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Quantifying the Environmental Impact of Private and Commercial Pilot License Training in Canada

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Abstract: As the global aviation sector expands to accommodate increasing air travel demand, the subsequent rise in flights exacerbates carbon dioxide (CO_2) emissions, challenging the sector's environmental sustainability. Targeting net-zero emissions by 2050, international aviation agencies are stressing the imperative of reducing emissions directly at their source. While the literature provides abundant estimates of aviation emissions from airline flights, there has been a lack of work aimed at quantifying CO_2 emissions specific to the general aviation sector. This study investigates CO_2 emissions attributed to the pilot training sub-sector within Canada's general aviation sector. It specifically examines the initial phase of pilot training, known as ab initio training, extending through to the attainment of a commercial pilot license. Utilizing a mathematical framework alongside assumptions, combined with data on license issuances over a 23-year period, it estimated that each hour of flight training emits about 70.4 kg of CO_2, varying between 44.9 kg and 94.9 kg per hour. Annual CO_2 emissions from Canada's ab initio pilot training are estimated at approximately 30,000 tons, with a possible range of 19,000 to 40,000 tons. The study also explores mitigation opportunities, such as flight simulation training devices and electric aircraft. Though focusing on Canada's ab initio pilot training, the findings have international relevance.

Keywords: CO_2 emissions; ab initio training; mitigation opportunities; flight simulation training device (FSTD); electric aircraft

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1. Introduction

The civil aviation industry has significantly grown over the years, with air transport now regarded as one of the world's fastest-growing modes of transportation. Although a severe disruption occurred at the height of the COVID-19 pandemic, the post-pandemic outlook indicates a tremendous demand for air travel. Consequently, the aviation sector is estimated to register an average annual growth of over 4% in the next few decades, with steady expansion expected across all regions [1]. Broadly speaking, sustainability can be defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [2,3]. Therefore, the projections for the aviation sector are sustainable only when growth is embraced in a multi-dimensional manner. To put that into perspective, sustaining this level of growth requires a holistic approach that emphasizes economic, social, and environmental sustainability [4,5]. Economic prosperity, awareness of social consequences, and a commitment to environmental protection are all essential for fostering responsible and ongoing operations. Therefore, for the aviation sector to grow sustainably, the focus must extend beyond infrastructure investments, new technologies, business strategies, and operational enhancements. It is equally important to address the ecological and human consequences resulting from the expansion of aviation activities [6].

Environmental sustainability has been a longstanding, industry-wide issue in aviation, with engine emissions being one of the key focus areas. Aircraft engines release a variety of greenhouse gases and other air pollutants from the burning of aviation gasoline or jet fuel. Carbon dioxide (CO_2), being a direct by-product of combustion, comprises the vast majority of aircraft emissions [7]. Because CO_2 exhibits persistence in the atmosphere [8,9], it is a potent greenhouse gas and one of the main contributors to climate change. Given the strong growth that the aviation sector has experienced in the last few decades, CO_2 emissions from global aviation have risen steadily. International air transportation data indicated that in 2013, global passenger and cargo airline operations contributed 706 million tons of CO_2 emissions [10]. By 2019, this figure rose to 920 million tons—a surge of over 30% in just 6 years, translating to an average annual growth rate exceeding 4.5% [10]. Given that the global CO_2 emissions for 2019 were estimated at 33.2 billion tons [11,12], the global airline operations contribution of 920 million tons constituted approximately 2.8% of global CO_2 emissions. However, this emission estimation does not include general aviation due to limited flight tracking and the availability of a comprehensive public database for general aviation [13–18]. Notably, general aviation encompasses all private and non-commercial aviation operations, excluding routine airline flights and fee-based cargo transport services, as defined by the International Civil Aviation Organization (ICAO) [19]. This distinction is critical as it highlights the broader aviation landscape beyond commercial airlines and cargo services, capturing the essence of private and non-commercial aviation activities that also impact the environment but are less frequently accounted for in global emissions data.

It is worth noting that the widespread grounding of flights during the COVID-19 pandemic in 2020 brought global aviation CO_2 emissions down to an annual estimate of 600 million tons. However, as travel restrictions began to ease with the pandemic's recovery, over a third of this temporary reduction was offset in 2021, resulting in an estimated annual 720 million tons of aviation CO_2 emissions [20]. Projections from [21,22] suggest that aviation CO_2 emissions will likely surpass 2019 levels by 2024 and are anticipated to rise rapidly in subsequent years. Given the expected growth in the aviation sector, its current 2.8% share of global CO_2 emissions could potentially increase to 15% by 2050 if environmental issues are not adequately addressed [23–26].

