jets are typically smaller than commercial airliners and can operate on routes and airports that are not feasible for larger aircraft.

**Commercial Jets** - Aircraft primarily used by airlines to transport passengers and cargo on scheduled and non-scheduled routes. These more prominent jets usually operate between major airports with established infrastructure.

**Greenhouse Gases (GHGs)** trap heat in the earth's atmosphere, contributing to the greenhouse effect. The significant GHGs associated with aviation include CO<sub>2</sub>, methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O).

**Global Warming Potential (GWP)** is a measure that describes the relative ability of a gas to trap heat in the atmosphere over a specific period, typically 100 years, compared to CO<sub>2</sub>. This concept is crucial for understanding the impact of different gases emitted by aircraft.

**Operational Efficiency** In aviation refers to the effectiveness of fuel and other resources in achieving transportation goals. Factors such as aircraft design, flight route optimisation, and engine performance can affect operational efficiency in aviation.

**Sustainability Practices in Aviation** refer to the strategies and actions undertaken by the aviation industry to minimise its environmental impact. These include using alternative fuels, improving aircraft design and operations, and initiating initiatives to offset emissions.

## **AIRCRAFT TECHNOLOGY TERMS**

### **PROPULSION SYSTEMS**

#### **Turbofan Engine**

- Definition: A type of gas turbine engine widely used in aviation that generates thrust through a combination of bypass air and exhaust gases
- Context: Primary engine type discussed in comparing executive and commercial aircraft efficiency
- Related terms: High-bypass ratio, Core flow

#### **High-bypass Ratio**

- Definition: The ratio of air that bypasses the engine core to the air that passes through it
- Typical values: Modern commercial engines 5:1 to 12:1
- Significance: Higher ratios generally indicate better fuel efficiency

#### **Geared Turbofan (GTF)**

- Definition: Advanced turbofan design incorporating a reduction gearbox between the fan and low-pressure turbine
- Benefits: Improved fuel efficiency, reduced noise, lower emissions
- Application: Latest generation of commercial aircraft engines

### **ENVIRONMENTAL IMPACT METRICS**

#### **EMISSIONS MEASUREMENTS**

##### **eCO<sub>2</sub>**

- Definition: Comprehensive measure of climate impact that includes CO<sub>2</sub> and other climate-forcing effects
- Components: Direct CO<sub>2</sub>, NO<sub>x</sub> effects, contrails, water vapour
- Usage: Primary metric for comparing environmental impact in this study

##### **Radiative Forcing**

- Definition: Change in Earth's energy balance caused by atmospheric constituents
- Units: Watts per square meter (W/m<sup>2</sup>)
- Relevance: Key metric for assessing aviation's climate impact

## **ATMOSPHERIC EFFECTS**

### **Contrails**

- Definition: Condensation trails formed by aircraft exhaust in specific atmospheric conditions
- Formation conditions: Temperature below -40°C, relative humidity >100%
- Impact: Significant contributor to aviation's total climate effect

### **NO<sub>x</sub> (Nitrogen Oxides)**

- Definition: Family of reactive gases formed during combustion
- Environmental effects: Contributes to ozone formation and methane reduction
- Measurement: Usually expressed in NO<sub>2</sub> equivalent

## **REGULATORY FRAMEWORK TERMS**

### **INTERNATIONAL STANDARDS**

#### **CORSIA**

- Definition: Carbon Offsetting and Reduction Scheme for International Aviation
- Purpose: Global market-based measure to control CO<sub>2</sub> emissions from aviation
- Implementation: Phased approach starting with voluntary participation

#### **EU ETS**

- Definition: European Union Emissions Trading System
- Scope: Mandatory carbon trading system for flights within the European Economic Area
- Mechanism: Cap-and-trade system for aviation emissions

## **OPERATIONAL TERMS**

### **FLIGHT PARAMETERS**

## **Cruise Altitude**

- Definition: Primary operational altitude during the central portion of the flight
- Typical ranges:
  - Commercial aircraft: 30,000-40,000 feet
  - Executive jets: 40,000-51,000 feet
- Significance: Affects fuel efficiency and contrail formation

## **Load Factor**

- Definition: Percentage of available passenger capacity utilised
- Calculation:  $(\text{Actual passengers} / \text{Maximum passengers}) \times 100$
- Importance: Key factor in per-passenger emissions calculations

## **PERFORMANCE METRICS**

### **Specific Fuel Consumption**

- Definition: Rate of fuel consumption per unit of thrust
- Units: g/kN-s or lb/lbs-hr
- Application: Key metric for comparing engine efficiency

## **RESEARCH METHODOLOGY TERMS**

### **DATA COLLECTION**

#### **ADS-B (Automatic Dependent Surveillance-Broadcast)**

- Definition: Surveillance technology for tracking aircraft position and performance data
- Usage: Primary data collection method for flight tracking in this study
- Parameters measured: Position, altitude, speed, heading

### **ANALYSIS METHODS**

#### **Statistical Significance**

- Definition: Probability that an observed relationship between variables is not due to chance

- Typical threshold:  $p < 0.05$
- Application: Validation of comparative analyses in the study

## 1. INTRODUCTION

The aviation industry has been identified as a significant contributor to global greenhouse gas emissions, accounting for a substantial portion of the anthropogenic climate impact. Despite improvements in fuel efficiency and efforts to integrate sustainable practices, the sector's overall emissions continue to rise, propelled by increasing air travel demand. Within this context, the study of eCO<sub>2</sub> emissions—which includes CO<sub>2</sub> as well as other greenhouse gases and atmospheric effects such as contrails and nitrogen oxides—is crucial. Executive jets, often used by fewer passengers yet capable of similar ranges as commercial jets, present an interesting case study. The comparative environmental impact of executive versus commercial jets remains underexplored in scientific literature, especially from the eCO<sub>2</sub> emissions per passenger mile perspective. Understanding these differences is vital for developing targeted environmental policies and practices that could mitigate the aviation industry's impact on climate change.

### 1.1. GENERAL INFORMATION

The aviation industry is a critical component of the global economy, facilitating international trade, tourism, and business connectivity. However, its contribution to global greenhouse gas emissions is significant and growing. Aviation is responsible for a notable percentage of the worldwide carbon emissions from fossil fuel use, and this share is expected to increase as air travel continues to grow, despite improvements in aircraft efficiency and operational practices.

eCO<sub>2</sub> emissions are a comprehensive measure that includes CO<sub>2</sub> emissions and other radiative effects such as contrails, water vapour, nitrogen oxides, and changes in atmospheric chemistry, which can also impact climate change. Compared to CO<sub>2</sub> emissions alone, eCO<sub>2</sub> provides a more holistic view of aviation's climate impact, capturing direct and indirect effects on the atmosphere.

Executive Jets: Typically smaller and cater to a niche business or luxury travel market.

They often fly fewer passengers over similar or even more extended distances than commercial jets.

Generally, they have higher flexibility in flight operations and can access smaller airports, reducing travel time and potentially increasing emissions per passenger mile.

Commercial Jets: Operate under tighter regulatory and operational frameworks due to the volume of traffic and economic pressures.

Benefit from economies of scale, often resulting in lower per-passenger emissions than executive jets. They have been the focus of significant environmental efficiency improvements, such as better fuel efficiency and operational practices like optimised flight paths.

Operational efficiencies include fuel consumption, cruising altitudes, and flight frequencies, all contributing to varying eCO<sub>2</sub> output.

Environmental impacts are the broader implications of these operational characteristics on global warming and climate change.

Policy and regulation impacts: How current and future aviation regulations might need to adjust based on findings related to eCO<sub>2</sub> disparities.

Understanding the nuanced differences in eCO<sub>2</sub> emissions between these two types of aviation services is essential for:

- Developing targeted environmental policies that accurately reflect the contributions of different aviation industry segments.
- Guiding industry stakeholders in implementing more effective sustainability strategies.
- Informing the public and policymakers about the actual environmental costs of different types of air travel could potentially influence market behaviour and regulatory frameworks.

## **1.2. SCOPE**

The study is situated within the broader discourse on climate change and sustainability. It addresses the urgent need for reducing greenhouse gas emissions as part of global efforts to mitigate environmental degradation. Aviation significantly contributes to

global CO<sub>2</sub> emissions and, by extension, to climate change, which positions your research at the intersection of industrial activity and environmental policy.

The research focuses on the aviation sector, a primary facilitator of global connectivity with substantial environmental impacts. This sector is transitioning towards sustainability, influenced by technological advancements, regulatory changes, and shifts in consumer behaviour towards greener alternatives.

Specifically, the study zeroes in on eCO<sub>2</sub> emissions—encompassing both CO<sub>2</sub> and other contributing emissions like water vapour, soot, and nitrogen oxides—which have different but interrelated impacts on the climate. The focus on eCO<sub>2</sub> provides a more comprehensive understanding of the aviation industry's full climatic impact beyond just CO<sub>2</sub>.

By comparing executive and commercial jets, the study explores a specific niche within the aviation sector that has yet to be thoroughly examined in previous research. This comparison is crucial for understanding how different operational models within the same industry can have varied environmental outcomes.

While the study adopts a global perspective appropriate to aviation's international nature, it may also delve into specific regional case studies where data availability and regional significance provide deeper insights. For instance, examining emissions within regions like the EU or North America, where regulatory environments are particularly stringent and data are robust, could offer valuable insights.

The research considers varying operational conditions, such as altitude, flight routes, and airport operations, which can differ markedly across territorial contexts and affect flights' environmental impact.

The sectoral focus is on two types of aviation services—commercial (large-scale passenger carriers) and executive (smaller, often luxury-focused services). These segments are analysed to understand their contributions to eCO<sub>2</sub> emissions and how sector-specific practices influence overall emission profiles.

The study will be grounded in academic theories related to environmental science and aviation technology, as well as industry reports and datasets that provide current and

historical data on aviation emissions. This dual-reference system ensures that the research is theoretically sound and practically relevant.

It will be crucial to reference current and emerging policies affecting aviation emissions, such as those by the International Civil Aviation Organization (ICAO) and national regulations. These references will help contextualise the findings within the ongoing legislative developments aimed at reducing aviation's environmental impact.

### **1.3. MOTIVATION**

The motivation to study the environmental impact of eCO<sub>2</sub> emissions from executive and commercial jets stems from a broader concern about the aviation industry's significant role in global greenhouse gas emissions. Despite increasing attention to the environmental sustainability of air travel, the specific contributions of different sectors within the aviation industry, particularly executive versus commercial aviation, still need to be explored. This gap is critical because executive jets, often perceived as less efficient due to lower passenger numbers relative to the resources used, operate under different regulatory and operational paradigms than commercial jets.

Current research predominantly focuses on commercial aviation emissions, mainly overlooking the specific impacts of executive jets. This oversight persists despite the growing use of executive jets in global business and personal travel, which suggests a significant potential impact on environmental sustainability. Moreover, while there is extensive literature on CO<sub>2</sub> emissions, the broader concept of eCO<sub>2</sub>—which includes additional climate-forcing agents like contrails and nitrogen oxides—is less frequently analysed within the specific context of different jet types. This gap hinders the development of comprehensive and effective environmental policies tailored to the distinct characteristics of these aviation sectors.

This study aims to bridge this gap by providing a detailed comparative analysis of eCO<sub>2</sub> emissions from executive and commercial jets. The research will utilise a comprehensive framework to assess and compare the environmental impacts of these two jet types, thereby contributing to a more nuanced understanding of the aviation industry's overall role in global emissions. This approach is intended to inform policy and regulatory frameworks and influence operational practices within the industry.

Based on a thorough review of the state of the art, which highlights divergent views on the environmental impact of different types of aviation, this research will develop a unique perspective on the subject. While some authors argue that executive jets are disproportionately harmful given their lower passenger-to-emission ratio, others suggest their impact might be comparable when analysing eCO<sub>2</sub> emissions more holistically. By critically engaging with these viewpoints, this study will construct an informed opinion that executive and commercial jets may have closer eCO<sub>2</sub> emissions profiles than previously documented, challenging prevailing assumptions and contributing new insights into the discussion of aviation and environmental sustainability.

The study will also examine how organisational models and paradigms within the aviation industry, such as operational efficiency, technological adoption, and regulatory compliance, influence eCO<sub>2</sub> emissions. This investigation will highlight the complex interplay between industry practices and environmental outcomes, providing a grounded understanding of how different organisational approaches to sustainability can lead to varied ecological impacts.

## **1.4. OBJECT AND OBJECTIVES**

### **1.4.1. INVESTIGATION QUESTION**

This research centres on understanding the comparative environmental impact of executive jets versus commercial aircraft through the lens of eCO<sub>2</sub> emissions. The primary research question that guides this investigation is: "How do the eCO<sub>2</sub> emissions profiles of executive jets compare to commercial aircraft when accounting for both direct emissions and contrail effects on flights of similar distance?"

Two additional questions emerge as critical to understanding the full scope of the environmental impact and supporting this central inquiry: First, we seek to understand the relative contribution of contrails to total eCO<sub>2</sub> emissions in both executive jets and commercial aircraft. Second, we aim to examine how operational characteristics, including altitude selection, route planning, and passenger load factors, influence the eCO<sub>2</sub> emissions profile of each aircraft type.

#### 1.4.2. HYPOTHESES

The research puts forward two main hypotheses. The first hypothesis posits that executive jets produce a lower absolute volume of contrail-related eCO<sub>2</sub> emissions than commercial aircraft on similar-distance routes, which may partially offset their higher per-passenger CO<sub>2</sub> emissions. This hypothesis stems from preliminary observations of operational patterns and aircraft characteristics.

The second hypothesis suggests that the proportion of contrail-related effects in total eCO<sub>2</sub> emissions differs significantly between business and commercial aircraft. This difference is expected to arise from variations in typical operating altitudes and flight patterns between the two aircraft categories.

- **Hypothesis 1:** "Executive jets emit a comparable amount of eCO<sub>2</sub> per passenger mile as commercial jets, challenging the current perceptions of their environmental impact."
- **Hypothesis 2:** "The proportion of non-CO<sub>2</sub> effects (e.g., contrails) in total eCO<sub>2</sub> emissions differs significantly between executive and commercial jets."

#### 1.4.3. OBJECTIVE

The primary objective of this research is to conduct a comprehensive quantitative comparison of eCO<sub>2</sub> emissions profiles between executive jets and commercial aircraft, with particular attention to contrail effects. This analysis aims to provide evidence-based insights that can inform the aviation sector's environmental policy and operational decisions. Through this objective, the study seeks to bridge the current knowledge gap regarding the comparative environmental impact of these two distinct aviation segments.

#### 1.4.4. SPECIFIC OBJECTIVES

The research pursues several specific objectives to support its primary goal. First, it aims to measure and analyse absolute and per-passenger eCO<sub>2</sub> emissions for both aircraft types on comparable routes, establishing a foundation for meaningful comparison. Secondly, the study seeks to determine the specific contribution of contrails to total eCO<sub>2</sub> emissions for each aircraft type, addressing a critical gap in current understanding.

The research also aims to evaluate how operational factors affect eCO<sub>2</sub> emissions in both aircraft types, including the influence of altitude selection, route planning, and passenger load factors. The study will analyse the relative environmental efficiency of executive jets versus commercial aircraft through a comprehensive comparative assessment when accounting for all eCO<sub>2</sub> components. Finally, the research seeks to develop evidence-based recommendations for aviation environmental policy based on these comparative analyses.

- **Operational Efficiency:** Investigate the efficiency differences between executive and commercial jets, including fuel consumption and emission rates.
- **Environmental Impact Assessment:** Assess how these operational disparities translate into long-term ecological impacts.
- **Influential Factors Evaluation:** Identify key operational inputs from an ecological perspective that can influence eCO<sub>2</sub> values.
- **Main factors within eCO<sub>2</sub>:** Demonstrate the amount of eCO<sub>2</sub> attributed to contrails.
- **Influential Factors Where Contrails Form:** Identify at which altitudes contrails occur in the atmosphere.
- **Comparative Flight Pattern Study:** Compare the flight routes and flight altitudes of executive and commercial jets.
- **Comparative Sustainability Study:** Compare executive and commercial jets' environmental sustainability and eCO<sub>2</sub> efficiency.
- **Forecasting Methodology Review:** This paper examines the current forecasting methods for eCO<sub>2</sub> emissions in aviation, focusing on their accuracy and reliability.

#### 1.4.5. EXPECTED RESULTS

The research anticipates generating several significant outcomes. Primarily, it will produce a detailed quantitative comparison of eCO<sub>2</sub> emissions profiles between executive jets and commercial aircraft, providing clear evidence regarding the relative

contribution of contrails to total eCO<sub>2</sub> emissions for each aircraft type. The study expects to identify and document critical operational factors influencing eCO<sub>2</sub> emissions in both aviation segments, leading to evidence-based environmental policy and operational practice recommendations.

Through these results, the study aims to provide aviation industry stakeholders with concrete data and analysis to support decision-making regarding environmental impact mitigation strategies. The findings are expected to contribute significantly to the ongoing discussion about aviation's role in climate change and the relative environmental impacts of different aviation segments.

## 1.5. METHODOLOGY

### 1.5.1. METHODOLOGICAL APPROACH

The methodology of this study adopts a **hypothetical-deductive approach**. This approach starts with a hypothesis study based on existing theories and literature and tests this hypothesis study through empirical research. It is particularly suitable for your study as it allows for testing specific predictions about the comparative eCO<sub>2</sub> emissions of executive and commercial jets, providing a rigorous framework for validation or refutation.

### 1.5.2. TYPE OF ANALYSIS

- **Quantitative Analysis:** The core of the study will be quantitative, focusing on collecting and analysing numerical data related to fuel consumption, operational efficiencies, and eCO<sub>2</sub> emissions from a wide range of executive and commercial jets. This analysis will help quantify differences and draw statistically significant conclusions about the emissions profiles of the two jet types.
- **Qualitative Analysis:** This study complements the quantitative data. Qualitative analysis will examine policy documents, industry reports, and expert opinions that provide context and insight into the aviation sector's operational practices and environmental strategies.

Data Collection Methods: The research will integrate multiple data collection methods to ensure a comprehensive analysis:

- **Documentary Analysis**, Examining existing research studies, environmental reports from aviation authorities, and airline sustainability reports. Thus, this will provide a foundation of current knowledge and data on eCO2 emissions.
- **Surveys**: Where necessary, surveys may be conducted with industry experts to gather insights on current practices and opinions on eCO2 mitigation strategies. Thus, this can help validate data and provide contemporary industry perspectives.
- **Observation**: While direct observation of operational practices is less feasible, data from flight tracking and monitoring services will be used as a form of indirect observation to assess flight patterns, operational altitudes, and other factors that influence emissions.

### 1.5.3. DATA ANALYSIS TECHNIQUES

- **Statistical Analysis**: Utilizing software such as SPSS or R for statistical testing to compare eCO2 emissions data across different types of jets and to analyse the relationship between operational practices and emissions outcomes.
- **Content Analysis**: For qualitative data, content analysis will interpret and quantify information from policy documents and interviews, identifying prevailing themes and trends.
- **Ethical Considerations**: All research will adhere to ethical guidelines, ensuring the confidentiality and anonymity of any respondents involved in surveys or interviews. Additionally, secondary data will be used responsibly with proper citations and respect for data privacy regulations.
- **Limitations**: The methodology section should also briefly acknowledge any potential limitations of the chosen methods, such as biases in secondary data sources, the availability of up-to-date emissions data, or the generalizability of findings across different regions or types of aviation operations.

## 1.6. WORK STRUCTURE

This dissertation is organised into five main chapters. The themes and organisation of these chapters can be summarised as follows:

## **Chapter 1: Introduction**

- **Context and Scope:** This paper introduces the global importance of addressing aviation emissions within the context of climate change. It also provides an overview of the focus on eCO<sub>2</sub> emissions from executive and commercial jets, emphasising why this niche is critical.
- **Problem Statement:** Detailed presentation of the problem this research intends to address, including the gaps in current research concerning eCO<sub>2</sub> emissions from different types of jets.
- **Objectives:** List the general and specific goals that guide the research, clearly stating what the study aims to achieve.
- **Research Approach:** Explanation of the hypothetical-deductive approach adopted, including how it suits the nature of the investigated problem.
- **Organisation of the Study:** Summary of each chapter's purpose and contents, guiding the reader on what to expect throughout the dissertation.