Research [23–26] extensively covers the environmental impact of commercial airline flights; however, a comprehensive evaluation of emissions across the entire aviation sector is essential for advancing sustainability. Recognizing the urgency for sustainability, international aviation agencies have emphasized the need for a detailed understanding of the environmental footprint across different aviation activities. This is crucial for devising effective reduction strategies. Among these, general aviation—comprising private flying, flight training, agricultural aviation, law enforcement surveillance, medical air transport, land surveying, and various non-scheduled commercial operations—stands out as a particularly underexplored area. The quantification of emissions from this wide array of activities is essential for developing targeted strategies to enhance the sustainability of the aviation sector as a whole. This paper narrows its focus to flight training within general aviation, aiming to pinpoint specific emission contributions and explore strategies for reducing their impact, thereby contributing to the advancement of sustainable aviation practices.

2. Literature Review and Motivation

Our literature review encompassed several databases, including Google Scholar, BASE, CORE, WorldCat, and RefSeek, using keywords relevant to our focused research area. These keywords encompassed 'Pilot Training Environmental Impact', 'General Aviation Emissions', 'Sustainability in Pilot Training', 'Eco-friendly Flight Training Practices', and 'General Aviation Sustainability Measures'. This approach was driven by the acknowledged need for a deeper dive into the environmental impacts within the general aviation sector, specifically within the realm of pilot training. Initially, our search returned over 500 articles, indicating a significant volume of work. However, through rigorous screening, we identified 39 papers based on their direct pertinence to understanding and addressing aviation emissions. From these, seven were selected for an in-depth review.

A Transport Canada report [27], developed with contributions from the aviation industry, reviews CO_2 emissions from domestic and international civil aviation operations from 2008 to 2019. It emphasizes the importance of collaborative actions, such as investing in new technologies and enhancing operations to reduce emissions. However, the report lacks a detailed methodology for calculating CO_2 emissions and does not provide a breakdown by sub-sector within civil aviation. Thus, to effectively set ambitious goals and devise strategies for reducing the sector's carbon footprint, precise emissions data and a clear analysis of different aviation sub-sectors are essential.

Wilkerson J et al.'s study offers a detailed analysis of CO_2 and other emissions from global commercial aviation in 2004 and 2006, serving as a baseline for assessing the impact of future technologies, operational improvements, and sustainable aviation fuels [28]. However, it is important that while the paper provides a thorough analysis of aviation emissions for specific years, it only focuses on commercial aviation, not other sectors of civil aviation.

Abrantes I et al.'s study estimates global CO_2 emissions reductions in the aviation sector by 2050, emphasizing the role of advanced aircraft technologies and sustainable aviation fuels [29]. By developing scenarios, the study assesses the impact of these strategies on global air transport fleet emissions. It offers detailed projections of CO_2 reductions in aviation, highlighting the sector's potential to significantly reduce its climate impact. The analysis is based on assumptions regarding technological progress, sustainable aviation fuel production, and adoption rates, which might not reflect the future complexities of these evolving areas. Additionally, the study considers the civil aviation sector uniformly, without providing a detailed breakdown of emissions across different sectors of aviation.

Masiol M and Harrison R's study analyzes aircraft engine emissions and airport-related air pollution, covering data until 2012 [30]. It evaluates civil aviation's environmental impact, focusing on CO_2 and other pollutants. The study highlights the sector's expansion due to developing economies and globalization, addressing the environmental challenges of emissions at cruising altitudes and air quality near airports. It stresses the importance of accurately estimating and mitigating aviation CO_2 emissions. While it does not provide new CO_2 emission estimates for aviation, it synthesizes existing research to underscore the significance of aviation emissions on both global and local air quality and the overall environmental footprint of civil aviation.

Zhou W et al.'s study estimates and analyzes future CO_2 emissions from China's civil aviation sector from 2015 to 2030 using scenario analysis [31]. This includes factors like low carbon jet fuel adoption, technological advancements in fuel efficiency, and rising air traffic demand. The study also reviews historical emissions from 1980 to 2013, noting a significant increase due to air traffic growth, to set a baseline for future growth projections. By providing a detailed analysis of historical and future emissions and suggesting policy measures for reduction, the study contributes to aviation CO_2 emissions literature. However, its focus is solely on China's civil aviation.