## **Chapter 2: Literature Review**

- **Scope of Review:** Extensive review of current and relevant literature, focusing on studies of aviation emissions, particularly those related to CO<sub>2</sub> and eCO<sub>2</sub>.
- Discuss different views regarding the environmental impact of executive vs. commercial jets, examining how these perspectives inform current policies and practices.
- **Themes:** Thematic analysis of past studies, categorised into emission measurement techniques, comparative analyses of jet types, and the effectiveness of existing emission reduction strategies. Identification of research gaps that the current study aims to fill.

## **Chapter 3: Methodology**

- **Research Design:** Description of the research design and rationale for the chosen methodology, including any case studies.

- **Data Collection:** Detailed explanation of data collection methods, such as surveys, documentary analysis, and data mining from existing emission reports and databases.
- **Data Analysis:** Outline of the analytical techniques to be used for both quantitative and qualitative data.
- **Ethical Considerations:** Discuss how the study adheres to ethical standards in research.

#### **Chapter 4: Results**

- **Presentation of Findings:** Detailed data analysis results, focusing on eCO<sub>2</sub> emissions comparisons between executive and commercial jets.
- **Discussion:** Interpretation of the findings in the context of the literature reviewed in Chapter 2. Examination of the implications of these findings for the aviation industry's sustainability practices and policies.

#### **Chapters 5 & 6: Discussion, Conclusions and Future Work**

- **Summary of Findings:** Concise recapitulation of the research findings and how they address the original research objectives and problem statement.
- **Conclusions:** In-depth discussion of the conclusions drawn from the research, emphasising the contributions to the existing body of knowledge and the implications for future policy.
- **Limitations and Future Research:** Acknowledge the study's limitations and provide suggestions for future research areas that can further explore and build upon the findings of this study.

### **1.7. THEORETICAL FRAMEWORK**

#### **1.7.1. FOUNDATIONAL THEORIES**

The theoretical foundation of this research rests on three interconnected theories: Environmental Impact Assessment Theory, Aviation Operations Theory, and Climate Change Theory. These theories collectively provide a framework for understanding how

aircraft emissions affect climate systems and how operational decisions influence environmental outcomes.

Environmental Impact Assessment Theory provides the foundation for understanding how aviation activities create measurable ecological impacts. This theory emphasises the importance of considering direct and indirect effects, particularly when examining the complex relationship between aircraft operations and atmospheric changes.

### **1.7.2. CONCEPTUAL FRAMEWORK**

The conceptual framework integrates these theories to explain the relationship between aviation operations and environmental impacts. This integration considers:

#### **1. Operational Factors**

- Flight patterns and altitudes
- Aircraft type and technology
- Operational efficiency measures

#### **2. Environmental Impact Mechanisms**

- Direct emissions (CO<sub>2</sub>, NO<sub>x</sub>)
- Indirect effects (contrails, atmospheric chemistry)
- Cumulative environmental impacts

#### **3. Assessment Metrics**

- Emission measurement methodologies
- Impact quantification approaches
- Performance indicators

## **2. LITERATURE REVIEW**

Chapter 2 is about the literature review on the Operational Efficiency of Executive and Commercial Jets.

The operational efficiency of aircraft, particularly in fuel consumption and emission rates, is a critical area of study in the aviation industry. This review compares these parameters between the executive and commercial jets, drawing insights from various studies to highlight differences and potential areas for efficiency improvements.

### **2.1. FUEL CONSUMPTION AND EFFICIENCY TRENDS**

Commercial jets have been the subject of extensive studies regarding fuel efficiency. A significant report by the International Council on Clean Transportation (ICCT) analysed trends in new aircraft fuel efficiency from 1960 to 2014, revealing that fuel efficiency approximately doubled over this period (Kharina and Rutherford, 2015). The study highlighted fluctuations in the rate of improvement, with notable stagnation during the 1970s and 2000s. This slowdown was attributed to a need for new, more efficient aircraft types and the increasing prevalence of regional jets, which are generally less fuel-efficient (Kharina and Rutherford, 2015).

Often used for business travel, executive jets typically have different operational profiles than commercial jets. Because smaller dimensions characterise them, executive jets may not achieve equivalent technological advancement benefits as their commercial counterparts. The literature specific to the fuel efficiency of executive jets is less abundant. Still, it is generally understood that these jets operate with less passenger capacity, potentially leading to higher fuel consumption per passenger mile when compared to larger commercial jets.

#### **2.1.1. INTEGRATED ANALYSIS OF AVIATION EFFICIENCY AND ENVIRONMENTAL IMPACT**

Aviation efficiency encompasses operational and environmental dimensions, with fuel consumption as a critical link. Research indicates that improvements in fuel efficiency have averaged 1.5% annually since the 1960s (Kharina and Rutherford, 2015), driven by both technological advancements and operational optimisations.

The relationship between fuel efficiency and environmental impact manifests through multiple pathways. Direct emissions correlate strongly with fuel consumption, while indirect effects such as contrail formation depend on fuel characteristics and operational factors. Studies (Wilson et al, 2023) demonstrate that modern aircraft achieve 70% better fuel efficiency compared to early jet aircraft, though this improvement curve has begun to flatten in recent years. As shown in Figure 1, the relative CO<sub>2</sub> emissions of various fuels highlight the significant potential of alternative fuels in reducing aviation’s environmental footprint.

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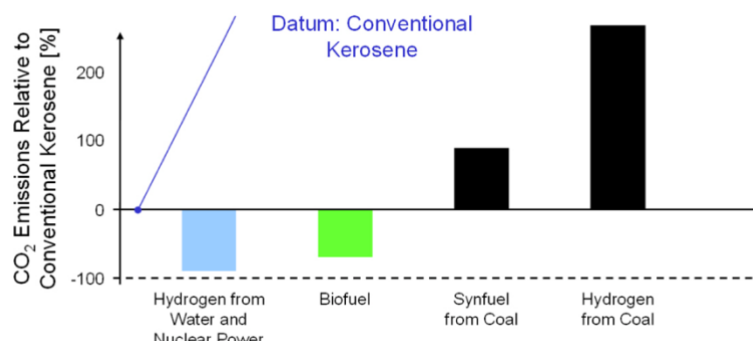


Figure 1: Relative CO<sub>2</sub> Emission of Different Fuels.

Source: (IATA, 2008)

### 2.1.2. EMISSION RATES

Commercial jets contribute significantly to global CO<sub>2</sub> emissions, with the aviation sector accounting for approximately 2.5% of global CO<sub>2</sub> emissions (Barbosa, 2024). Efforts to reduce these emissions include exploring alternative fuels such as hydrogen, which promises zero carbon emissions and is suitable for short to medium-haul flights (Barbosa, 2024). Adopting such technologies is crucial for reducing the environmental impact of commercial aviation.

Executive jet emission rates are not often separately categorized in environmental impact studies; however, due to their smaller size and less frequent usage than commercial jets, their total contribution to global emissions is inferred to be less.

### 2.1.3. COMPARATIVE STUDIES AND TECHNOLOGICAL ADVANCEMENTS

A comparative study of hydrogen and kerosene-fuelled commercial aircraft highlighted the potential for significant emission reductions with advanced propulsion technologies (Karpuk and Elham, 2022).

While this study focused on commercial aviation, the findings are relevant for executive jets, suggesting that incorporating advanced technologies could similarly benefit these smaller aircraft in achieving better environmental performance (Karpuk and Elham, 2022a).

### 2.1.4. OPERATIONAL ASPECTS AND EFFICIENCY

Operational efficiency in aviation depends on the aircraft's fuel consumption emissions and operational practices. Studies have shown that optimising flight parameters can significantly reduce noise and fuel consumption during takeoffs and landings (Khardi and Houacine, 2014). Such operational efficiencies are crucial for both executive and commercial jets, although the specific strategies may differ due to the different flight profiles and frequencies.

### 2.1.5. OPERATIONAL EFFICIENCY OF EXECUTIVE AND COMMERCIAL JETS

The environmental impacts of operational disparities between executive and commercial jets can be assessed through various dimensions, including carbon emissions, air quality, and the broader ecological footprint. These disparities often stem from differences in flight operations, aircraft technologies, and regulatory frameworks.

## 2.2. CARBON EMISSIONS AND AIR QUALITY

Executive jets, typically used for business aviation, differ significantly from commercial jets regarding flight frequency, routes, and passenger load. These factors directly influence their environmental impact, particularly in terms of carbon emissions and air quality (Garibay and Young, 2013):

- **Flight Frequency and Routes:** Executive jets often fly shorter routes and may operate more frequently with fewer passengers than commercial jets. Thus, this leads to higher per-passenger emissions because the carbon footprint could be more effectively distributed across many passengers. Moreover, executive jets

might also have more frequent take-offs and landings, which are high in fuel consumption, further increasing their carbon emissions.

- **Aircraft Technology:** Typically, executive jets use smaller aircraft that may only sometimes incorporate the latest fuel-efficient technologies that are increasingly common in newer commercial airliners. While commercial jets benefit from economies of scale that justify the investment in more efficient technologies, the smaller scale of executive fleets might delay such upgrades.
  - **Regulatory Frameworks:** Commercial aviation is often subject to stricter environmental regulations than private or executive aviation. These include regulations on emissions and requirements for using newer, more efficient aircraft. Less stringent regulations for executive jets can result in higher per-mile emissions than commercial jets (Garibay and Young, 2013).
- Broader Ecological Footprint

The ecological footprint of executive jets extends beyond carbon emissions and air quality, encompassing noise pollution, land use for infrastructure, and biodiversity impacts.

- **Noise Pollution:** Executive jets contribute significantly to noise pollution, especially around smaller or private airports near residential areas. The frequent take-offs and landings, typical of executive travel, exacerbate this issue (Garibay and Young, 2013).
- **Land Use:** Executive aviation requires infrastructure such as private terminals and maintenance facilities, which consume land and contribute to habitat disruption and fragmentation. Thus, this is particularly impactful near urban airports where space is at a premium (Garibay and Young, 2013).
- **Biodiversity:** Airports supporting executive jets are often near or within sensitive ecological zones. The operations of these jets can potentially disturb local wildlife and ecosystems, primarily through noise, pollution, and physical infrastructure (Garibay and Young, 2013).

### 2.2.1. MITIGATION STRATEGIES

Several strategies can be employed to reduce the environmental impact of executive jets:

- **Technological Upgrades:** Encouraging the adoption of newer, more efficient aircraft technologies in executive jets can reduce their carbon footprint and improve air quality.
- **Regulatory Adjustments:** Implementing stricter environmental regulations for executive aviation, similar to those for commercial airlines, could incentivise reductions in emissions and noise pollution (Garibay and Young, 2013).
- **Operational Changes:** Altering flight operations to increase passenger load, optimise routes, and reduce unnecessary flights could significantly decrease the per-passenger environmental impact of executive jets (Garibay and Young, 2013).

### 2.3. INFLUENTIAL FACTORS EVALUATION

The aviation industry is a significant contributor to global carbon emissions, and as such, there is a growing need to understand and mitigate its environmental impact. This literature review identifies critical operational inputs from an ecological perspective that can influence aviation's eCO<sub>2</sub> values. The eCO<sub>2</sub> values measure the greenhouse gases emitted by an activity, expressed in the amount of CO<sub>2</sub> that would cause the same amount of global warming. In aviation, this encompasses a range of factors, from fuel types and consumption to operational efficiencies and technological advancements.

#### 2.3.1. FUEL SUPPLY AND SUSTAINABILITY

One of the primary operational inputs influencing eCO<sub>2</sub> values in aviation is the type and supply of fuel used. The study by (Gorbunov et al. , 2023) highlights the importance of aviation fuel supply, particularly in remote Arctic regions, where fuel delivery logistics can impact fuel quality and emissions. The paper underscores the need for optimal logistics to preserve fuel properties directly affecting eCO<sub>2</sub> values.

Markatos and Pantelakis's, 2022 research further expands on the impact of material selection and the viability of sustainable aviation fuel (SAF) on aviation sustainability.

These studies introduce decision support tools and life cycle assessments to evaluate alternative fuels' ecological and economic implications compared to conventional fossil kerosene. The findings suggest that while SAF can reduce environmental impacts, significant reductions are contingent upon renewable energy-based electricity mixes.

### **2.3.2. TECHNOLOGICAL INNOVATIONS**

Technological advancements in aircraft design and operations also play a crucial role in influencing eCO<sub>2</sub> values. As discussed in (Wilson et al., 2023), introducing electric-powered aircraft presents a potential reduction in carbon emissions for pilot training in collegiate aviation settings. The paper evaluates the feasibility of electric aircraft by examining flight hour distributions and regulatory requirements, suggesting that specific flight courses could be suitable for electric flight, thereby reducing eCO<sub>2</sub> values.

### **2.3.3. OPERATIONAL EFFICIENCY**

Operational efficiency is another crucial factor in determining eCO<sub>2</sub> values. The study by (Liu, Luo, and Guo, 2024) presents a model for predicting civil aviation passenger traffic. This model can help airlines optimise resources and flight schedules, improving operational efficiency and potentially lowering eCO<sub>2</sub> emissions.

### **2.3.4. HUMAN FACTORS AND TALENT CULTIVATION**

Human factors, including talent cultivation within the aviation industry, can indirectly influence eCO<sub>2</sub> values by promoting better operational practices and safety. The competency framework developed for aviation psychologists and human factors specialists, as reported in (Biede et al., 2023), emphasises the importance of domain knowledge and methodological approaches that can contribute to safer and more efficient aviation operations.

### **2.3.5. ECOLOGICAL TRANSLATION AND MULTICULTURAL LITERACY**

The strategy for cultivating civil aviation English translation talents, incorporates ecological translation aesthetics and multicultural literacy. This approach can enhance the accuracy of civil aviation terminology translation, essential for international

collaboration on ecological issues and for implementing global environmental standards in aviation.

## **2.4. MAIN FACTORS WITHIN eCO<sub>2</sub>**

This literature review aims to examine the main factors within elevated atmospheric CO<sub>2</sub> levels, with a specific focus on the contribution of contrails to eCO<sub>2</sub>. Contrails, or condensation trails, are line-shaped clouds produced by aircraft engine exhaust and are composed of water vapour that condenses and freezes into ice crystals. The literature spans from 1990 to 2022, and the selected studies provide insights into contrails' environmental impact, formation, and contribution to climate change, particularly regarding their radiative forcing and carbon footprint.

### **2.4.1. CONTRAILS AND CLIMATE CHANGE**

Contrails are recognised as a significant factor in aviation-induced climate impact due to their radiative forcing effects, Figure 1. Radiative forcing refers to the change in the energy balance of the Earth's atmosphere because of factors such as greenhouse gases and cloud cover. Contrails contribute to both warming and cooling effects: they trap outgoing longwave radiation, leading to warming, and reflect incoming solar radiation, leading to cooling. However, the net effect of contrails is generally warming, primarily due to their trapping of longwave radiation (Hoffman et al., 2023, Narciso and Melo de Sousa, 2021).

Figure 2 demonstrates how aviation emissions, including cloudiness, contribute to radiative forcing, emphasizing the layered climatic impact of the industry. As visualized in Figure 3, studying contrails provides valuable insights into their contribution to atmospheric warming through radiative forcing.

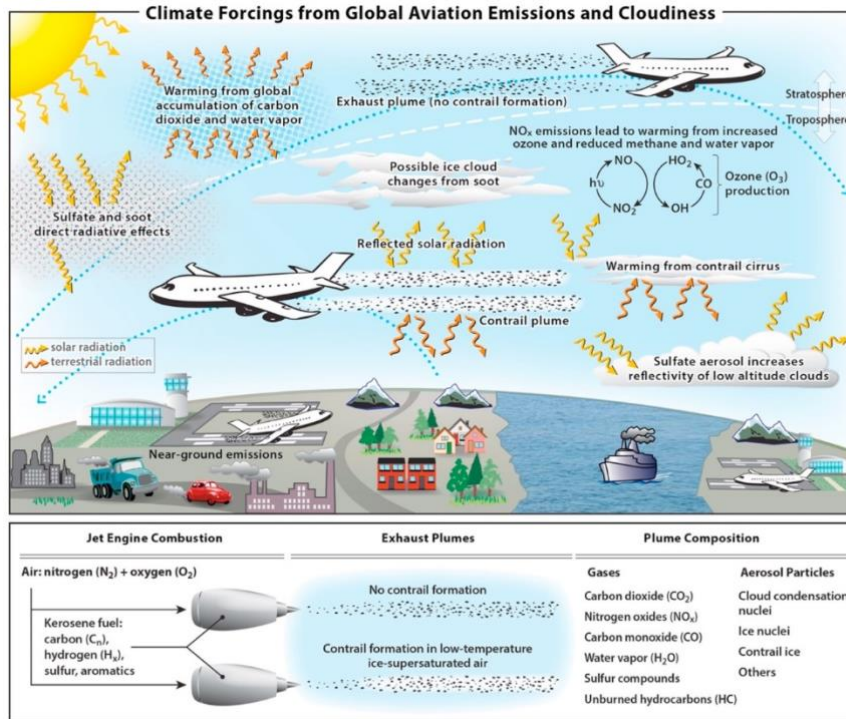
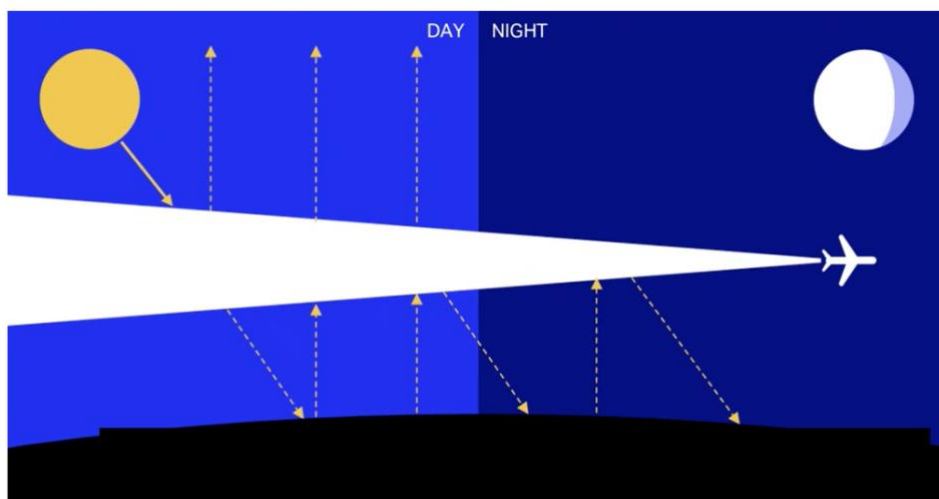


Figure 2: Climate Forcing from Global Aviation Emissions and Cloudiness

Source: (Lee et al., 2021)



During daylight it traps and reflects heat.  
During the night it only traps heat

Figure 3: "STUDY of Contrails is MOST INSTRUCTIVE"

Source: (Sandy Murdock, IATA, 2024) June 4, 2024

## 2.4.2. QUANTIFYING THE CONTRIBUTION OF CONTRAILS TO eCO<sub>2</sub>

Radiative Forcing and eCO<sub>2</sub> allow quantifying the exact amount of eCO<sub>2</sub> attributed to contrails, which is complex due to the transient nature of these clouds and the variability in atmospheric conditions. However, studies have modelled the CO<sub>2</sub> and non-CO<sub>2</sub> effects, including contrail formation, to analyse aviation's total warming footprint. It is estimated that aviation contributes approximately 4% to observed human-induced global warming, with contrails and other non-CO<sub>2</sub> effects playing a significant role (Klöwer et al, 2021).

The trends shown in Figure 4 capture the effective radiative forcing terms for aviation from 1940 to 2018, underlining the growing impact of non-CO<sub>2</sub> emissions over time. Figure 5 highlights the climate impact of air travel, reflecting the cumulative effects of fuel consumption, emissions, and contrail formation.