Puliafito S's study compiles a comprehensive CO_2 emissions inventory for Argentine civil aviation, covering both domestic and international flights from 2001 to 2021 [32]. It uses a methodology that considers flight altitude, aircraft types, and airline data, assessing efficiency improvements and sustainable aviation fuel production potential, with implications for environmental policy and industry practices. However, the study's generalized approach does not account for the specific operational and efficiency differences across aviation sub-sectors like commercial airlines, cargo flights, and general aviation, potentially obscuring variations in emissions intensity and reduction opportunities.

Quadros F et al.'s study estimates global civil aviation CO_2 emissions from 2017 to 2020, utilizing ADS-B receiver flight data, the BADA 3.15 model for aircraft specifics, and an international database for engine emissions [33]. This approach calculates the pollution generated by airplanes worldwide during this period. However, limitations include the lack of ADS-B transmitters on some aircraft and uneven geographical ADS-B coverage, possibly leading to emission underestimations in sparsely covered areas. Additionally, while the study showcases global estimates, it does not attempt to capture emissions variations across distinctive sectors within civil aviation.

Our literature review highlights a notable research gap regarding the estimation of CO_2 emissions within the civil aviation sector, both in Canada and globally. Existing research studies provide estimates that generalize the civil aviation sector, ignoring the nuanced differences of sub-sectors like general aviation. This lack of differentiation is critical, as a sub-sector like general aviation, covering a range of non-commercial and private operations, varies significantly from commercial aviation in fleet composition, operational practices, and fuel efficiency. Such variations imply that general aviation may have distinct CO_2 emissions trends, which are likely overlooked in broader sector analyses. Also, given the limited examination of sub-sectors within the civil aviation sector, the undertaking of estimating and understanding emissions related to operations in a specific sub-sector like general aviation remains largely unexplored. Consequently, the uniform approach to civil aviation emissions research may lead to generalized conclusions that fail to capture the sector's varied operational landscapes, potentially masking significant variations in emissions intensity and reduction opportunities across its respective sub-sectors.

To address this research gap, our study underscores the importance of dissecting emissions by sub-sector to uncover distinct challenges and opportunities for emissions mitigation. By zeroing in on general aviation, with a particular focus on flight training operations, we seek to determine the CO_2 emission contributions in this under-researched area and explore strategies for reducing their impact. This focused approach is imperative for creating holistic strategies that enhance the aviation sector's sustainability, thereby contributing significant insights to the progress of eco-friendly aviation practices.

3. Scope and Objective

Student pilots pursuing a Private Pilot License (PPL) or a Commercial Pilot License (CPL) in Canada must complete ground school, pass a written test, receive the requisite flight training, log the applicable number of flight hours, and pass a flight test administered by a certified examiner to obtain their license. Current training practice mainly uses the method of instructor tutoring, which has mostly been the same over the past decades.

The term 'ab initio', derived from Latin, means 'from the start' and is used to describe initial flight training programs for student pilots with no prior flying experience. Student pilots acquire pertinent aviation knowledge, such as rules of the air, navigation, and aircraft systems, in classrooms. Subsequently, they develop their flying skills through dual flight training with an instructor and solo flight in aircraft. Consequently, flight training contributes hundreds of thousands of tons of CO_2 emissions every year. While the demand for new pilots dropped significantly in 2020, the civil aviation industry foresees a notable uptick in the need for new pilots as air travel recovers post-pandemic. A Pilot Demand Outlook [34] published by CAE Inc. projects that between 2020 and 2030, Canada and the USA will require over 65,000 new pilots, while globally, the demand is set to exceed 264,000 new pilots. Age-based retirement, attrition, and fleet growth are projected to be the main drivers of the increasing demand for pilots. Although the training of airline pilots has increasingly relied on simulators, ab initio pilot training will still produce substantial emissions over at least several decades if it still follows the current practice.

This study examines CO_2 emissions originating from ab initio flight training within Canada's general aviation sector, covering the journey from the initial stages to the attainment of both the PPL and the CPL. While numerous studies in the past have estimated airline emissions, this study distinguishes itself by specifically analyzing the environmental impact of ab initio training in the general aviation sector and quantifying it in terms of CO_2 emissions. This area remains unexplored in the current body of literature, and quantifying these emissions addresses that research gap. To assess CO_2 emissions associated with ab initio flight training, the analysis in this study focuses on Canada as the geographical area of interest and relies on Transport Canada pilot licensing regulations and Canadian civil aviation licensing statistics to draw data-driven conclusions. The primary objective of this study is to provide methodological research to establish a baseline for CO_2 emissions associated with ab initio flight training.