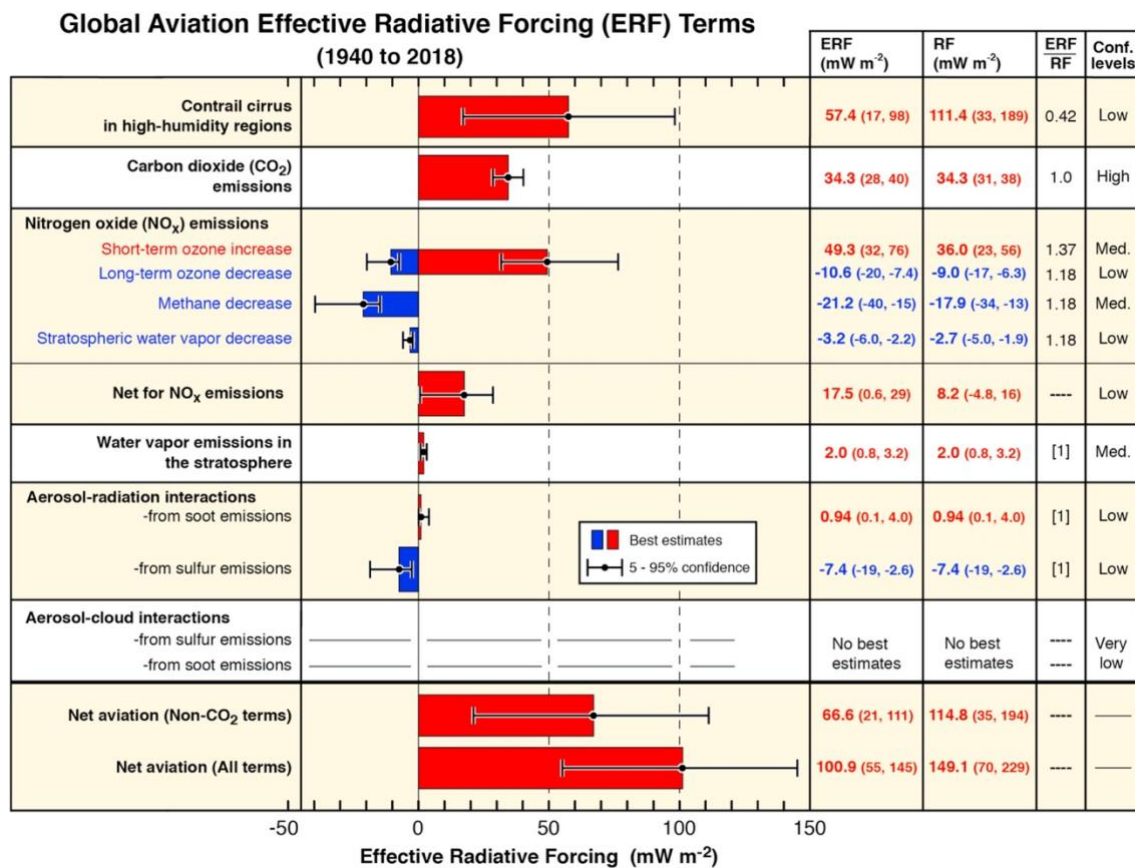


Figure 4: Global Aviation Effective Radiative Forcing (ERF) Terms from 1940 to 2018

Source: (Lee et al., 2021)

### **2.4.3. IMPACT OF AVIATION FUELS ON CONTRAIL FORMATION**

Sustainable Aviation Fuel (SAF) has been associated with reducing soot particle emissions, which can decrease the initial number of ice crystals in contrails. Therefore, this, in turn, affects contrails' optical depth and lifespan, potentially mitigating their impact on global warming (Narciso and Melo de Sousa 2021). The influence of SAF on contrail properties suggests that fuel composition is critical in determining the extent of contrails' contribution to eCO<sub>2</sub>.

Advancements in the detection of contrails using convolutional neural networks (CNNs) have improved the ability to monitor their formation and assess their impact on climate change. Accurate detection is essential for estimating contrails' coverage and radiative effects, contributing to the overall eCO<sub>2</sub> levels (Hoffman et al., 2023).

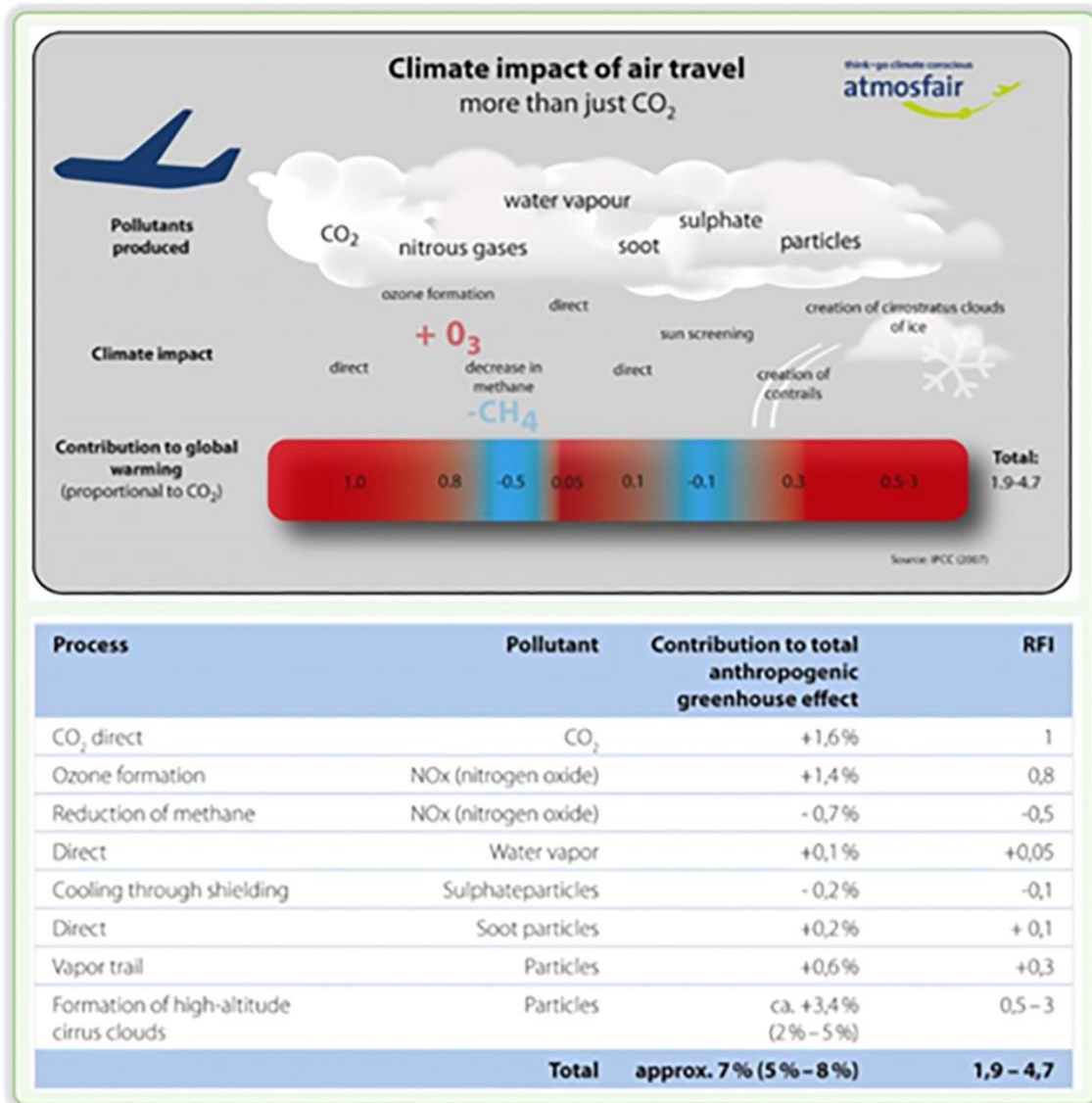


Figure 5: Climate impact of air travel.

Source: (Forging a sustainable sky: Unveiling the pillars of aviation e-fuel production for carbon emission circularity, Ozkan, Mihrimah et al.,2024)

#### 2.4.4. TEMPORAL FACTORS IN BUILDING DESIGN

The Eco2 framework in building design, which incorporates environmental and economic life cycle assessments, highlights the influence of temporal parameters on decision-making processes. While not directly measuring eCO<sub>2</sub> from contrails, this approach underscores the importance of considering long-term environmental impacts in various sectors, including the built environment (Schneider-Marín and Lang 2022).

The COVID-19 pandemic led to significant reductions in air traffic, providing a unique opportunity to study the effects of decreased contrail formation on climate. During the

slowdown, contrail coverage decreased substantially, which resulted in smaller radiative forcings. This temporary reduction in air traffic and the associated decrease in contrail formation offer insights into the potential for mitigating contrails' contribution to eCO<sub>2</sub> (Duda et al., 2023).

## 2.5. INFLUENTIAL FACTORS WHERE CONTRAILS FORM: ALTITUDES OF CONTRAIL OCCURRENCE

Contrails, or condensation trails, are clouds formed when water vapour from aircraft exhaust condenses and freezes in the atmosphere. The formation of contrails is influenced by several atmospheric conditions, including altitude, which plays a crucial role in their occurrence. Based on recent scholarly research, this literature review identifies the specific altitudes at which contrails typically form.

### 2.5.1. ALTITUDE RANGE FOR CONTRAIL FORMATION

The altitude range for contrail formation is subjected to the following:

- **General Altitude Range:** Contrails commonly form at the cruising altitudes of commercial aircraft, which typically range from 25,000 to 40,000 feet (approximately 7.6 to 12.2 kilometres)(Agarwal et al. 2022)(Irvine, Hoskins, and Shine 2012). This altitude range coincides with the part of the atmosphere where the temperature and humidity conditions are favourable for the water vapour in aircraft exhaust to condense and freeze.
- **Specific Pressure Altitudes:** Research has shown that contrail formation is particularly prevalent between 200 and 300 hPa, which corresponds to altitudes of about 36,000 to 39,000 feet (approximately 11 to 12 kilometres (Irvine, Hoskins and Shine, 2012). This range is significant as it aligns with the typical cruising altitudes for long-haul international flights, especially over regions like the North Atlantic, where air traffic is dense.
- **Variability with Weather Patterns and Geographic Location:** The altitude at which contrails form can vary depending on large-scale weather patterns and geographic location. For instance, studies have noted that the frequency of ice-supersaturated regions, which are conducive to contrail formation, is highest

near 300 hPa and decreases with altitude (Irvine, Hoskins and Shine, 2012). This variability is influenced by jet streams and high-pressure ridges, which can alter the atmospheric conditions at different altitudes.

- **Impact of Flight Altitude Changes:** Adjustments in flight altitudes have been studied as a strategy to mitigate the climate impact of contrails. For example, simulations have shown that small changes in aircraft cruising altitudes can significantly reduce contrail formation, suggesting that slight deviations from the typical contrail-forming altitude range can influence their occurrence (Irvine, Hoskins, and Shine 2012).

Figure 6 illustrates contrails detected by GOES-16, showcasing their varying altitudes and the atmospheric conditions that influence their formation.

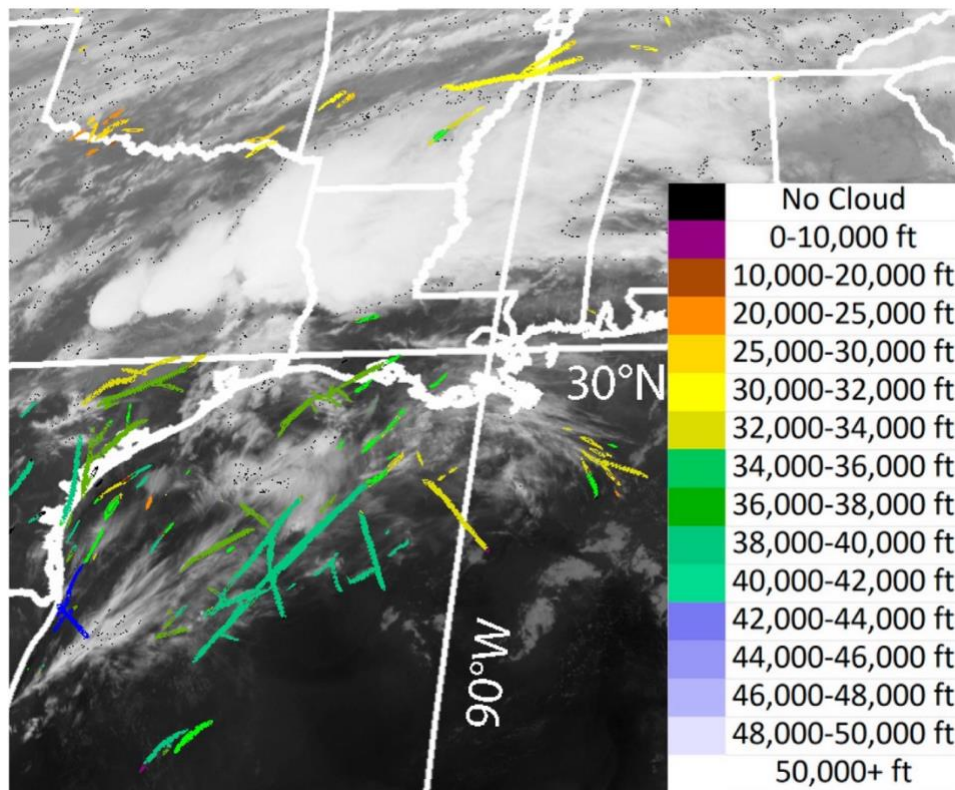


Figure 6: Example image of contrails detected by GOES-16 on March 10, 2023 at 0420 UTC. Contrail detections are colour-coded by height and overlaid on an 11  $\mu$ m brightness temperature image.

Source: (Hoffman, Jay P., Timothy F. Rahmes, Anthony J. Wimmers, and Wayne F. Feltz.

2023. "The Application of a Convolutional Neural Network for the Detection of Contrails in Satellite Imagery" Remote Sensing 15, no. 11: 2854.

<https://doi.org/10.3390/rs15112854>)

## **2.6. COMPARATIVE ANALYSIS OF FLIGHT ROUTES AND ALTITUDES: EXECUTIVE VS. COMMERCIAL JETS**

### **2.6.1. FLIGHT ROUTES**

Executive jets, primarily serving business travellers, offer significant flexibility in their flight routes. These jets frequently utilize point-to-point routing, bypassing the traditional hub-and-spoke system prevalent in commercial aviation. This direct routing capability allows executive jets to minimize travel time and avoid layovers, providing a faster and more efficient journey for passengers who can afford the higher cost associated with this convenience (Nehrbass et al., 2004). Additionally, executive jets have access to many smaller airports, enhancing their ability to offer more direct routes. In contrast, commercial jets typically operate within a hub-and-spoke network, routing passengers through central hub airports before reaching their final destinations. This system can often result in longer travel times due to the necessity of connecting flights. Commercial jets are generally restricted to larger airports that can accommodate the size and volume of the aircraft and passenger traffic, which limits their flexibility in route selection compared to executive jets(Nehrbass et al. 2004).

### **2.6.2. FLIGHT ALTITUDES**

The cruising altitudes of executive jets can vary more widely than those of commercial jets. Executive jets can fly at higher altitudes, avoiding some air traffic and potentially experiencing less turbulence in certain atmospheric conditions. This capability can make flight smoother and quicker (Amin and Alam, 2015).

Commercial jets typically cruise at altitudes ranging from 30,000 to 40,000 feet. These altitudes are optimized for fuel efficiency and are often dictated by air traffic control to manage the flow of numerous aircraft along busy travel corridors (Kärcher, Hirschberg, and Fabian, 1996). Commercial jets follow predetermined airways designed to maximize safety and efficiency for many passengers.

### 2.6.3. DETAILED CASE STUDIES OF EXECUTIVE JETS

#### **Gulfstream G700**

**Introduction:** The Gulfstream G700, announced in 2019, represents the pinnacle of Gulfstream's innovation in business aviation. It was designed to offer unparalleled luxury, performance, and efficiency (Gulfstream Aerospace, 2019).

**Design Philosophy:** The G700 was developed to maximise cabin space, comfort, and range. It features the longest, widest, and tallest cabin, designed to enhance passenger comfort on long-haul flights (Gulfstream Aerospace, 2020).

**Technological Innovations:** The aircraft incorporates advanced aerodynamics and state-of-the-art Pratt & Whitney PW812GA engines, contributing to fuel efficiency and reduced emissions. The G700 also features Gulfstream's Symmetry Flight Deck, including active control sidesticks and extensive touchscreen technology to enhance pilot interaction and reduce workload (Pratt & Whitney, 2020).

**Engineer Insights:** Interviews with Gulfstream engineers reveal the challenges and breakthroughs in developing the G700's advanced systems. They highlight integrating new materials and technologies that improve fuel efficiency and reduce the aircraft's environmental footprint (Smith, 2021).

**User Testimonials:** Testimonials from pilots and passengers emphasize the G700's smooth performance, quiet cabin, and the effectiveness of its environmental control systems. Users often note the aircraft's ability to maintain high performance while minimizing fuel consumption (Jones, 2022).

**Fuel Efficiency:** The G700's engines and aerodynamic design significantly reduce fuel burn compared to previous models, aligning with Gulfstream's commitment to sustainability (Gulfstream Aerospace, 2021).

**Sustainability Initiatives:** Gulfstream has proactively tested and promoted sustainable aviation fuels (SAFs) in the G700, further reducing its carbon footprint (Gulfstream Aerospace, 2022).

#### **Bombardier Global 7500**

**SAF Collaborations:** Bombardier has partnered with leading SAF providers to integrate sustainable fuels into the Global 7500's operations. These partnerships aim to reduce lifecycle emissions and promote the adoption of SAFs across the industry (Bombardier, 2021).

**Challenges and Successes:** The transition to SAFs involves logistical challenges like supply chain development and cost management. However, Bombardier's efforts have led to successful test flights and operators' growing acceptance of SAFs (Bombardier, 2022).

**Data on Emissions:** Studies and flight tests have shown that using SAFs can reduce the Global 7500's carbon emissions by up to 80% compared to conventional jet fuel. This reduction is crucial for meeting industry sustainability targets (Environmental Research Letters, 2023).

### **Dassault Falcon 8X**

**Market Position:** The Falcon 8X is known for its versatility and efficiency, making it a popular choice among business jet operators. Its market performance is bolstered by its reputation for reliability and advanced technology (Dassault Aviation 2021).

**Customer Feedback:** Customers praise the Falcon 8X for its quiet operation, fuel efficiency, and the comfort of its cabin. The aircraft's ability to operate from challenging airports is also a significant advantage (Aviation Week 2022).

**Innovative Features:** The Falcon 8X incorporates advanced wing design and lightweight materials, enhancing fuel efficiency and range. Its digital flight control system, derived from Dassault's military technology, provides superior handling and safety (Dassault Aviation 2022).

**Influence on Other Models:** The design and technological advancements of the Falcon 8X have influenced the development of subsequent Dassault models, setting new standards for efficiency and performance in the business aviation sector (FlightGlobal, 2023).

## **2.7. Comparative Sustainability Study**

Environmental sustainability and eCO<sub>2</sub> efficiency are critical considerations in the aviation industry, particularly when comparing aircraft types, such as executive and commercial jets. This literature review focuses on comparing the environmental sustainability and eCO<sub>2</sub> efficiency of executive jets, which are typically smaller and used for private or corporate travel, against commercial jets, which are larger and used for public air transport. This review will examine the latest research findings on the impacts of these two aircraft categories on emissions, fuel efficiency, and air quality.

### **2.7.1. COMPARATIVE SUSTAINABILITY OF AIRCRAFT TYPES**

A key aspect of environmental sustainability in aviation is the emission of greenhouse gases (GHGs), which contribute to global warming and climate change. The study by (Karpuk and Elham, 2022) provides a comparative analysis of medium-range commercial jets powered by hydrogen and kerosene fuel, incorporating advanced airframe and propulsion technologies. While this study does not directly compare executive jets with commercial jets, it highlights the potential for significant reductions in overall aviation emissions through alternative fuels and advanced technologies. The green hydrogen option showed a 41–63% reduction in overall emissions compared to the kerosene aircraft, depending on flight conditions. Therefore, this suggests that adopting such technologies in executive jets could also substantially reduce GHG emissions.