4. Method and Materials

4.1. Mathematical Equation

A mathematical equation was developed to estimate the annual CO_2 emissions arising from flight training operations. This model incorporates a set of dependent variables, each playing an important role in determining the overall emissions. The mathematical model, along with a detailed description of each variable involved and the resulting output, is outlined below as Equation (1).

$$Annual\ Flight\ Training\ CO_2\ Emissions\ (average) = \overline{H} \times \overline{E} \times \overline{C} \times \overline{L} \quad (1)$$

where,

$\overline{H}$ = Flight Training Hours
$\overline{E}$ = Efficiency Factor
$\overline{C}$ = CO_2 emitted per flight hour
$\overline{L}$ = Annual Number of Licenses Issued.

The variable $\overline{H}$ represents the flight training hours, quantifying the average amount of hours spent on flight training operations over a year. The efficiency factor $\overline{E}$ variable accounts for variations in flight performance due to factors such as aircraft maintenance quality, pilot proficiency, weather conditions, or the specific nature of training maneuvers executed during flight hours. This non-dimensional coefficient adjusts the emissions estimate to reflect the operational efficiency or inefficiency of an aircraft relative to its baseline fuel consumption rate. The variable $\overline{C}$ represents the CO_2 emission rate per flight hour, specifying the average quantity of CO_2 produced for every hour of flight training. Meanwhile, the annual number of pilot licenses issued $\overline{L}$ denotes the average count of pilot licenses granted each year. Each of these is then multiplied together, with a resultant figure representing the average annual flight training CO_2 emissions, offering an estimate of the total carbon dioxide emissions generated by flight training operations over the span of a year. This mathematical equation considers not only the total training hours but also factors in the execution efficiency and the environmental impact measured through CO_2 emissions per training hour, alongside an influx of new pilots into the aviation sector.

4.2. Flight Training Hours ($\overline{H}$)

This study reviews private and commercial pilot license training with fixed-wing airplanes, the most common training pathway for aspiring pilots in Canada, and discusses the associated environmental impact. These training prerequisites strictly adhere to Transport Canada's regulatory standards, which mandate the required minimal numbers of flying hours for the development of psychomotor skills. In practice, students usually need more hours than the required minimal numbers to meet proficiency standards.

Pilot licensing in Canada is a staged process. In the context of private pilot license (PPL) requirements, the Canadian Aviation Regulations [35] indicates that a student pilot must complete a minimum of 45 h of private pilot-focused flight training in airplanes. Only a maximum of 5 h out of these 45 h can be completed in an approved flight simulation training device (FSTD). It should be noted that FSTD is an umbrella term used to refer to any synthetic training device or simulator, and aviation authorities must formally certify each FSTD before it can be used for pilot training. While the minimum regulatory flying requirements could equate to a total of 45 h (assuming no FSTD utility), there is emergent evidence [36–40] that the total flight hours typically accumulated by student pilots to obtain their private pilot license is closer to an average of 65 h. The process of determining this average flight duration of 65 h involved examining training record testimonies from multiple flight schools across Canada. This evaluation also incorporated insights reported by experienced flight instructors, ensuring a wide-ranging representation of perspectives and experiences. This average represented the overall number of flying hours, including both dual instruction training (in-aircraft training with a student pilot and instructor) and solo flight training (in-aircraft training with only the student pilot). The dynamic interaction of individual differences, such as variations in student pilots' abilities and aptitudes, influences the need for additional hours beyond the regulatory minimum requirement [41]. Therefore, an estimated average of 65 h for PPL aircraft training was identified to be a consistent estimate and was consequently used in this study. This decision was made due to the lack of sufficient data to accurately estimate the range or distribution of these training hours.