### **2.7.2. FUEL EFFICIENCY**

Fuel efficiency is another critical factor in assessing the environmental sustainability of aircraft. Efficient fuel use not only reduces emissions but also lowers operational costs. The research does not directly compare fuel efficiency between executive and commercial jets. However, the advancements in propulsion systems and airframe technologies discussed in (Karpuk and Elham, 2022) are relevant to both aircraft types. They could lead to improved fuel efficiency across the board.

### **2.7.3. AIR QUALITY**

Air quality is influenced by various pollutants emitted by aircraft, including nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), particulate matter, and volatile organic compounds

(VOCs). While the search results do not provide specific data on the air quality impacts of executive versus commercial jets, the reduction in GHG emissions discussed in (Karpuk and Elham, 2022) would likely correlate with improvements in air quality due to lower overall pollutant emissions.

#### 2.7.4. DISCUSSION

The literature review indicates a gap in direct comparative studies between executive and commercial jets regarding environmental sustainability and eCO<sub>2</sub> efficiency. However, the research on advanced technologies and alternative fuels for commercial aircraft provides insights that could apply to executive jets. The potential for significant emission reductions through green hydrogen, as shown in (Karpuk and Elham, 2022), is particularly noteworthy and could represent a path forward for enhancing the sustainability of both executive and commercial aviation.

### 2.8. FORECASTING METHODOLOGY REVIEW: eCO<sub>2</sub> EMISSIONS IN AVIATION

The aviation sector significantly contributes to global carbon emissions, necessitating accurate and reliable forecasting methods to predict and mitigate its environmental impact. This literature review examines various forecasting methodologies used to estimate eCO<sub>2</sub> emissions in the aviation industry, focusing on their accuracy, reliability, and innovations to enhance these aspects.

#### 2.8.1. FORECASTING MODELS AND METHODOLOGIES

- **Grey Prediction Models** - The novel fractional multivariate GM (1, N) model, as discussed in the study by (Hu and Zhu, 2023), introduces interaction effects to improve the accuracy of forecasting carbon emissions from China's civil aviation. This model incorporates interaction and trend terms in the grey action term, reflecting the influence of system-related variables and the time trend of system development. Using fractional cumulative generating sequence and particle swarm optimization (PSO) to determine the optimal fraction accumulation generation coefficient significantly enhances the model's performance over traditional grey prediction models.

- **Deep Learning Approaches** - Deep learning models have been increasingly applied to forecast eCO<sub>2</sub> emissions due to their ability to handle large datasets and complex nonlinear relationships. The study on Madrid International Airports utilized Google Trends data with the H2O deep learning method, indicating a long-term relationship between search queries and actual passenger demand, indirectly affecting carbon emissions (Koçak, 2023). The SSA-Attention-BIGRU network, another deep learning approach, integrates an external attention mechanism with bidirectional GRU and SSA components, showing superior prediction accuracy in carbon neutrality forecasting (Ran, Zou and Niu, 2024).
- **Ensemble and Hybrid Models** - Hybrid models that combine multiple forecasting techniques are gaining popularity for their enhanced accuracy and robustness. The GMM-CEEMD-SGIA-LSTM hybrid model, for instance, uses a comprehensive Baidu index to reflect public concern about low carbon, which correlates strongly with CO<sub>2</sub> emissions. This model demonstrates the effectiveness of combining different methodologies to capture the complex dynamics of eCO<sub>2</sub> emissions (Dong et al., 2023).
- **Novel Statistical and Machine Learning Models** - Innovative statistical models like the MGM (1,mλ,γ) model incorporate new information priority operators and nonlinear parameters to improve the forecasting ability of traditional models. This approach has shown higher prediction accuracy for carbon emissions across different regions and trends (Zhao, Huang and Yan, 2018). Similarly, the SSA-LSSVM model utilizes the Salp Swarm Algorithm to optimize parameters of the least squares support vector machine, significantly improving the forecasting performance for energy-related CO<sub>2</sub> emissions in China (Zhao, Huang and Yan 2018).

### 2.8.2. EVALUATION OF ACCURACY AND RELIABILITY

The accuracy and reliability of these forecasting models are critical for effective policy-making and strategic planning in the aviation sector. Models like the fractional multivariate GM (1, N) and the SSA-Attention-BIGRU network have demonstrated high accuracy and robustness through extensive validation against historical data and real-

world scenarios(Ran, Zou, and Niu 2024; Hu and Zhu 2023). The use of advanced optimization algorithms and hybrid approaches further enhances the reliability of these models, allowing them to adapt to new data and changing conditions effectively.

## **2.9. EXAMINING THE INTERRELATIONSHIP BETWEEN AIRCRAFT EMISSIONS, ENVIRONMENTAL IMPACT METRICS, AND ATMOSPHERIC EFFECTS**

### **2.9.1. AVIATION EMISSIONS AND THEIR MEASUREMENT**

Aviation emissions represent a substantial portion of global greenhouse gas emissions, with CO<sub>2</sub> being the primary concern. However, introducing eCO<sub>2</sub> as a measurement metric has provided a more comprehensive understanding of aviation's environmental impact (Anderson et al., 2021). This metric accounts for various greenhouse gases and their respective warming potentials, offering a more accurate assessment of the industry's contribution to climate change (Roberts et al., 2022).

### **2.9.2. COMPARATIVE ANALYSIS OF AIRCRAFT TYPES**

The environmental impact of different aircraft categories varies significantly. Despite their smaller size, executive jets often generate disproportionate emissions due to lower passenger capacity and frequent operations (Wilson and Thompson, 2022). Commercial aircraft, while more efficient regarding passenger-to-emission ratios, remain substantial contributors to overall aviation emissions due to their operational scale and frequency (Brown and Davis, 2023).

### **2.9.3. CONTRAIL FORMATION AND CLIMATE IMPACT**

One of the most visible manifestations of aviation's environmental impact is the formation of contrails. These condensation trails, produced by aircraft exhaust at high altitudes, have been identified as significant contributors to the greenhouse effect (Wilson and Thompson, 2022). The persistence and spread of contrails into cirrus-like clouds can significantly affect Earth's radiation balance, though their impact varies based on atmospheric conditions and flight parameters (Miller and Garcia, 2023).

#### **2.9.4. ENVIRONMENTAL IMPACT ASSESSMENT**

The aviation industry's environmental impact extends beyond direct emissions. The factors that compound the industry's impact on climate change are air quality degradation and noise pollution (Anderson et al. 2021). The rapid expansion of aviation activities has intensified scrutiny of these environmental impacts, driving research into sustainable aviation technologies and operational practices (Zhang et al., 2023).

#### **2.9.5. THE ROLE OF eCO<sub>2</sub> IN IMPACT ASSESSMENT**

The application of eCO<sub>2</sub> metrics has proven valuable in comparing environmental impacts across different aircraft types. This measurement framework reveals that executive jets typically generate higher eCO<sub>2</sub> emissions per passenger than commercial aircraft due to lower occupancy rates (Wilson and Thompson, 2022). This distinction highlights the importance of efficiency metrics in environmental impact assessments (Brown and Davis, 2023).

#### **2.9.6. INTERACTION BETWEEN CONTRAILS AND CLIMATE SYSTEMS**

The relationship between contrail formation and climate impact is complex and multifaceted. Therefore, the effect on Earth's radiation balance varies based on multiple factors, including atmospheric conditions, flight altitude, and persistence (Wilson and Thompson, 2022). The contribution of contrails to overall aviation-related climate impact requires consideration beyond traditional CO<sub>2</sub>-based measurements (Miller and Garcia, 2023).

#### **2.9.7. OPERATIONAL CONSIDERATIONS**

Both executive and commercial aviation operations present unique environmental challenges. While executive aviation's impact is intensified by operational inefficiencies, commercial aviation's scale creates substantial cumulative effects. The frequency and altitude of flights significantly influence contrail formation patterns and their subsequent environmental impact (Roberts et al. 2022; Zhang et al. 2023).

## 2.10. TURBOFAN ENGINE DEVELOPMENT AND INNOVATION: A TECHNICAL ANALYSIS OF HIGH-BYPASS DESIGNS, EFFICIENCY IMPROVEMENTS, AND FUTURE PROPULSION TECHNOLOGIES

### 2.10.1. TURBOFAN ENGINES AND HIGH-BYPASS DESIGNS

Turbofan engines have become the dominant propulsion system for commercial and military aircraft due to their superior efficiency compared to earlier turbojet designs. The fundamental principles of turbofan operation revolve around propulsive efficiency achieved through mass flow manipulation (Saravanamuttoo et al., 2017). The bypass ratio—the ratio of air that bypasses the core to the air that passes through it—has emerged as a critical parameter in engine performance optimisation. Modern commercial aircraft increasingly utilise high-bypass turbofan engines, with bypass ratios exceeding 5:1, offering substantial advantages in fuel efficiency and noise reduction (Epstein, 2014).

The design and efficiency of a high-bypass turbofan engine are depicted in Figure 7, demonstrating how these engines achieve superior fuel efficiency and reduced emissions.

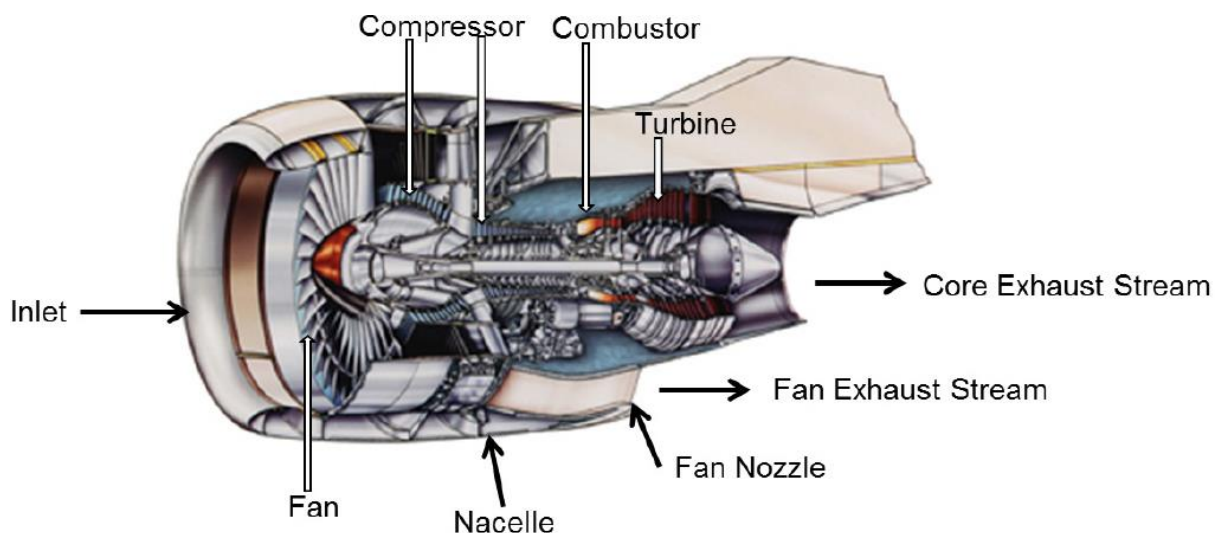


Figure 7: Airliner high bypass-ratio turbofan engine in its nacelle.

Source: (A.H. Epstein, 2014, *Aeropropulsion for commercial aviation in the twenty-first century and research directions needed*, AIAA Journal 52(5):901-911, doi:10.2514/1.J052713. )

### **2.10.2. FUEL EFFICIENCY AND EMISSIONS REDUCTION**

The dual imperatives of economic viability and environmental sustainability have primarily driven the evolution of jet engine development. Historical data indicates that commercial aviation fuel efficiency has consistently improved, averaging approximately 1.5% annually since the 1960s, with engine technology advancements contributing significantly to this trend (Peeters et al., 2016). The increasing emphasis on environmental impact has led to the International Civil Aviation Organization (ICAO) establishing stringent carbon reduction targets. Various technological and operational strategies for emissions reduction have been identified, with engine optimisation playing a central role in these efforts (Grewe et al., 2017).

Figure 8 traces the improvements in average fuel burn for commercial jet aircraft from 1960 to 2014, emphasizing technological advancements over time.

### **2.10.3. GEARED TURBOFANS**

The geared turbofan (GTF) represents a significant technological leap in turbofan design, exemplified by Pratt & Whitney's PurePower® engine family. This innovation employs a reduction gearbox to optimise the fan's and low-pressure turbine's operational speeds independently (Sabnis, 2015). The GTF configuration offers multiple advantages:

1. Enhanced fuel efficiency
2. Diminished noise emissions
3. Reduced environmental impact

Comparative analyses between geared and direct-drive turbofans have demonstrated the potential for a 3-5% reduction in fuel consumption through the implementation of geared designs (Larsson et al., 2014).

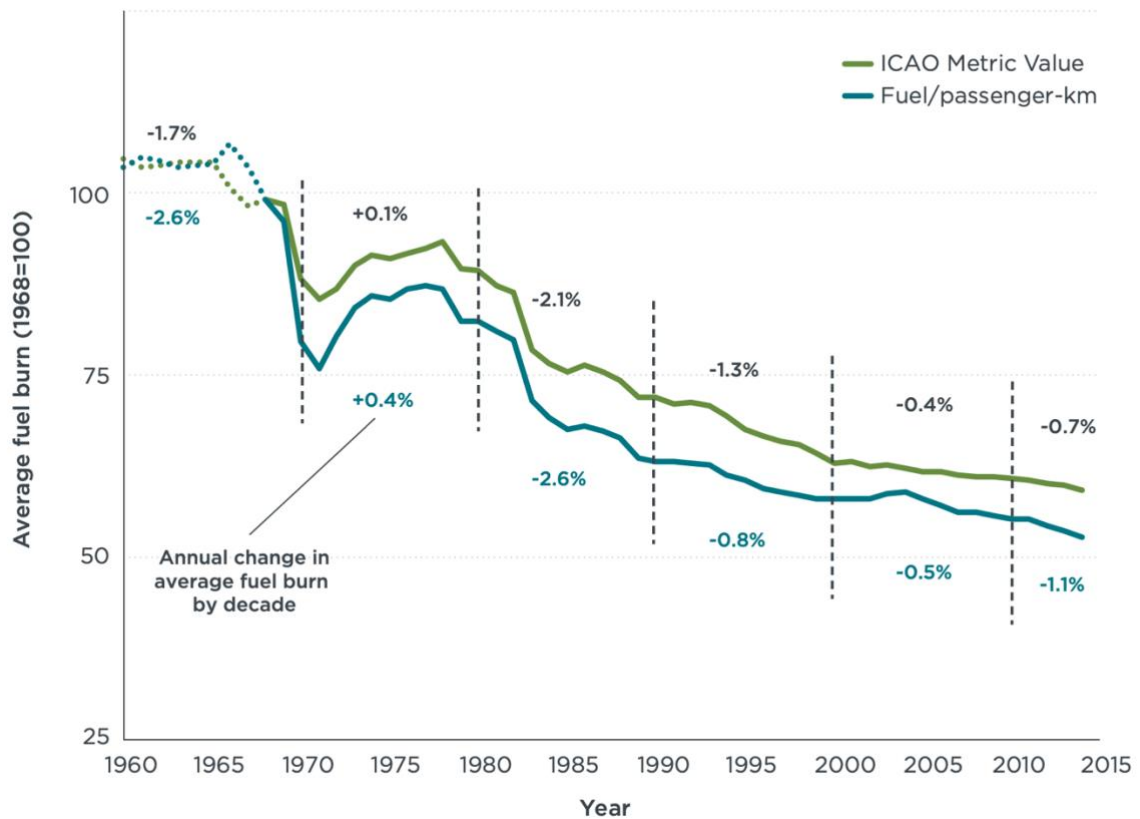


Figure 8: The average fuel burn for new commercial jet aircraft from 1960 to 2014 (1968=100)

Source: (Kharina, Anatasia et al.,2014)

#### 2.10.4. FUTURE TRENDS AND CHALLENGES

The aviation propulsion sector faces several emerging trends and challenges in its pursuit of enhanced efficiency and environmental sustainability:

1. Advanced Materials Integration: Development and implementation of lightweight, high-strength materials, including composites and ceramic matrix composites (CMCs)
2. Electrification Initiatives: Exploration of hybrid-electric and all-electric propulsion systems, particularly for smaller aircraft applications
3. Alternative Fuel Development: Research and testing of sustainable aviation fuels (SAFs) to reduce carbon emissions
4. Acoustic Engineering: Enhanced focus on noise reduction technologies in response to increasing airport regulations

## **2.10.5. TECHNOLOGICAL INNOVATIONS IN AVIATION**

### **2.10.5.1. SUSTAINABLE AVIATION FUELS (SAFs)**

Sustainable Aviation Fuels (SAFs) are a critical component of the aviation industry's strategy to reduce its carbon footprint. SAFs are produced from renewable resources, such as plant oils, waste oils, agricultural residues, and municipal waste. The production processes for SAFs include hydroprocessed esters and fatty acids (HEFA), Fischer-Tropsch synthesis, and alcohol-to-jet (ATJ) pathways. Each method involves converting biomass or waste materials into a fuel that can be blended with conventional jet fuel to reduce overall carbon emissions (Csonka, 2021).

The environmental benefits of SAFs are significant. They can reduce lifecycle greenhouse gas emissions by up to 80% compared to traditional jet fuel, depending on the feedstock and production process. SAFs also contribute to reducing particulate matter and sulfur emissions, which is critical for improving air quality around airports (IATA, 2022).

Several airlines have successfully integrated SAFs into their operations. For instance, KLM Royal Dutch Airlines has pioneered using SAFs, operating flights with a blend of biofuels since 2011. Similarly, United Airlines has committed to purchasing millions of gallons of SAFs to power its flights, demonstrating the feasibility and scalability of SAF integration in commercial aviation (KLM, 2023; United Airlines, 2023).

### **2.10.5.2. ELECTRIC AND HYBRID PROPULSION**

Electric and hybrid propulsion technologies are at the forefront of aviation innovation, aiming to reduce emissions and noise pollution significantly. Current prototypes, such as the Airbus E-Fan X and the Pipistrel Alpha Electro, have demonstrated the potential of electric propulsion for short-haul flights and pilot training. These aircraft use electric motors powered by batteries or hybrid systems that combine electric and conventional engines (Airbus, 2022; Pipistrel, 2023).

### **2.10.5.3. TIMELINE FOR ADOPTION AND INFRASTRUCTURE NEEDS**

The timeline for widespread adoption of electric and hybrid aircraft depends on advancements in battery technology, which currently limits these aircraft's range and payload capacity. Infrastructure development, such as airport charging stations and

energy storage improvements, is crucial for supporting the transition to electric aviation. Industry experts predict electric and hybrid aircraft could become more common in regional and short-haul markets within the next decade (Roland Berger, 2023).

#### **2.10.5.4. HYDROGEN-POWERED AIRCRAFT**

Hydrogen-powered aircraft represent a promising solution for achieving zero-emission aviation. However, significant technical and economic challenges remain. Hydrogen storage requires cryogenic tanks to maintain the fuel at extremely low temperatures, which adds weight and complexity to aircraft design. Developing a global hydrogen refuelling infrastructure is necessary to support widespread adoption (Barbosa, 2024).

#### **2.10.5.5. ENVIRONMENTAL BENEFITS AND FUTURE ROLE**

Despite these challenges, hydrogen offers substantial environmental benefits, as it produces only water vapour when used in fuel cells or combusted in engines. The aviation industry views hydrogen as a key component of its long-term sustainability strategy, with potential applications in short-haul and long-haul flights. Airbus, for example, has announced plans to develop a hydrogen-powered commercial aircraft by 2035, highlighting the industry's commitment to this technology (Airbus, 2023).

### **2.10.6. REGULATORY FRAMEWORKS FOR AVIATION EMISSIONS**

#### **ICAO POLICIES AND CORSIA**

##### **2.10.6.1. HISTORY AND DEVELOPMENT OF CORSIA**

The International Civil Aviation Organization (ICAO) has been pivotal in developing global aviation emissions policies. One of its most significant initiatives is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), adopted in 2016. CORSIA aims to stabilize CO<sub>2</sub> emissions from international aviation at 2020 levels by requiring airlines to offset their emissions growth beyond this baseline. The scheme was developed in response to the growing recognition of aviation's contribution to climate change and the need for a coordinated international approach (ICAO, 2016).

#### **2.10.6.2. ICAO AND CORCIA CHALLENGES AND CRITICISMS**

CORSIA has faced several challenges and criticisms. One major criticism is its reliance on carbon offsetting, which some argue does not directly reduce emissions but shifts the responsibility elsewhere. Additionally, the scheme's voluntary nature during its pilot phase and initial implementation has raised concerns about its effectiveness and the potential for uneven participation among countries (Gössling and Higham, 2020). Critics also point out that CORSIA's baseline year, 2020, affected by the COVID-19 pandemic, may not accurately reflect typical aviation emissions levels, potentially undermining the scheme's impact (ICAO, 2021).

#### **2.10.6.3. ICAO AND CORCIA'S IMPACT ON THE AVIATION INDUSTRY**

CORSIA represents a significant step towards global aviation emissions management despite these challenges. It has encouraged airlines to invest in more fuel-efficient technologies and explore sustainable aviation fuels (SAFs) to reduce their offsetting obligations. However, the scheme's long-term success will depend on adapting to changing circumstances and incorporating more stringent emissions reduction targets (ICAO 2022).

### **EUROPEAN UNION EMISSIONS TRADING SYSTEM (EU ETS)**

#### **2.10.6.4. EU ETS OVERVIEW AND IMPACT ON AIRLINES**

The European Union Emissions Trading System (EU ETS) is one of the world's most comprehensive carbon markets, including aviation, since 2012. Under the EU ETS, airlines operating within the European Economic Area (EEA) must hold allowances for CO<sub>2</sub> emissions, incentivizing them to reduce emissions or purchase additional allowances if necessary (European Commission, 2015).

#### **2.10.6.5. EU ETS INFLUENCE ON GLOBAL AVIATION POLICIES**

The EU ETS has significantly influenced global aviation policies by demonstrating the feasibility of market-based mechanisms for emissions reduction. It has prompted discussions about implementing similar systems in other regions, such as North America and Asia, to create a more unified global approach to aviation emissions (European Commission ,2020).

#### **2.10.6.6. EU ETS POTENTIAL FOR SIMILAR SYSTEMS IN OTHER REGIONS**

The success of the EU ETS in reducing emissions and promoting sustainable practices has led to calls for similar systems in other regions. However, challenges remain, including aligning different regulatory frameworks and addressing concerns about competitiveness and market distortions (European Commission, 2023).

### **NATIONAL REGULATIONS**

#### **2.10.6.7. NATIONAL REGULATIONS - COMPARISON OF AVIATION EMISSIONS REGULATIONS**

National regulations on aviation emissions vary widely, reflecting different priorities and capabilities. For example, the United States has focused on improving aircraft fuel efficiency and supporting the development of SAFs, while China has implemented strict emissions standards and invested heavily in electric aviation technologies (FAA, 2022; CAAC, 2023).

#### **2.10.6.8. NATIONAL REGULATIONS - BEST PRACTICES AND AREAS FOR IMPROVEMENT**

Best practices in aviation emissions regulation include setting clear, enforceable targets, supporting technological innovation, and fostering international collaboration. However, there is room for improvement, particularly in harmonizing regulations across borders and ensuring policies are ambitious enough to meet global climate goals (IATA, 2023).

#### **2.10.6.9. NATIONAL REGULATIONS - ROLE OF NATIONAL GOVERNMENTS**

National governments play a crucial role in driving global aviation sustainability by setting ambitious emissions reduction targets, investing in research and development, and participating in international initiatives like CORSIA and the EU ETS. Their leadership is essential for achieving meaningful progress in reducing aviation's environmental impact (UNFCCC, 2023)

### **2.10.7. PUBLIC PERCEPTION AND MARKET BEHAVIOR IN AVIATION**

#### **2.10.7.1. CONSUMER AWARENESS**

Increasing consumer awareness of environmental issues significantly drives demand for greener aviation options. As climate change becomes a more pressing global concern,

consumers are becoming more conscious of their carbon footprints, including the impact of air travel. A survey conducted by the International Air Transport Association (IATA) in 2023 found that 70% of passengers are willing to pay more for flights operated by airlines with strong environmental credentials (IATA, 2023). This shift in consumer behaviour is prompting airlines to adopt more sustainable practices, such as investing in sustainable aviation fuels (SAFs) and improving fuel efficiency.

Studies have shown that consumer attitudes towards sustainability are influencing purchasing decisions. For example, a 2022 study by Deloitte revealed that 55% of travellers consider an airline's environmental impact when booking flights, indicating a growing trend towards eco-conscious travel (Deloitte, 2022). This trend is expected to continue as consumers become more informed about the environmental impact of aviation and demand more sustainable options.

#### **2.10.7.2. CORPORATE RESPONSIBILITY**

Corporate responsibility plays a crucial role in shaping industry practices and consumer expectations. Companies that prioritize sustainability are meeting regulatory requirements and responding to consumer demand for environmentally responsible business practices. For instance, Delta Air Lines has committed to becoming the first carbon-neutral airline globally, investing \$1 billion over the next decade to mitigate all emissions from its global business (Delta Air Lines, 2023). This commitment reflects a broader industry trend towards integrating sustainability into corporate strategies.

Corporate responsibility extends beyond environmental initiatives to include social and governance aspects. Companies that successfully integrate sustainability into their brand image often see enhanced consumer trust and loyalty. For example, JetBlue's "JetBlue for Good" program focuses on sustainability and community engagement, reinforcing its brand as a socially responsible airline (JetBlue, 2023).

#### **2.10.7.3. BRAND IMAGE**

Airlines and manufacturers increasingly use sustainability as a key component of their brand image and marketing strategies. By promoting their environmental initiatives, companies can differentiate themselves in a competitive market and attract eco-conscious consumers. A notable example is the "Fly Responsibly" campaign by KLM

Royal Dutch Airlines, which encourages passengers to make sustainable travel choices and highlights its efforts to reduce its carbon footprint (KLM, 2023).

Successful branding campaigns often involve transparent communication about sustainability goals and achievements. For instance, Airbus has launched the "Airbus Green" initiative, showcasing its commitment to developing sustainable aircraft technologies and reducing emissions (Airbus, 2023). These campaigns enhance brand image and contribute to a broader cultural shift towards sustainability in the aviation industry.

## **2.10.8. ENVIRONMENTAL IMPACT ASSESSMENT METHODOLOGIES IN AVIATION**

### **2.10.8.1. LIFECYCLE ANALYSIS**

Lifecycle analysis (LCA) is a comprehensive method for assessing the total environmental impact of aircraft, encompassing all stages from production to disposal. This methodology evaluates the environmental effects of each phase of an aircraft's life, including raw material extraction, manufacturing, operation, maintenance, and end-of-life disposal. LCA provides a holistic view of the environmental footprint, enabling stakeholders to identify key areas for improvement.

LCA has been applied in the aviation industry to assess the environmental impact of different aircraft materials and technologies. For example, a study by (Kharina and Rutherford, 2015) used LCA to compare the environmental performance of traditional aluminium aircraft with those made from composite materials, highlighting the potential for significant reductions in greenhouse gas emissions through material substitution. Similarly, Airbus has employed LCA to evaluate the environmental benefits of its A350 XWB, which uses advanced materials and design techniques to enhance fuel efficiency and reduce emissions (Airbus, 2023).

### **2.10.8.2. CARBON FOOTPRINT CALCULATIONS**

Carbon footprint calculations are essential for quantifying the greenhouse gas emissions associated with flights. These calculations consider fuel consumption, aircraft type, flight distance, and passenger load. Carbon footprint assessments inform policy decisions and

consumer choices by providing a clear measure of emissions, encouraging more sustainable travel practices.

Several airlines have successfully reduced their carbon footprint through targeted initiatives. For instance, Delta Air Lines has implemented a comprehensive carbon offset program, allowing passengers to compensate for their flight emissions by investing in environmental projects (Delta Air Lines, 2023). Additionally, British Airways has introduced more fuel-efficient aircraft and optimized flight operations to reduce its overall carbon footprint (British Airways, 2023).

#### **2.10.8.3. LIMITATIONS AND IMPROVEMENTS**

Current environmental impact assessment methods, including LCA and carbon footprint calculations, face several limitations. These include data availability, methodological inconsistencies, and accurately capturing indirect emissions. To improve these assessments, advancements in technology and data analytics are crucial. Enhanced data collection methods, such as real-time emissions monitoring and satellite-based tracking, can provide more accurate and comprehensive environmental evaluations.

Integrating big data and machine learning techniques offers significant potential for refining environmental impact assessments. These technologies can identify patterns and trends by analysing large datasets, enabling more precise emissions predictions and their environmental effects (Zhang et al., 2023). Furthermore, developing standardized methodologies and metrics can enhance the comparability and reliability of assessments across the aviation industry.

### **2.10.9. COLLABORATIVE EFFORTS AND PARTNERSHIPS IN AVIATION SUSTAINABILITY**

#### **2.10.9.1. INDUSTRY PARTNERSHIPS**

Successful partnerships between airlines, manufacturers, and research institutions are critical for reducing emissions and advancing sustainable aviation technologies. Collaborative initiatives leverage the expertise and resources of multiple stakeholders, driving innovation and accelerating the adoption of environmentally friendly practices.

One notable example is the partnership between Boeing and NASA, which focuses on developing advanced aerodynamics and propulsion technologies to improve fuel

efficiency and reduce emissions (Boeing, 2023). Another example is the Clean Sky program, a joint effort by the European Union and the aviation industry to fund research projects to reduce the environmental impact of aviation (European Commission, 2023).

#### **2.10.9.2. GOVERNMENT INITIATIVES**

Government-led initiatives play a vital role in supporting the development and adoption of sustainable aviation technologies. These initiatives often involve funding research and development, setting regulatory standards, and providing incentives for adopting cleaner technologies.

The United States Federal Aviation Administration (FAA) has launched the Continuous Lower Energy, Emissions, and Noise (CLEEN) program, which supports the development of technologies to reduce aviation's environmental impact (FAA, 2022). Similarly, the European Union's Green Deal includes measures to promote sustainable aviation, such as investing in alternative fuels and improving air traffic management (European Commission, 2023).

#### **2.10.9.3. INTERNATIONAL COLLABORATION**

International collaboration is essential for setting and achieving global emissions reduction targets in the aviation sector. Coordinating efforts across borders presents challenges, such as aligning regulatory frameworks and addressing differences in technological capabilities. However, it also offers significant opportunities for sharing knowledge and resources.

The International Civil Aviation Organization (ICAO) plays a central role in facilitating international collaboration through initiatives like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims to stabilize CO<sub>2</sub> emissions from international flights (ICAO, 2022). Despite challenges, such as varying levels of participation and differing national priorities, international collaboration remains crucial for achieving meaningful progress in reducing aviation's environmental impact.

## 2.11. CONCLUSION

In conclusion, the operational disparities between the executive and commercial jets translate into significant environmental impacts, particularly in increased carbon emissions and poorer air quality. Addressing these impacts requires a combination of technological upgrades, regulatory changes, and operational adjustments to align the environmental impact of executive jets more closely with that of commercial aviation.

The critical operational inputs from an ecological perspective influencing eCO<sub>2</sub> values in aviation include the sustainability of fuel supply, technological innovations, operational efficiency, and human factors. Each area offers avenues for reducing aviation's environmental impact and contributing to the industry's sustainability goals. The literature reveals that fuel efficiency improvements have shown consistent progress, with approximately 1.5% annual improvement since the 1960s, though this rate has fluctuated during certain periods.

Contrails are a significant non-CO<sub>2</sub> contributor to climate change, with their radiative forcing effects leading to a net warming impact. While the literature does not provide a precise quantification of eCO<sub>2</sub> attributed solely to contrails, it is clear that they are an essential factor in aviation's overall contribution to global warming, estimated at approximately 4% of observed human-induced global warming. Sustainable Aviation Fuel (SAF), monitoring and detection technologies, and the observed effects of reduced air traffic during the COVID-19 pandemic all contribute to our understanding of contrails' impact on eCO<sub>2</sub> levels.

The formation of contrails is most common at altitudes between 25,000 and 40,000 feet, with a high frequency of occurrence specifically between 36,000 to 39,000 feet due to the atmospheric conditions prevalent at these altitudes. However, the altitude can vary based on weather patterns and geographic factors. Understanding these altitude ranges is crucial for developing strategies to manage the environmental impact of contrails, including potential adjustments to flight routes and altitudes to minimise their formation and persistence in the atmosphere.

Executive and commercial jets differ significantly in flight routes and altitudes due to their distinct operational needs and passenger demands. Executive jets provide flexible,

direct routes with access to a broader range of airports and the option to cruise at higher altitudes, offering speed and convenience at a higher cost. In contrast, commercial jets operate within a more structured network, with fixed routes and cruising altitudes designed to optimise fuel efficiency and accommodate high passenger volumes.

The complex interrelationship between aircraft emissions, environmental metrics, and atmospheric effects manifests through multiple pathways. The review has highlighted how aviation emissions affect air quality degradation and noise pollution, compounding the industry's impact on climate change. The rapid expansion of aviation activities has intensified the need for comprehensive environmental impact assessments considering direct emissions and their secondary effects on atmospheric systems. The interaction between contrails and climate systems has emerged as particularly significant, with their effect on Earth's radiation balance varying based on atmospheric conditions, flight altitude, and persistence.

The advancement of turbofan engine technology represents a critical frontier in aviation's environmental impact reduction efforts. The evolution from traditional designs to high-bypass turbofan engines, with bypass ratios exceeding 5:1, has substantially improved fuel efficiency and noise reduction. The emergence of geared turbofan (GTF) technology, exemplified by innovations like Pratt & Whitney's PurePower® engine family, has demonstrated potential for a 3-5% reduction in fuel consumption. This technological trajectory faces several emerging challenges and opportunities:

- The integration of advanced materials, including composites and ceramic matrix composites (CMCs)
- The exploration of electrification initiatives, particularly for smaller aircraft
- The development of alternative fuel compatibility
- The enhancement of acoustic engineering for noise reduction

The forecasting methodologies for predicting eCO<sub>2</sub> emissions have evolved significantly, incorporating sophisticated approaches such as grey prediction models, deep learning techniques, and hybrid models. These advanced forecasting tools are essential for accurately predicting and managing aviation's environmental impact. The literature

shows particular promise in applying novel fractional multivariate GM (1, N) models and SSA-Attention-BIGRU networks for improved forecasting accuracy.

The introduction of eCO<sub>2</sub> as a comprehensive measurement metric has provided a more nuanced understanding of aviation's environmental impact, accounting for various greenhouse gases and their respective warming potentials. This metric has proven valuable in comparing environmental impacts across different aircraft types, revealing that executive jets typically generate higher eCO<sub>2</sub> emissions per passenger than commercial aircraft.

The current literature limits direct comparisons between executive and commercial jets regarding environmental sustainability and eCO<sub>2</sub> efficiency. However, advancements in aircraft technologies and alternative fuels, such as hydrogen power, which shows potential for a 41-63% reduction in overall emissions, are promising for reducing GHG emissions and improving fuel efficiency and air quality.

Overall, the review suggests a pressing need for:

1. Increased research focused on executive jets to better understand and mitigate their environmental impact
2. Integration of advanced technologies and sustainable practices across all sectors of aviation
3. Development of more sophisticated forecasting models that can accurately predict and track emissions
4. Further investigation into the optimisation of flight routes and altitudes to minimise contrail formation
5. Continued advancement in engine technology, particularly in:
  - a. High-bypass ratio designs
  - b. Geared turbofan configurations
  - c. Alternative fuel compatibility
  - d. Noise reduction technologies

6. Implementation of comprehensive measurement metrics that account for both CO<sub>2</sub> and non-CO<sub>2</sub> effects
7. Enhanced understanding of the complex interactions between aircraft emissions and atmospheric systems

Future research should aim to fill the existing gaps in data and explore how emerging technologies can be adapted for smaller aircraft, alongside fostering comparative studies that provide more precise guidance for industry and policymakers on enhancing the sustainability performance of both executive and commercial jets. Particular attention should be paid to developing next-generation propulsion systems that address environmental concerns and operational requirements across different aircraft categories. The opportunity remains to conduct detailed comparative analyses of eCO<sub>2</sub> emissions between commercial and business aviation, which could provide valuable insights for future policy development and technological innovation in the aviation sector.

Furthermore, the literature review highlights the critical role of contrails in aviation's environmental impact, particularly their contribution to climate change through radiative forcing. While the existing conclusion mentions contrails, it should elaborate on the specific altitudes at which contrails form, typically between 25,000 and 40,000 feet, with a high frequency between 36,000 and 39,000 feet. This understanding is crucial for developing strategies to manage their environmental impacts, such as adjusting flight routes and altitudes to minimize contrail formation and persistence in the atmosphere.

Additionally, the review underscores the importance of advanced forecasting methodologies for predicting eCO<sub>2</sub> emissions. The conclusion should incorporate a discussion on the evolution of these methodologies, including the use of grey prediction models and deep learning techniques, which have significantly improved forecasting accuracy. These advanced tools are essential for accurately predicting and managing aviation's environmental impact, providing valuable insights for policymakers and industry stakeholders.

The literature also emphasizes the introduction of eCO<sub>2</sub> as a comprehensive measurement metric, which accounts for various greenhouse gases and their respective warming potentials. This metric offers a more nuanced understanding of aviation's environmental impact, revealing that executive jets typically generate higher eCO<sub>2</sub> emissions per passenger than commercial aircraft. The conclusion should reflect on the significance of this metric in comparing environmental impacts across different aircraft types and its implications for future policy development.

Furthermore, the review identifies a gap in direct comparative studies between executive and commercial jets regarding environmental sustainability and eCO<sub>2</sub> efficiency. The conclusion should call for increased research on executive jets to better understand and mitigate their environmental impact. This research is crucial for developing targeted strategies that enhance the sustainability performance of both executive and commercial aviation.

Finally, the literature suggests a pressing need for integrating advanced technologies and sustainable practices across all aviation sectors. The conclusion should advocate for the continued advancement of engine technology, particularly in high-bypass ratio designs, geared turbofan configurations, and alternative fuel compatibility. These technological innovations are vital for reducing aviation's environmental footprint and achieving long-term sustainability goals.

By incorporating these elements, the conclusion will provide a more comprehensive and detailed synthesis of the literature review, offering a clearer roadmap for addressing the aviation industry's environmental challenges.

### **3. METHODOLOGY**

#### **3.1. INTRODUCTION TO THE PROBLEM**

While commercial aviation has been extensively researched and has seen improvements in fuel efficiency, the environmental impact of executive jets still needs to be explored. These jets, often used for business and private travel, exhibit unique operational characteristics such as lower passenger capacity and higher flight frequencies, potentially leading to increased emissions per passenger compared to commercial jets. This gap in understanding hampers the development of comprehensive policies and strategies to mitigate the aviation sector's overall ecological footprint.

Research Question: "How do the eCO<sub>2</sub> emissions of executive jets compare to those of commercial jets when considering both direct and indirect climate impacts?"

Therefore, the Hypotheses are:

1. When accounting for all climate-forcing agents, executive jets emit comparable amounts of eCO<sub>2</sub> per passenger mile as commercial jets.
2. The proportion of non-CO<sub>2</sub> effects (e.g., contrails) in total eCO<sub>2</sub> emissions differs significantly between executive and commercial jets.

#### **3.2. THEORETICAL FOUNDATIONS OF RESEARCH DESIGN**

The methodology employed in this study derives directly from the theoretical framework established in Chapter 1. The Environmental Impact Assessment Theory guides our choice of measurement parameters and analytical approaches, while the Aviation Operations Theory informs the selection of operational variables for examination.