With respect to commercial pilot license (CPL) requirements after obtaining PPL, Canadian Aviation Regulations (CARs) [35] require CPL student pilots to complete a minimum of 65 h (dual instruction and solo flying combined) of commercial pilot flight training in airplanes. Only a maximum of 10 h out of these 65 h can be completed in an approved FSTD. However, in order to be eligible for the CPL flight examination, a student pilot must accumulate a minimum of 200 h of overall flight experience, with a minimum of 100 h as pilot-in-command (PIC). Flight hours gained as part of both PPL and CPL training can be applied towards fulfilling this 200-h minimum criterion. PIC refers to when a student pilot is the sole manipulator of the flight controls and also bears full responsibility, authority, and accountability for the operation and safety of the aircraft during flight time. PIC hours do not necessarily involve solo flying, though; hence, PIC hours can also be logged with a two-person or more crew on a flight, with the student pilot serving as PIC. However, depending on the student pilot's ability, aptitude, and skill level, the regulatory minimums of flight hours may not always suffice for them. Consequently, a higher number of training flight hours are undertaken to develop the necessary proficiency to commercial license standards. An exploratory study [42] examined the relationship between additional training hours and various factors, including individual learning curves. This investigation analyzed data from 688 commercial pilot license issuances, providing a basis for estimating the average duration of extended flight training. The study revealed that student pilots had amassed a significantly higher number of training hours, surpassing the mandated regulatory minimum by 26%. Hence, an average length of flight time accumulated for CPL (after obtaining PPL) can be determined to be 195 flight hours (155 h increased by 26%). These 155 h represent 65 h from CPL training (assuming no FSTD utility) and an additional 90 flying hours to accumulate the necessary PIC experience while meeting the minimum overall flight experience requirement of 200 h. Due to the absence of sufficient data to support an accurate estimation of the range or distribution of these training hours, we have opted to adopt 155 h as the estimated average for CPL aircraft training hours.

4.3. *Efficiency Factor* ($\overline{E}$) *and* CO_2 *Emitted per Flight Hour* ($\overline{C}$)

To estimate the CO_2 emissions for each hour of flight training, it is essential to first establish the rate of fuel consumption. The fuel consumption rate is a parameter influenced by various factors, including aircraft type, engine specifications, training maneuvers, and weather conditions. Although there are various airplane types available for flight training, a list of commonly used training aircraft was established after making inquiries at over 30 Canadian-based flying schools. Known to have the right combination of features and flight training characteristics along with simple systems and procedures that are ideally suited for flight school students—these aircraft bolster a reputation of being among the most common types of trainer aircraft used by flight schools not just in Canada, but also globally [43–45]. For simplicity, we applied an Efficiency Factor of 1 to represent average efficiency, where values above or below 1 denote conditions with increased or decreased fuel use. The application of an Efficiency Factor of 1 aid in establishing a baseline for comparison and simplifies the calculation process while acknowledging that real-world conditions may vary. Building on this simplification and employing the standard cruising power typical at optimal conditions, the fuel consumption rates at cruising altitude for the commonly used aircraft models were determined. These are detailed in Table 1. Although different flight maneuvers—such as landing, slow flight, takeoff, and climb—could have varying fuel consumption rates, either lower or higher than the rates at cruising altitude, the limited availability of data concerning these diverse maneuvers and their associated fuel consumption rates made a thorough investigation of these scenarios unachievable. This led to the decision not to delve further into these conditions.

Table 1. Types of Aircraft Used for Flight Training and their Fuel Burn Rates.

Aircraft Type	Associated Conditions		Fuel Burn Rate (AVGAS) (U.S. Gallons Per Hour, Gph)
Cessna 172S	6000 ft pressure altitude and at standard temperature	2600 RPM @ 73% rated power	9.9 [46]
Cessna 150M		2700 RPM @ 73% rated power	5.4 [47]
Cessna 152		2500 RPM @ 75% rated power	6.1 [48]
Diamond DA20 C1		2800 RPM @ 70% rated power	6.5 [49]
Diamond DA40-180		2400 RPM @ 65% rated power	8.5 [50]
Piper Archer (PA-28-181)		2605 RPM @ 75% rated power	11 [51]
Piper Warrior (PA-28-161)		2660 RPM @ 75% rated power	11.4 [52]
Average			8.4 gph

Given the variability in fuel consumption rates among commonly used aircraft, an estimated average fuel burn rate of 8.4 gph (approximately 32 L per hour) was derived from training aircraft data in Table 1. This estimate encompasses variations from 5.4 gph to 11.4 gph across different aircraft models. The selected average fuel burn rate of 8.4 gph effectively accommodates the variability in fuel efficiency observed across various models and is consistent with industry insights, thereby providing a well-grounded and balanced foundation for estimating CO_2 emissions in flight training contexts. Therefore, the utility of this rate was deemed a reasonable estimate, mirroring the spectrum of rates observed in commonly utilized training aircraft.