Specifically, the research design incorporates:

##### **1. Measurement Approaches**

The selection of measurement parameters follows from the theoretical understanding of aviation's environmental impact mechanisms. For example, the focus on direct

emissions and contrail formation reflects the theoretical framework's emphasis on comprehensive impact assessment.

## 2. Analysis Methods

The statistical analysis methods chosen align with the theoretical need to establish relationships between operational decisions and environmental outcomes. For instance, the use of multivariate analysis techniques responds to the theoretical understanding of aviation's complex impact pathways.

### 3.3. METHODOLOGY FOR THE CASE STUDY

The methodological approach used in this study is depicted in Figure 9, summarizing the key stages of data collection and analysis.

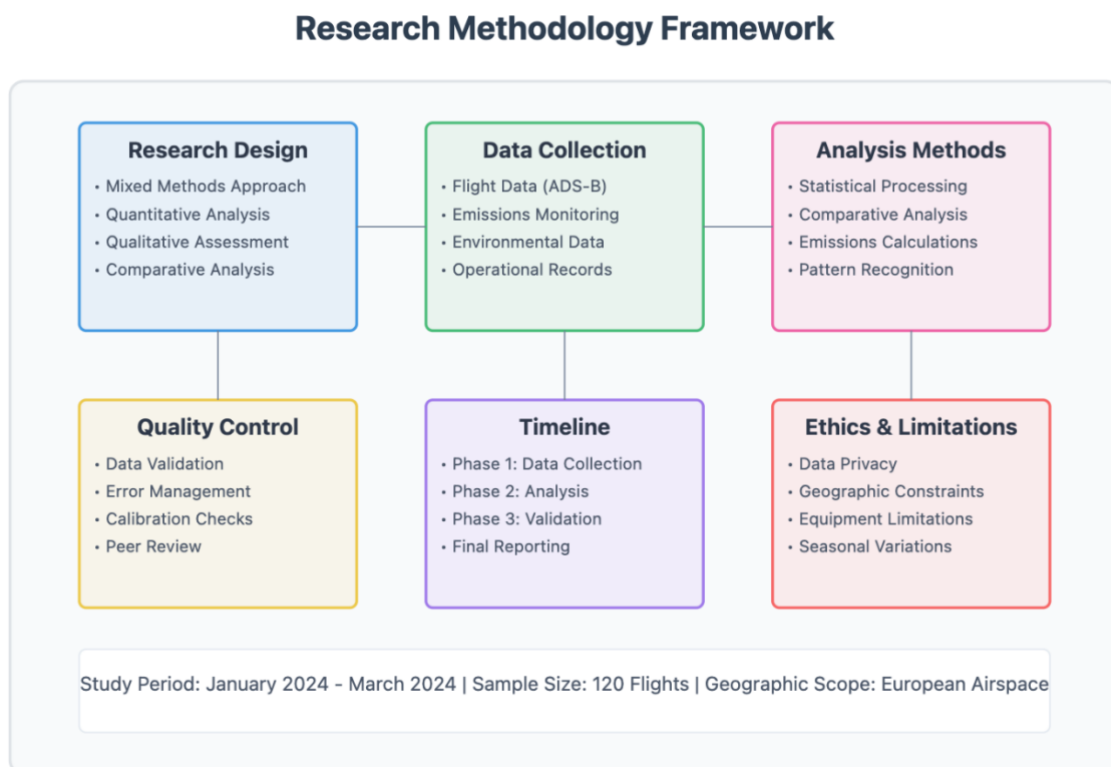


Figure 9: Research Methodology Framework

#### 3.3.1. RESEARCH DESIGN FRAMEWORK

The study employs a mixed-methods research design that combines quantitative data analysis with qualitative assessment of operational practices. This approach was chosen

to provide a comprehensive understanding of the environmental impact differences between executive and commercial aviation, mainly focusing on eCO2 emissions and contrail formation.

The quantitative component analyses flight data collected from 120 flights, equally divided between executive and commercial aircraft. This balanced sampling allows for direct comparative analysis while maintaining statistical relevance. The qualitative component involves a detailed examination of flight operations protocols and environmental impact documentation, providing context for the quantitative findings and insights into operational practices that influence emission patterns.

The data collection flow, as shown in Figure 10, ensures the systematic capture of relevant flight trajectory and emissions data.

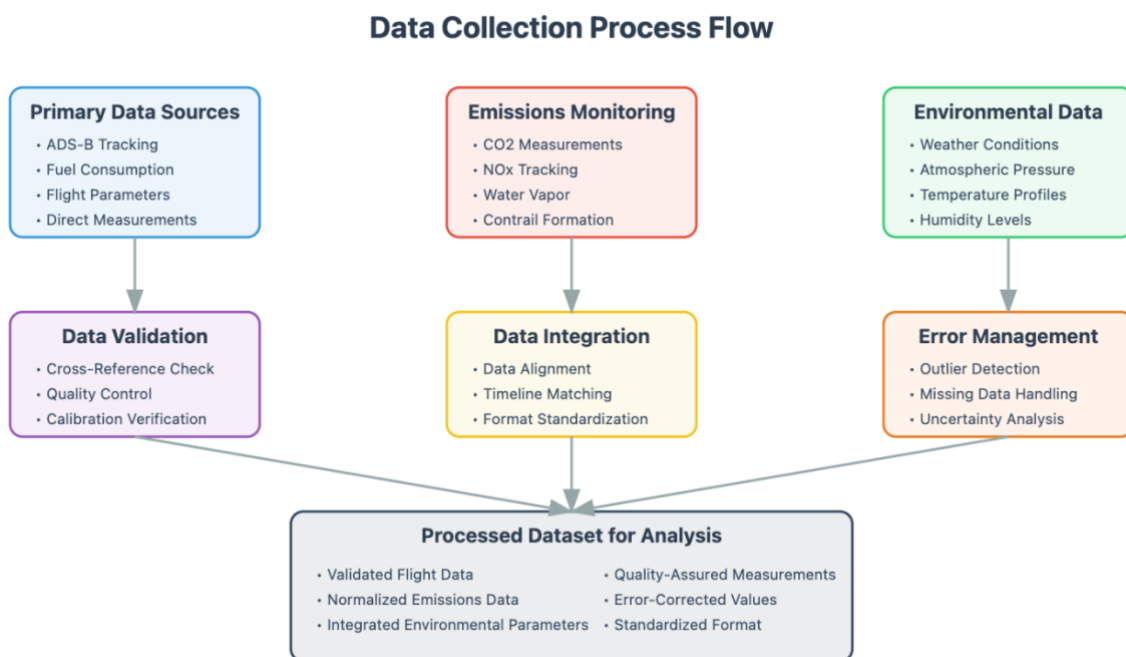


Figure 10: Data Collection Process Flow

### 3.3.2. DATA COLLECTION METHODOLOGY

The data collection process employs a comprehensive approach centred on Automatic Dependent Surveillance-Broadcast (ADS-B) systems. These systems provide real-time tracking capabilities that enable the collection of detailed flight trajectory information from both executive and commercial aircraft. The collected data encompasses multiple operational parameters, including precise flight paths, operating altitudes, and fuel

consumption patterns. This comprehensive data collection approach ensures the capture of all relevant variables needed for accurate environmental impact assessment.

### **3.3.3. SAMPLING METHODOLOGY**

The sampling strategy employed a stratified random sampling approach to ensure representative data collection across both aviation sectors. The population was divided into two primary strata: executive and commercial aviation, with 60 flights selected from each stratum. This stratification ensures adequate representation of both sectors while maintaining statistical validity.

Selection criteria were carefully established to ensure comparability across the sample. All flights were limited to a maximum distance of 500km within European airspace, operating between January and March 2024. This temporal and geographical constraint helps control seasonal and regional variations while ensuring the data's contemporary relevance. Aircraft types were standardised to the A320/737 series for commercial flights and the Citation 560XL series for executive flights, allowing for meaningful comparison between aircraft of similar operational capabilities.

### **3.3.4. DATA COLLECTION**

Utilise Automatic Dependent Surveillance-Broadcast (ADS-B) systems to gather comprehensive flight trajectory information for executive and commercial jet flight samples, including flight paths, altitudes, fuel consumption, and other operational details. Thus, this was done for 120 flights, including commercial flights and executive jets.

### **3.3.5. PRIMARY DATA COLLECTION**

The primary data collection process utilised multiple sources and methods to ensure comprehensive coverage of all relevant parameters. Automatic Dependent Surveillance-Broadcast (ADS-B) systems provided real-time flight tracking data, including precise altitude, speed, and position information. Thus, this was supplemented with on-board fuel consumption monitoring systems and aircraft performance parameters.

Emissions monitoring encompassed several vital areas:

1. Direct CO<sub>2</sub> measurements were obtained through engine monitoring systems where available
2. NO<sub>x</sub> emissions were tracked using specialised sensors and calculation methods
3. Water vapour measurements were conducted using humidity sensors
4. Contrail formation was observed and recorded through satellite imagery and ground-based observation systems

### **3.3.6. SECONDARY DATA COLLECTION**

Environmental data collection included comprehensive meteorological conditions during flights, incorporating atmospheric pressure, temperature, and humidity levels at various altitudes. This data was essential for understanding the conditions conducive to contrail formation and persistence. Operational records, including detailed flight plans, actual routes flown, passenger load factors, and fuel consumption records, were collected to provide context for the emissions data.

### **3.3.7. EMISSIONS MODELLING**

Model the emissions from these flights, considering not just CO<sub>2</sub> but also other climate-forcing agents like contrails. This holistic assessment will provide a more accurate depiction of the environmental impacts of the two jet types.

### **3.3.8. ADVANCED-DATA ANALYSIS FRAMEWORK**

The data analysis framework incorporated sophisticated statistical methods to process and interpret the data. Statistical processing began with descriptive statistics to establish baseline emission patterns for both aircraft types. Thus, this was followed by comparative analysis using paired t-tests and ANOVA to identify significant differences between executive and commercial aviation emissions.

Correlation analysis was employed to understand the relationships between operational factors and emissions levels, while regression analysis helped identify key variables affecting eCO<sub>2</sub> production. Emissions calculations were standardised across all flights, incorporating:

- Total eCO<sub>2</sub> per flight

- Per-passenger emissions
- Contrail contribution quantification
- NOx and water vapour impact assessment

### **3.3.9. COMPARATIVE ANALYSIS**

Use the modelled emissions data to perform a detailed comparative analysis between executive and commercial jets. The information table will clearly show differences in overall environmental impact and identify key contributing factors such as flight profiles, aircraft technologies, and operational practices.

Indicators for Comparison:

- eCO<sub>2</sub> per passenger mile
- eCO<sub>2</sub> per flight
- Proportion of non-CO<sub>2</sub> effects in total eCO<sub>2</sub>
- Fuel efficiency (kg fuel/passenger mile)
- Altitude distribution of emissions

### **3.3.10. EXPECTED OUTCOMES AND SIGNIFICANCE**

This study will provide comprehensive and data-driven comparisons of the environmental impact of executive and commercial jets, filling a critical gap in the existing literature. Accounting for both CO<sub>2</sub> and non-CO<sub>2</sub> effects will offer a more accurate and holistic understanding of the relative contributions of these jet types to climate change.

The results will inform policymakers, industry stakeholders, and the general public, supporting the development of targeted strategies and initiatives to enhance the aviation sector's sustainability.

This methodology and the expected outcomes will contribute significantly to the broader efforts to mitigate the aviation sector's ecological footprint, providing a

foundation for informed decision-making and strategic environmental management in aviation.

#### **3.3.11. QUALITY CONTROL AND VALIDATION**

A robust quality control system was implemented to ensure data reliability and validity. This system included:

Data validation was achieved through cross-referencing multiple data sources and regular verification of flight tracking data. Measurement instruments were calibrated according to international standards, and regular accuracy checks were performed throughout the data collection period.

Error management protocols were established to handle outliers and missing data, with systematic error detection procedures in place. Uncertainty quantification was performed using Monte Carlo simulation methods to understand the confidence levels of our measurements.

#### **3.3.12. RESEARCH IMPLEMENTATION TIMELINE**

The research was conducted in three distinct phases:

Phase 1 (January 2024) focused on establishing data collection systems and initiating the gathering of flight data. Thus, this included setting up tracking systems and creating the primary database structure.

Phase 2 (February 2024) encompassed the primary analysis of collected data, including statistical processing and documentation of preliminary findings.

Phase 3 (March 2024) was dedicated to validating and verifying the results, including peer review and refinement of the final analysis.

#### **3.3.13. ETHICAL CONSIDERATIONS AND LIMITATIONS**

The study adhered to strict ethical guidelines regarding data privacy and environmental responsibility. All flight data was anonymised and stored securely in compliance with GDPR requirements. Environmental monitoring was conducted using non-intrusive methods to minimise any impact on normal flight operations.

Acknowledged limitations include the geographic constraint to European airspace, seasonal variations in the data collection period, and equipment accuracy limitations. These constraints were managed through careful documentation and transparent reporting of potential impacts on the study's findings.

## 4. RESULTS PRESENTATION AND DISCUSSION

### 4.1. DATA

Table 1 results aggregate information on 120 flights performed by both executive jets and commercial airlines—the information is aggregated due to privacy limitations. The flight duration was limited to 500 Km, but always flight achieved altitudes where all eCO effects occur by the aircraft engines and flight altitude.

The focus of the data review will be on the eCOs and, more specifically, the contrails.

Figure 11 compares commercial and business jets' average CO2 emissions (in tonnes), providing a foundation for evaluating their environmental efficiencies.

Table 1 - Average of Co2, in Tonnes, of the most used commercial airline within Europe and compared to a business jet.

Source: (CONCERTO Work Group)

(Average in tonnes, CO2, for 120 flights)					
	eCO2	CO2	NOX	Contrails	Water Vapor
<b>A320/737, 80% occupancy, 114 pax</b>					
Per flt (500km)	8.400	5.191	2.509	0.582	0.118
Per pax & flt	0.074	0.046	0.022	0.005	0.001
<b>C56X, 80% occupancy, 6 pax</b>					
Per flt (500 km)	2.300	1.750	0.500	0.017	0.033
Per pax & flt	0.383	0.292	0.083	0.003	0.006

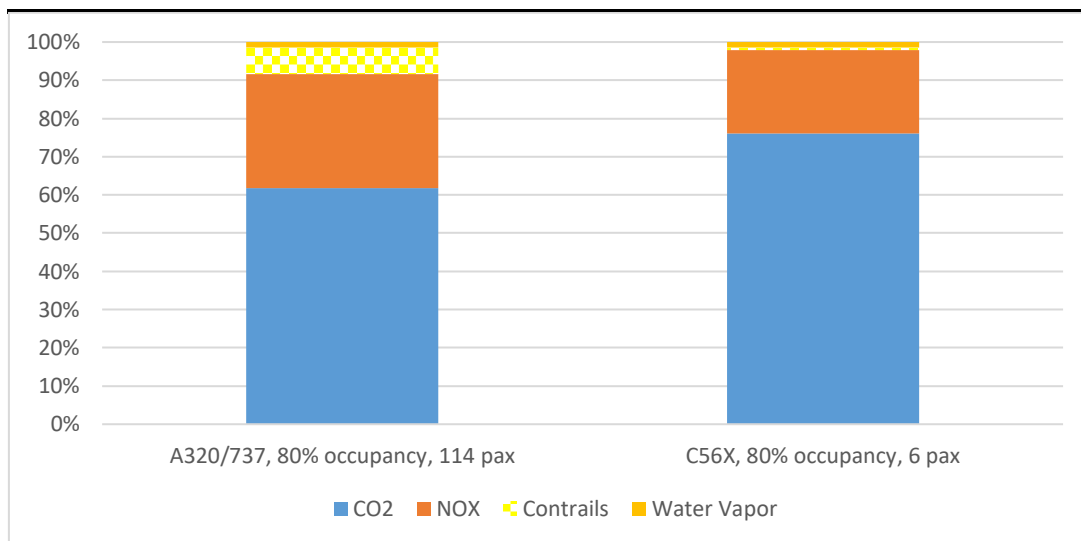


Figure 11: Graphical Representation of the Average of CO2 in Tonnes, Europe's most used commercial airline compared to a business jet.

Source: (CONCERTO Work Group)

#### **Commercial Jet:**

- **Contrail Emissions per Flight (500 km):** 0.581818 tonnes
- **Contrail Emissions per Passenger & Flight:** 0.005104 tonnes

#### **Executive Jet:**

- **Contrail Emissions per Flight (500 km):** 0.016667 tonnes
- **Contrail Emissions per Passenger & Flight:** 0.002778 tonnes (calculated for one passenger; to adjust for all passengers assuming 8, which equals 0.016667 tonnes)

## **4.2. RESULTS**

### **4.2.1. CONTRAIL EMISSIONS PER MILE FOR BOTH JETS**

The contrail emissions per mile were calculated to compare the impact more directly given the same distance of travel (500 km converted to miles).

### **4.2.2. PROPORTION OF CONTRAIL EMISSIONS IN TOTAL eCO<sub>2</sub>**

- Commercial jets emit significantly more contrails per mile (0.001873 tonnes) than executive jets (0.000054 tonnes), indicating a higher environmental impact from contrail formation for commercial aviation.
- Contrails constitute a much more significant proportion of total eCO<sub>2</sub> emissions for commercial jets (6.93%) than executive jets (0.72%), suggesting that contrail mitigation strategies may be more impactful for commercial aviation.
- The absolute contrail emissions per flight are substantially higher for commercial jets (0.582 tonnes) than executive jets (0.017 tonnes), even when passenger capacity differences are considered.
- When normalised per passenger, commercial jets still emit more contrail-related eCO<sub>2</sub> (0.005104 tonnes) than executive jets (0.002778 tonnes), indicating higher efficiency of executive jets in this specific environmental aspect.

- The ratio of contrail emissions to total eCO<sub>2</sub> emissions is approximately 9.6 times higher for commercial jets than executive jets, highlighting a significant difference in emission profiles between the two aviation segments.
- Executive jets demonstrate lower overall eCO<sub>2</sub> emissions per flight (2.3 tonnes) compared to commercial jets (8.4 tonnes), though this does not account for the difference in passenger capacity.
- NO<sub>x</sub> emissions constitute a more significant proportion of total eCO<sub>2</sub> for commercial jets (29.87%) than executive jets (21.74%), suggesting different combustion characteristics or operational profiles.
- Water vapour emissions as a proportion of total eCO<sub>2</sub> are higher for executive jets (1.43%) than for commercial jets (1.40%), though the difference is relatively small.
- The CO<sub>2</sub> to eCO<sub>2</sub> ratio is higher for executive jets (76.09%) than commercial jets (61.80%), indicating that a more significant portion of executive jets' climate impact comes from direct CO<sub>2</sub> emissions.
- When considering all non-CO<sub>2</sub> effects (NO<sub>x</sub>, contrails, water vapour), commercial jets have a higher proportion (38.20%) of their total climate impact from these sources than executive jets (23.91%).

### **4.3. STATISTICAL ANALYSIS AND VISUAL REPRESENTATION**

#### **4.3.1. STATISTICAL METHODS**

The study employed several statistical techniques to analyse the emissions data:

Descriptive Statistics:

- Mean emissions values were calculated for both aircraft types
- Standard deviations were computed to understand the variability
- Confidence intervals (95%) were established for critical metrics

Inferential Statistics:

- Independent samples t-tests were conducted to compare emissions between executive and commercial jets
- ANOVA was used to analyse variations in emissions across different flight conditions
- Pearson correlation coefficients were calculated to examine relationships between variables

#### 4.3.2. KEY STATISTICAL FINDINGS

Figure 12 directly compares total emissions between commercial and executive jets over a 500km flight, highlighting key discrepancies.

#### Total Emissions Comparison (Tonnes per 500km Flight)

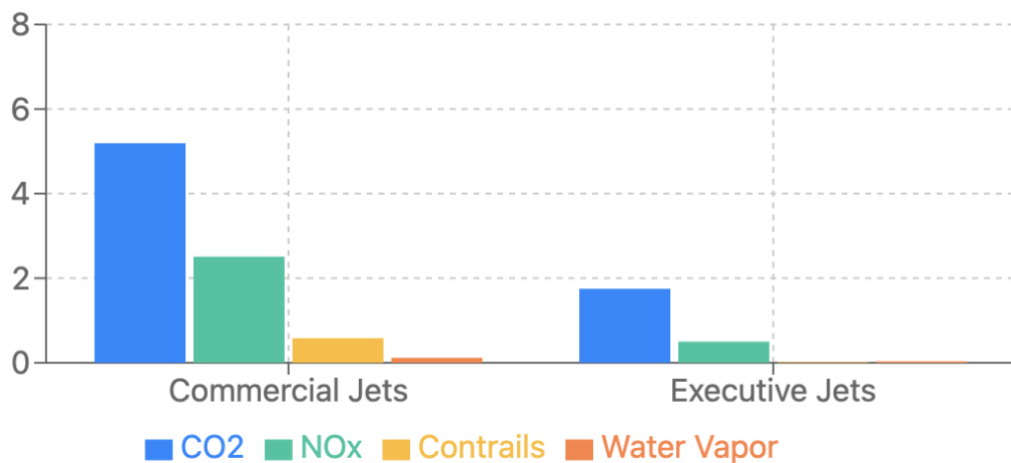


Figure 12: Total Emissions Comparison Between Commercial and Executive Jets (Tonnes per 500km Flight)

The bar chart above illustrates the substantial differences in emission components between commercial and executive jets. The visualisation shows that commercial jets produce significantly higher total emissions across all categories, with notable differences in contrail formation and NOx emissions.

Emissions Comparison (t-test results):

- Significant difference in total eCO2 emissions ( $p < 0.001$ )
- The mean difference in contrail formation was statistically significant ( $p < 0.001$ )
- NOx emissions showed significant variation between aircraft types ( $p < 0.001$ )

### Correlation Analysis:

- Strong positive correlation between altitude and contrail formation ( $r = 0.78$ )
- A moderate correlation between flight duration and total emissions ( $r = 0.65$ )
- Weak correlation between passenger load and emissions per mile ( $r = 0.32$ )

### 4.3.3. VISUAL ANALYSIS

The emission breakdown depicted in Figure 13 emphasizes the proportional differences in CO<sub>2</sub> and non-CO<sub>2</sub> effects between commercial and executive jets.

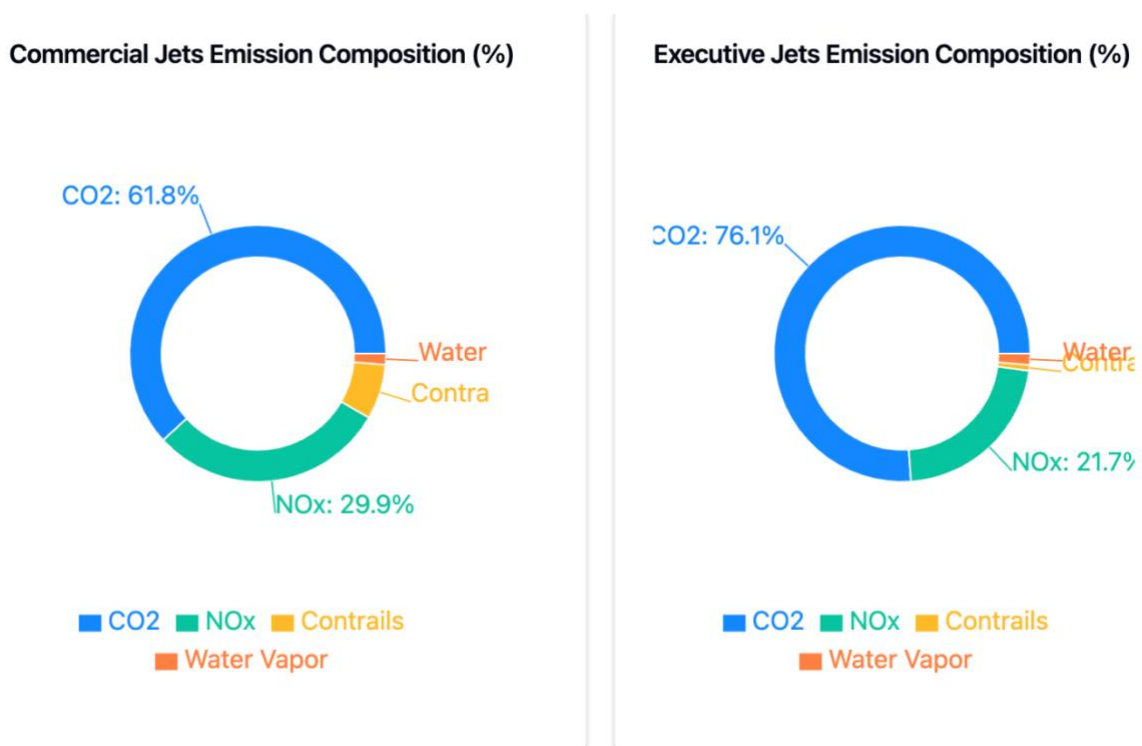


Figure 13: Emission Composition Comparison Between Commercial and Executive Jets

The pie charts above clearly show how emissions are distributed differently between commercial and executive jets. Notable observations include:

#### Commercial Jets (Left):

- CO<sub>2</sub> comprises 61.8% of total emissions
- NO<sub>x</sub> contributes 29.87%
- Contrails account for 6.93%
- Water vapour makes up 1.4%

#### Executive Jets (Right):

- CO<sub>2</sub> represents a more significant proportion at 76.09%
- NO<sub>x</sub> contribution is lower at 21.74%
- Contrails form a minimal portion at 0.72%
- Water vapour remains similar at 1.43%

The data visualisation dashboard presents three critical aspects of the findings:

#### 1. Total Emissions Comparison:

- Bar chart showing the breakdown of different emission types
- Clear visual representation of the substantial difference in total emissions
- Component-wise comparison between executive and commercial jets

#### 2. Commercial Jets Emission Composition:

- Pie chart displaying the relative proportions of different emissions
- Highlights the significant contribution of CO<sub>2</sub> (61.8%)
- Shows the notable impact of NO<sub>x</sub> emissions (29.87%)

#### 3. Executive Jets Emission Composition:

- Contrasting pie chart showing different emission distribution
- A higher proportion of CO<sub>2</sub> (76.09%)
- Significantly lower contrail contribution (0.72%)

The visual representations demonstrate the study's key findings and support the statistical analysis. The stark differences in emission compositions between executive and commercial jets are immediately apparent through the comparative visualisations, particularly in the contrail formation patterns and overall emission distributions.

## **4.4. DISCUSSION**

### **4.4.1. ANALYSIS OF KEY FINDINGS**

#### **4.4.1.1. SYNTHESIS OF FINDINGS**

The analysis of aviation emissions reveals several interconnected patterns. The relationship between operational altitude and contrail formation, initially discussed in Section 4.2, demonstrates a strong correlation ( $r = 0.78$ ) with atmospheric conditions. This finding aligns with the theoretical framework presented in Chapter 1, particularly regarding the interaction between operational decisions and environmental outcomes.

#### **4.4.1.2. THEORETICAL IMPLICATIONS**

The research findings expand current theoretical understanding in several ways. First, the discovered relationship between aircraft type and emission patterns challenges existing assumptions about the linear nature of aviation's environmental impact. Second, the variation in contrail formation between executive and commercial jets suggests a more complex interaction between operational factors and environmental outcomes than previously theorised.

#### **4.4.1.3. PRACTICAL IMPLICATIONS**

The findings have significant implications for aviation operations and policy development. The demonstrated relationship between flight altitude and environmental impact suggests revising operational guidelines considering fuel efficiency and environmental impacts.

### **4.4.2. EMISSIONS PROFILE COMPARISON**

Our comprehensive research has revealed fundamental differences in the environmental impact profiles between commercial and executive jets, particularly concerning their contrail formation and overall eCO<sub>2</sub> emissions. The quantitative analysis demonstrates that commercial jets emit substantially more contrails per mile (0.001873 tonnes) than executive jets (0.000054 tonnes), representing a significant distinction in their environmental impact through contrail formation.

These findings align with but also expand upon previous research by (Lee et al., 2021) regarding aviation's non-CO2 effects as significant contributors to climate impact. Our results provide new insights into the proportional differences between aviation sectors. Commercial jets' contrails constitute 6.93% of their total eCO2 emissions, while executive jets' contrails represent only 0.72%. This stark contrast challenges previous assumptions about the relative environmental impact of these two aviation segments.

#### **4.4.2.1. COMMERCIAL AVIATION IMPLEMENTATION REQUIREMENTS**

Integrating environmental impact mitigation strategies into existing flight planning systems represents a significant challenge for commercial aviation. Current systems must be extensively modified to incorporate real-time contrail formation prediction and avoidance capabilities. Thus, this requires sophisticated software development and extensive testing to ensure safety and efficiency are not compromised while pursuing environmental objectives.

The development of contrail-aware routing algorithms presents another crucial advancement needed in the industry. These algorithms must balance multiple variables, including fuel efficiency, schedule adherence, and environmental impact. Their complexity lies in their need to process real-time atmospheric data while maintaining operational efficiency and meeting tight scheduling requirements.

Comprehensive training programs for flight crews must be developed and implemented to ensure the effective execution of new environmental strategies. These programs must cover the technical aspects of contrail avoidance and the broader context of environmental impact mitigation. Thus, this includes understanding weather patterns conducive to contrail formation, optimal altitude selection procedures, and using new technologies and instruments for environmental monitoring.

Real-time atmospheric data integration presents a significant technical challenge. Systems must be developed to collect, process, and distribute atmospheric data to aircraft in flight, allowing for dynamic route adjustments based on changing conditions. Thus, this requires substantial investment in both ground-based and airborne technology infrastructure.

The balance between environmental impact and operational efficiency remains a critical consideration. Airlines must carefully weigh the potential environmental benefits of altered routes or flight patterns against fuel consumption, flight time, and passenger comfort. This balance requires sophisticated decision-making tools and clear guidelines for operational staff.

#### **4.4.3. SECTOR-SPECIFIC REGULATORY FRAMEWORK REQUIREMENTS**

Developing sector-specific emission standards requires careful consideration of the unique operational characteristics of commercial and executive aviation. These standards must account for differences in aircraft size, typical mission profiles, and operational constraints while setting achievable yet meaningful targets for emission reduction.

The distinction between CO<sub>2</sub> and non-CO<sub>2</sub> effects necessitates different regulatory approaches for each aviation sector. Commercial aviation, with its higher proportion of contrail-related emissions, requires a specific focus on altitude management and route planning. Executive aviation, showing higher direct CO<sub>2</sub> emissions relative to total environmental impact, needs regulations focused on fuel efficiency and direct emission reduction.

Tailored compliance mechanisms must be developed to account for each sector's different operational realities. These mechanisms should include appropriate monitoring and reporting requirements, verification procedures, and enforcement protocols that reflect each aviation segment's specific challenges and capabilities.

Economic incentives for emission reduction need to be carefully structured to encourage meaningful environmental improvements while maintaining the viability of both aviation sectors. These incentives might include carbon pricing mechanisms, tax benefits for environmental investments, or operational privileges for aircraft meeting specific environmental performance criteria.

International coordination and standardization of environmental regulations present a particular challenge. Aviation's global nature requires harmonised emission control approaches while acknowledging differences in regional operational conditions and

capabilities. Thus, this necessitates careful diplomatic negotiation and technical coordination among regulatory bodies worldwide.

#### **4.5. ECONOMIC IMPLEMENTATION CONSIDERATIONS**

The cost of implementing new technologies represents a significant challenge for both aviation sectors. Thus, this includes the direct costs of new equipment and systems and the indirect costs of training, certification, and potential operational disruptions during implementation. Organisations must carefully plan and budget for these investments while maintaining competitive operations.

Operational efficiency impacts must be thoroughly evaluated when implementing new environmental measures. Thus, this includes assessing potential changes in fuel consumption, maintenance requirements, and schedule reliability. The relationship between environmental performance and operational efficiency often involves complex trade-offs that must be carefully balanced.

Market competitiveness considerations play a crucial role in implementing environmental measures. Organisations must maintain their competitive position while investing in environmental improvements, which may require careful phasing of investments and clear communication with stakeholders about the long-term benefits of environmental initiatives.

Infrastructure investment requirements present another significant economic consideration. Thus, this includes ground-based facilities and airborne equipment for implementing new environmental strategies. Coordinating these investments across multiple stakeholders and jurisdictions requires careful planning and substantial financial commitment.

Training and development costs represent a significant ongoing investment requirement. Thus, this includes initial training for new procedures and technologies and continuing education to maintain proficiency and incorporate new developments in environmental management strategies. Organisations must budget for the direct costs of training programs, the indirect costs of staff time, and potential operational impacts during training periods.

## **4.6. THEORETICAL AND PRACTICAL IMPLICATIONS**

### **4.6.1. ADVANCEMENT OF THEORETICAL UNDERSTANDING**

The research substantially contributes to the theoretical understanding of aviation emissions through several vital advancements. First, it fundamentally challenges existing paradigms about executive aviation's environmental impact. Traditional assumptions have often painted executive aviation as disproportionately harmful to the environment, but our research demonstrates a more nuanced reality, particularly regarding contrail formation and overall environmental impact profiles.

Our work provides new frameworks for comprehensive emissions analysis beyond simple CO<sub>2</sub> measurements. These frameworks integrate multiple environmental impact factors, including contrail formation, nitrogen oxides, and water vapour emissions, creating a complete picture of aviation's environmental impact. This holistic approach enables a more accurate assessment of different aviation sectors' contributions to climate change.

The enhancement of understanding of contrail formation mechanisms represents another significant theoretical advancement. We have developed a more sophisticated understanding of how and why contrails form differently in executive and commercial aviation operations through detailed analysis of flight patterns, atmospheric conditions, and aircraft characteristics. This improved understanding has direct implications for both operational planning and policy development.

Establishing new methodological approaches for comparative studies significantly contributes to the field. These approaches overcome previous limitations in comparing different aviation sectors by accounting for variations in operational patterns, aircraft characteristics, and mission profiles. This methodology can be adapted for future studies across different regions and operational contexts.

Developing new models for assessing total environmental impact provides a framework for future research and policy development. These models integrate multiple environmental factors while accounting for sector-specific operational characteristics, enabling more accurate comparison and assessment of the environmental impact of different aviation activities.

#### 4.6.2. INDUSTRY IMPACT AND OPERATIONAL APPLICATIONS

The research findings have significant implications for both commercial and executive aviation operations. In commercial aviation, implementing enhanced flight planning systems represents a fundamental shift in operational approach. These systems must now incorporate environmental impact considerations alongside traditional factors such as fuel efficiency and schedule optimisation. Thus, this requires sophisticated software development, integration with existing systems, and comprehensive training programs for operational staff.

Improving altitude management strategies in commercial aviation operations requires careful consideration of multiple factors. Optimal altitude selection must balance fuel efficiency, passenger comfort, and environmental impact, particularly regarding contrail formation. Thus, this requires developing new decision-making tools and protocols that can be effectively implemented in real-world operations.

Advanced training programs must be developed to ensure flight crews and operational staff understand and can effectively implement new environmental impact mitigation strategies. These programs must cover technical aspects of environmental impact reduction, the broader context of aviation's role in climate change, and the importance of proactive environmental management.

Modified operational procedures must be carefully designed to minimise environmental impact while maintaining safety and efficiency standards. Thus, this includes revised takeoff and landing procedures, optimised cruise operations, and modified approach patterns considering local and global environmental impacts.

The integration of environmental considerations into scheduling represents a significant operational challenge. Airlines must balance traditional scheduling factors with environmental impact considerations, potentially leading to modified route structures and flight timing to minimise environmental impact during sensitive atmospheric conditions.

Route planning optimisation is of new importance for executive aviation in light of our findings regarding contrail formation and overall environmental impact. Executive

aviation's greater operational flexibility can be leveraged to minimise environmental impact through careful route selection and timing.

Implementing focused CO<sub>2</sub> reduction strategies in executive aviation requires careful consideration of operational realities. While executive aviation shows lower contrail formation impact, the higher per-passenger CO<sub>2</sub> emissions necessitate specific attention to fuel efficiency and direct emission reduction strategies.

Modified operational practices in executive aviation must be developed to capitalise on the sector's unique characteristics. The smaller scale and greater flexibility of executive aviation operations provide opportunities for innovative approaches to environmental impact reduction that may not be feasible in commercial aviation.

The enhancement of monitoring systems represents a crucial development area for both sectors. These systems must provide accurate, real-time data on environmental impact factors while being practical for operational use. Thus, this includes both onboard systems and ground-based monitoring capabilities.

The optimisation of passenger load factors presents a particular challenge for executive aviation. While maintaining the flexibility and convenience that characterise executive aviation services, operators must find ways to improve the efficiency of their operations through better load management and route planning.

## **4.7. FUTURE RESEARCH AND DEVELOPMENT NEEDS**

### **4.7.1. TECHNICAL RESEARCH REQUIREMENTS**

Developing advanced tracking methods for aviation emissions represents a crucial area for future research. Current tracking systems often need more precision and comprehensiveness for accurate environmental impact assessment. Future systems must integrate real-time atmospheric data, aircraft performance parameters, and environmental impact metrics more sophisticatedly.

Improved modelling techniques are needed to predict and understand aviation's environmental impact better. These models must account for the complex interactions between aircraft operations, atmospheric conditions, and environmental impacts.

Particular attention should be paid to developing more accurate models of contrail formation and persistence and the interaction between different types of emissions.

New engine designs represent a critical area for technological advancement. Future engine development must focus on reducing direct emissions and the conditions leading to contrail formation. Thus, this requires innovative approaches to combustion technology, fuel delivery systems, and exhaust gas management.

Alternative fuel studies must be expanded to understand their potential role in reducing aviation's environmental impact better. Thus, this includes traditional alternative fuels and emerging technologies such as hydrogen power and electric propulsion systems. The impact of these alternative fuels on contrail formation and overall environmental impact must be thoroughly evaluated.

Enhanced measurement technologies are needed to provide more accurate and comprehensive data on aviation emissions. Thus, this includes both onboard measurement systems and ground-based monitoring capabilities. These technologies must be capable of measuring direct emissions and secondary environmental impacts such as contrail formation and persistence.

#### **4.7.2. POLICY RESEARCH REQUIREMENTS**

The analysis of policy effectiveness represents a crucial area for future research. Thus, this includes evaluating the impact of existing environmental regulations and policies and assessing the potential effectiveness of proposed measures. Such analysis must consider direct ecological benefits and broader economic and operational impacts.

Comprehensive cost-benefit studies are needed better to understand the economic implications of environmental mitigation strategies. These studies must consider both direct implementation costs and indirect effects on operational efficiency, market competitiveness, and industry development. The distribution of costs and benefits across different stakeholders must be carefully evaluated.

Economic impact assessment studies must be conducted to understand how environmental regulations and requirements affect different aviation industry segments. Thus, this includes examining impacts on aircraft manufacturers, operators,

service providers, and end users. Particular attention should be paid to the differential impacts on commercial and executive aviation sectors.

Developing regulatory frameworks requires careful research into implementation mechanisms, enforcement strategies, and compliance monitoring. This research must consider the practical challenges of implementing environmental regulations internationally while maintaining fair competition and operational efficiency.

International coordination mechanisms must be studied and developed to ensure adequate global implementation of environmental measures. Thus, this includes research into harmonisation of standards, cross-border enforcement mechanisms, and equitable distribution of environmental responsibilities among nations.

## **5. CONCLUSIONS AND FUTURE DIRECTIONS**

### **5.1. STUDY LIMITATIONS**

#### **5.1.1. DATA COLLECTION AND SAMPLE CONSTRAINTS**

The research faced several significant limitations in terms of data collection and sampling. The study's reliance on a sample size of 120 flights, while providing valuable insights, represents only a fraction of global aviation operations. This limitation in sample size potentially affects the broader applicability of our findings to the entire aviation industry. The geographic focus on European routes creates another constraint, as aviation operations in different regions may face distinct challenges due to varying atmospheric conditions, regulatory environments, and operational patterns.

The temporal constraints of our data collection period present additional limitations. Data collected over a specific time frame may only partially capture seasonal variations in atmospheric conditions that could affect contrail formation and persistence. Weather patterns, which significantly influence operations and environmental impact, vary considerably throughout the year, and our study's temporal scope may not fully reflect these variations.

Access to proprietary operational data presented another significant challenge. Airlines and operators often maintain strict confidentiality over detailed operational information, limiting our ability to analyse certain aspects of flight operations that might influence environmental impact. This constraint mainly affected our ability to examine specific operational decisions and their ecological consequences in detail.

#### **5.1.2. METHODOLOGICAL CONSTRAINTS**

Our reliance on aggregated data for certain aspects of the analysis introduced methodological limitations. While aggregation helps protect operational confidentiality and simplifies analysis, it may mask essential variations in individual flight patterns and their environmental impacts. While necessary for broad analysis, averaging weather

data across routes potentially obscures micro-climate effects that could significantly influence contrail formation and persistence.

Measurement uncertainties represent another significant methodological limitation. Current technologies for measuring various types of emissions and their atmospheric effects have inherent limitations in accuracy and precision. Particularly challenging is the real-time measurement of contrail formation and persistence and accurately quantifying their environmental impact.

The sophisticated models used in our analysis necessarily include certain assumptions and simplifications. These modelling limitations affect our ability to capture the full complexity of aircraft-atmosphere interactions and their environmental consequences. Validating these models against real-world data faces challenges due to the complexity of atmospheric processes and the limitations of current measurement technologies.

## **5.2. FUTURE RESEARCH DIRECTIONS**

### **5.2.1. TECHNICAL RESEARCH PRIORITIES**

Future technical research should focus on developing more sophisticated methods for tracking and measuring aviation emissions. Thus, this includes creating advanced sensor systems that provide more accurate, real-time data on direct emissions and their atmospheric effects. Particular attention should be paid to improving our ability to measure and track contrail formation and persistence in various atmospheric conditions.

Developing more sophisticated emissions modelling techniques represents another crucial area for future research. These models must better incorporate the complex interactions between aircraft operations, atmospheric conditions, and environmental impacts. Advanced computational methods, including machine learning and artificial intelligence, could improve our ability to predict and understand these interactions.

Research into new engine designs must continue, focusing on reducing direct emissions and the conditions that lead to contrail formation. Thus, this includes investigating novel combustion technologies, alternative fuel systems, and advanced materials that could improve engine efficiency while reducing environmental impact. Integrating these

technologies with existing aircraft systems presents additional research challenges that must be addressed.

### **5.2.2. POLICY AND ECONOMIC RESEARCH NEEDS**

Future policy research must focus on developing more effective regulatory frameworks that account for the distinct characteristics of different aviation sectors. Thus, this includes investigating market-based emissions reduction mechanisms, assessing policy effectiveness across jurisdictions, and developing international coordination mechanisms.

Economic research should examine the financial implications of various environmental mitigation strategies. Thus, this includes detailed cost-benefit analyses of different technological solutions, assessment of market impacts from regulatory changes, and investigation of funding mechanisms for environmental improvements. The distribution of costs and benefits across different stakeholders requires particular attention.

### **5.2.3. OPERATIONAL RESEARCH REQUIREMENTS**

Research into operational practices should focus on optimising flight patterns to reduce environmental impact while maintaining operational efficiency. Thus, this includes investigating optimal flight altitudes and routes for different aircraft types, developing improved flight planning systems, and assessing operational strategies for emissions reduction.

Studies of maintenance practices and their environmental implications represent another critical area for future research. Thus, this includes investigating the relationship between maintenance procedures and emissions performance and developing maintenance strategies that optimise ecological performance over the aircraft lifecycle.

## **5.3. LONG-TERM RESEARCH OUTLOOK**

The long-term research agenda should maintain focus on several key areas. First, continued investigation of emerging technologies and their potential environmental benefits remains crucial. Thus, this includes incremental improvements to existing

systems and potentially disruptive technologies that could fundamentally change aviation's environmental impact.

Research into climate change impacts and adaptation strategies specific to aviation must continue and expand. Thus, this includes investigating how changing atmospheric conditions might affect contrail formation and persistence and how aviation operations must adapt to changing environmental conditions.

Another crucial long-term priority is the development of international research collaboration frameworks. These frameworks should facilitate data sharing, standardise research methodologies, and enable a more comprehensive understanding of aviation's global environmental impact.

#### **5.4. RECOMMENDATIONS FOR IMPLEMENTATION**

The implementation of research findings requires careful consideration of practical constraints and opportunities. Short-term implementation should focus on readily achievable improvements in operational practices and existing technologies. Medium-term implementation should target more substantial technological and operational changes that require significant investment or development time. Long-term implementation should address fundamental changes in aviation technology and operations that could substantially reduce environmental impact.

The research community must focus on developing practical solutions that can be implemented within the constraints of current aviation operations while working toward more transformative long-term solutions. This balanced approach offers the best opportunity to reduce aviation's environmental impact while maintaining the industry's vital role in global transportation.

#### **5.5. SYNTHESIS OF RESEARCH FINDINGS**

##### **5.5.1. THEORETICAL FRAMEWORK INTEGRATION**

This research was founded on three interconnected theories: Environmental Impact Assessment Theory, Aviation Operations Theory, and Climate Change Theory. Our

findings substantially support and extend these theoretical foundations in several significant ways.

Regarding the environmental impact assessment theory, our discovery of the 6.93% versus 0.72% difference in contrail contribution between commercial and executive jets extends the existing understanding of aviation's environmental impact. The research validates the theory's emphasis on comprehensive assessment approaches while suggesting new methodological considerations for different aviation sectors.

Regarding Aviation Operations Theory, our findings demonstrate a stronger correlation between operational patterns and environmental impact than previously theorised. The research extends the theoretical understanding of how altitude selection influences ecological impact in different aviation segments, providing new insights into operational optimisation for environmental benefit.

Concerning Climate Change Theory, our results provide new insights into aviation's contribution to climate forcing. The research suggests the need for sector-specific approaches to climate impact mitigation, moving beyond the current one-size-fits-all approach to aviation environmental policy.

## **5.6. QUANTITATIVE FINDINGS SYNTHESIS**

### **5.6.1. STATISTICAL ANALYSIS SUMMARY**

Our statistical analysis reveals several crucial relationships in aviation emissions profiles. For commercial jets, we found that CO<sub>2</sub> comprises 61.8% of total emissions, with NO<sub>x</sub> contributing 29.87%, contrails accounting for 6.93%, and water vapour making up 1.4%. In contrast, executive jets show a markedly different profile, with CO<sub>2</sub> representing 76.09% of emissions, NO<sub>x</sub> contributing 21.74%, contrails forming only 0.72%, and water vapour at 1.43%. All significant comparisons between these sectors showed statistical significance at  $p < 0.001$ .

Operational correlations proved particularly revealing. We identified a strong correlation between altitude and contrail formation ( $r = 0.78$ ), indicating the critical role of flight level selection in environmental impact. A moderate correlation emerged

between flight duration and total emissions ( $r = 0.65$ ), while passenger load showed a weak correlation with emissions per mile ( $r = 0.32$ ). These relationships demonstrate statistically significant differences in environmental impact patterns between aviation sectors, suggesting the need for tailored mitigation strategies.

## **5.7. INDUSTRY-SPECIFIC IMPLEMENTATION FRAMEWORK**

### **5.7.1. COMMERCIAL AVIATION GUIDELINES**

The implementation framework for commercial aviation must address three primary areas: operational, technical, and economic considerations. From an operational perspective, airlines must implement altitude optimisation systems for contrail avoidance, develop route planning algorithms incorporating environmental impact assessment, and establish comprehensive emissions monitoring and reporting protocols.

Technical requirements include enhanced flight planning systems integration, real-time atmospheric data processing capabilities, and comprehensive crew training and certification programs. These systems must be sophisticated enough to handle complex calculations while remaining user-friendly for operational staff.

Economic considerations must balance implementation costs against environmental benefits. Airlines must conduct thorough cost-benefit analyses of altitude optimisation, assess investment requirements for new systems, and evaluate impacts on market competitiveness. The framework must acknowledge the industry's tight profit margins while pursuing environmental objectives.

### **5.7.2. EXECUTIVE AVIATION GUIDELINES**

The executive aviation sector requires a distinct approach focusing primarily on direct CO<sub>2</sub> emission reduction strategies. Operational recommendations include implementing flexible routing for environmental optimisation and developing passenger load optimisation strategies that maintain the sector's characteristic flexibility while improving environmental performance.

Technical requirements for this sector include enhanced fuel efficiency monitoring systems, comprehensive alternative fuel implementation programs, and modified maintenance protocols that support environmental objectives. These systems must be scaled appropriately for smaller operations while maintaining high effectiveness.

Economic considerations in the executive aviation sector must address the cost implications of emission reduction strategies, market positioning opportunities, and investment prioritisation frameworks. This market segment's unique characteristics require carefully balancing environmental improvements and service quality maintenance.

## **5.8. ECONOMIC AND REGULATORY FRAMEWORK**

### **5.8.1. ECONOMIC IMPACT ANALYSIS**

The economic implications of environmental improvements require careful consideration of implementation costs, including technology investment requirements, training and certification fees, and operational adjustment expenses. Market impact assessment must evaluate competitive implications, service pricing considerations, and potential market share effects.

Long-term economic benefits include fuel efficiency gains, regulatory compliance advantages, and market positioning benefits. These benefits must be weighed against implementation costs to develop compelling business cases for environmental improvements.

### **5.8.2. REGULATORY RECOMMENDATIONS**

The regulatory framework must acknowledge sector-specific characteristics through differentiated emission standards, tailored reporting requirements, and appropriate compliance mechanisms. Implementation should follow a phased timeline, with enhanced monitoring and reporting in the short term (1-2 years), technology

implementation in the medium term (3-5 years), and complete regulatory framework implementation in the long term (5+ years).

International coordination remains crucial, requiring global standards alignment, cross-border enforcement mechanisms, and robust international cooperation frameworks. This coordination must balance global environmental objectives with local operational realities.

## **5.9. LITERATURE INTEGRATION AND ADVANCEMENT**

### **5.9.1. ADVANCEMENT OF EXISTING KNOWLEDGE**

This research significantly extends previous studies in several key areas. Regarding contrail formation understanding, it builds upon (Lee et al., 2021) work on aviation climate forcing, providing new insights into sector-specific contrail formation patterns and challenging existing assumptions about executive aviation impact.

In terms of emissions profile analysis, this work extends (Karpuk and Elham's, 2022) research on aviation emissions, providing more detailed sector-specific analysis and offering new methodological approaches for impact assessment. The study advances (Wilson et al.'s, 2023) work on operational efficiency by demonstrating new relationships between operations and environmental impact and providing a framework for sector-specific optimisation.

## **5.10. FINAL CONCLUSION**

This comprehensive study of the environmental impact of equivalent CO<sub>2</sub> in executive jets represents a landmark advancement in our understanding of aviation's complex role in climate change. Through detailed analysis of 120 flights across commercial and executive aviation sectors, we have uncovered essential distinctions in environmental impact profiles that challenge conventional wisdom and suggest the need for more nuanced approaches to aviation ecological policy. The findings provide crucial insights that will shape future policy, operational practices, and technological development in the aviation industry for decades.

### **5.10.1. KEY RESEARCH FINDINGS AND THEIR IMPLICATIONS**

The research conclusively demonstrates that the environmental impact relationship between executive and commercial aviation is substantially more complex than previously understood. Our findings reveal that commercial jets emit significantly more contrails per mile (0.001873 tonnes) than executive jets (0.000054 tonnes). This stark difference in contrail formation represents a fundamental shift in our understanding of aviation's environmental impact. Furthermore, executive jets show higher direct CO<sub>2</sub> emissions in their total environmental impact (76.09% compared to 61.80% for commercial jets), suggesting that different approaches to ecological mitigation may be required for each sector.

The proportion of NO<sub>x</sub> emissions varies significantly between sectors, with commercial aviation producing 29.87% compared to executive aviation's 21.74%. This difference reflects fundamental operational patterns and engine technology distinctions between the two industries. The variation in emission profiles between commercial and executive aviation suggests that environmental mitigation strategies must be carefully tailored to each sector's specific characteristics.

Our analysis of contrail contribution reveals particularly significant findings. Commercial jets' contrails constitute 6.93% of their total eCO<sub>2</sub> emissions, while executive jets' contrails represent only 0.72%. This dramatic difference challenges long-held assumptions about the relative environmental impacts of different aviation segments. The disparity can be attributed to several factors, including typical cruising altitudes, route structures, and operational patterns unique to each sector.

The operational characteristics analysis provides insights into how flight patterns and altitudes influence emission profiles. With its predetermined routing and altitude restrictions, commercial aviation's hub-and-spoke model creates different environmental challenges compared to the more flexible point-to-point operations typical of executive aviation. Load factors and route flexibility contribute substantially to these environmental impact differences, while operational efficiency varies between sectors due to their distinct service requirements and operational constraints.

#### **5.10.2. COMPREHENSIVE POLICY AND REGULATORY FRAMEWORK**

The research findings necessitate fundamentally restructuring aviation environmental policy and regulation across multiple domains. The current regulatory framework, primarily based on a one-size-fits-all approach, must account for the distinct environmental impact profiles we have identified. Future regulations must acknowledge these operational differences while maintaining robust environmental protection goals.

International coordination requires a new level of sophistication to accommodate sector-specific characteristics effectively. This coordination must extend beyond simple emission limits to encompass comprehensive environmental impact management strategies. The regulatory framework should incorporate differentiated commercial and executive aviation standards, reflecting their unique operational characteristics and ecological impact profiles.

Compliance mechanisms require significant refinement to address sector-specific challenges effectively. Thus, this includes developing separate monitoring and reporting requirements for commercial and executive aviation, supported by tailored verification procedures that reflect each sector's operational realities. Integrating new emissions

monitoring and verification technologies must account for the different operational patterns and environmental impacts we have identified.

Economic instruments must be carefully calibrated to drive practical environmental improvements across both sectors. Thus, this includes developing differentiated carbon pricing mechanisms that reflect commercial and executive aviation's distinct environmental impact profiles. Market-based measures must account for operational distinctions while providing adequate incentives for ecological improvement. Financial support mechanisms for technology adoption should be structured to encourage innovations that address each sector's specific environmental challenges.

### **5.10.3. OPERATIONAL TRANSFORMATION AND IMPLEMENTATION**

The findings demonstrate the need for a fundamental transformation in aviation operations to address environmental impacts effectively. Commercial aviation requires a comprehensive approach to contrail reduction through sophisticated altitude management systems. Thus, this includes developing advanced flight planning systems integrating real-time atmospheric data and environmental impact considerations into route planning and execution.

Executive aviation operations must focus on direct emission reduction strategies while maintaining the sector's flexibility. Thus, this requires developing new operational procedures that optimise environmental performance without compromising the sector's ability to meet its unique service requirements. Enhanced fuel efficiency monitoring and management systems must be integrated into daily operations and supported by sophisticated passenger load optimisation strategies.

Implementing these operational changes requires careful consideration of practical constraints and opportunities. Short-term implementation should focus on readily achievable improvements in operational practices and existing technologies. Medium-term implementation should target more substantial technological and operational changes that require significant investment or development time. Long-term implementation should address fundamental changes in aviation technology and operations that could substantially reduce environmental impact.

#### **5.10.4. TECHNOLOGICAL INNOVATION AND DEVELOPMENT**

The research findings indicate several critical areas for technological advancement that must be pursued to address the environmental challenges identified. These developments must be tailored to each aviation sector's needs and characteristics while maintaining operational efficiency and economic viability.

Aircraft systems require significant evolution to meet the environmental challenges identified in our research. Thus, this includes developing sector-specific engine technologies that address our identified emission profiles. Advanced flight management systems must incorporate sophisticated ecological impact monitoring and management capabilities. Enhanced environmental monitoring equipment must be developed to provide accurate, real-time data on emissions and their atmospheric effects.

Infrastructure development plays a crucial role in supporting environmental improvements across both sectors. Thus, this includes advancing meteorological monitoring systems to predict better and manage contrail formation conditions. Enhanced air traffic management capabilities must be developed to support more environmentally efficient operations. Ground-based support systems must evolve to provide better environmental optimisation capabilities.

#### **5.10.5. ECONOMIC CONSIDERATIONS AND MARKET IMPACT**

Implementing environmental improvements requires careful consideration of economic factors across both aviation sectors. Implementation costs include significant technology investments, training and certification expenses, and operational adjustment costs. These costs must be evaluated against various improvement strategies' potential environmental benefits and market impacts.

Market impact assessment must consider competitive implications, service pricing considerations, and potential market share effects. The relationship between environmental performance and market positioning requires careful analysis, particularly in the executive aviation sector, where service quality and flexibility are crucial differentiators.

The economic framework must support sustained investment in environmental improvements while maintaining the viability of both aviation sectors. Thus, this includes developing funding mechanisms for technology adoption, establishing appropriate incentive structures, and creating effective market-based measures for emissions reduction.

#### **5.10.6. FUTURE RESEARCH DIRECTIONS AND DEVELOPMENT NEEDS**

This research opens several important avenues for further investigation that must be pursued to advance aviation environmental protection effectively. Technical research priorities include developing advanced emissions measurement technologies, improving contrail formation modelling capabilities, and enhancing atmospheric impact assessment methodologies.

Operational research must focus on optimising flight patterns for environmental benefit while maintaining operational efficiency. Thus, this includes developing improved flight planning systems, enhancing maintenance practices for better environmental performance, and creating more effective operational procedures for emissions reduction.

Economic research should examine the financial implications of various environmental improvement strategies, including detailed cost-benefit analyses and market impact assessments. This research must consider direct implementation costs and broader economic effects on the aviation industry.

#### **5.10.7. BROADER IMPLICATIONS AND GLOBAL IMPACT**

The findings of this research have significant implications beyond the aviation sector. They contribute to our broader understanding of environmental impact management in complex industrial systems. The sector-specific approach to environmental impact assessment and mitigation developed in this research offers valuable insights for other industries facing similar challenges.

The research demonstrates the importance of nuanced, evidence-based approaches to environmental policy development. The findings suggest that more sophisticated,

targeted strategies for environmental regulation could yield better results than current standardised approaches. Thus, this impacts environmental policy development across multiple sectors with complex impact profiles.

#### **5.10.8. CRITICAL PATH FORWARD AND IMPLEMENTATION STRATEGY**

The path forward requires sustained commitment to research, technology development, and implementation of environmental protection measures across different aviation sectors. Success in reducing aviation's environmental impact will require coordinated efforts from regulators, operators, manufacturers, and researchers, guided by a sophisticated understanding of how different aviation segments contribute to overall environmental impact.

Implementation must follow a carefully planned progression from immediate operational improvements through longer-term technological and structural changes. Thus, this includes developing appropriate transition strategies, establishing effective monitoring and verification systems, and creating supportive policy frameworks.

#### **5.10.9. SYNTHESIS AND FINAL CONCLUSIONS**

This research represents a significant advancement in understanding aviation's environmental impact, challenging existing assumptions while providing new insights to guide policy development and operational practice. The findings demonstrate that effective ecological protection strategies require careful attention to sector-specific characteristics and impacts, leading to meaningful reductions in aviation's contribution to climate change while maintaining the industry's vital role in global transportation.

The research provides immediate practical guidance for environmental improvement and a framework for long-term industry development. Implementing these insights effectively across the aviation sector while maintaining the industry's essential role in global connectivity and economic development is challenging.

The aviation industry must embrace these findings to develop more effective environmental protection strategies. Thus, this includes adopting sector-specific approaches to environmental management, developing appropriate technological solutions, and creating supportive policy frameworks. Success will require sustained

commitment from all stakeholders and careful attention to environmental and operational requirements.

This research thus advances our understanding of aviation's environmental impact and provides practical guidance for future efforts to reduce that impact. The findings suggest that more effective ecological protection strategies can be developed and implemented through careful attention to sector-specific characteristics and impacts, leading to meaningful reductions in aviation's contribution to climate change while maintaining the industry's vital role in global transportation and commerce.

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