With every liter of aviation gasoline (avgas) burned, about 2.2 kg of CO_2 [53] could be generated, subsequently producing an average of 70.4 kg of CO_2 per hour (32 L per hour $\times$ 2.2 kg), with a range from 44.9 kg to 94.9 kg given different aircraft models. For accurate calculations, understanding the specific avgas composition and combustion efficiency is necessary. Nevertheless, the simplified estimate of 2.2 kg of CO_2 per liter of avgas burned is practical. This estimate, based on Avgas's carbon content and typical piston engine combustion efficiency, aligns with combustion principles and Avgas's chemical properties [53]. Although it may not perfectly match every avgas variation, this figure serves as a justified baseline for assessing environmental impacts. It is also worth mentioning that a small proportion of general aviation aircraft, such as the DA40 NG, now operate on jet fuel rather than traditional avgas. However, these aircraft were not factored into our calculations due to their low prevalence (less than 10% of the fleet) in flight schools [54,55].

4.4. Annual Number of Licenses Issued ($\overline{L}$)

To determine the annual number of pilot licenses issued across Canada, we collaborated with Transport Canada to obtain this data. Data sourced from Transport Canada revealed the number of private and commercial pilot licenses issued over a 23-year period (2000–2022), as illustrated in Figure 1. On average, 2590 private and 1298 commercial pilot licenses were issued annually.

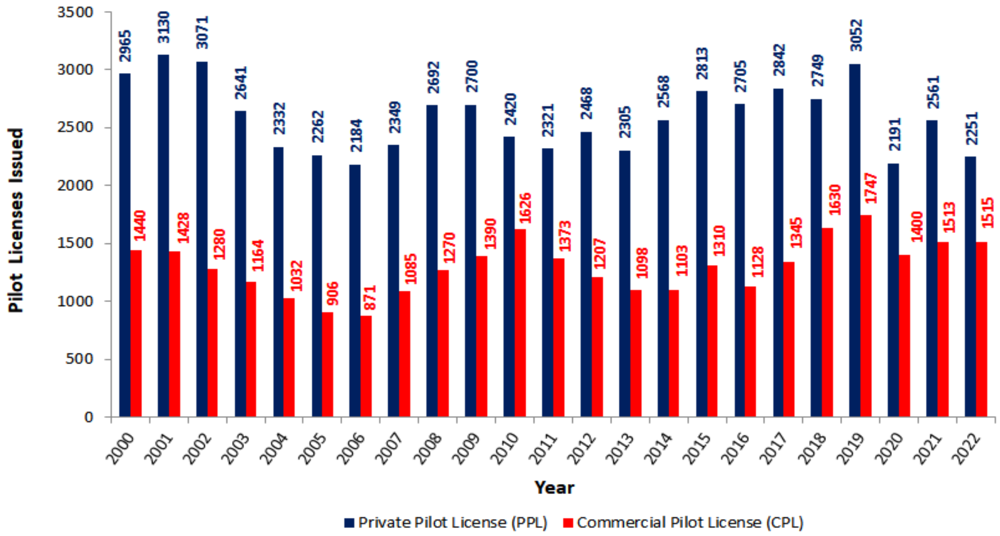

Figure 1. Historical issuances of licenses in Canada (Source of license data used: Transport Canada, 2023).

5. Results and Analysis

5.1. Annual Flight Training CO_2 Emissions

Utilizing the previously established average flight training durations—65 h for the PPL and 195 h for the CPL—along with an Efficiency Factor of 1, an average CO_2 emission rate of 70.4 kg per flight hour, and considering the annual issuance of approximately 2590 private and 1298 commercial pilot licenses, we calculated the CO_2 emissions associated with obtaining each type of license using Equation (1), as shown below.

$$PPL\ Annual\ Flight\ Training\ CO_2\ Emissions\ (average) = 65\ \text{h} \times 1 \times 70.4\ \frac{\text{kg}}{\text{h}} \times 2590\ licenses$$

$$CPL\ Annual\ Flight\ Training\ CO_2\ Emissions\ (average) = 195\ \text{h} \times 1 \times 70.4\ \frac{\text{kg}}{\text{h}} \times 1298\ licenses$$

On average, a little over 11,852 and 17,819 tons of CO_2 were contributed every year from PPL and CPL flight training respectively. This brings the average annual flight training CO_2 emissions to 29,671 tons in Canada, which can be rounded to approximately 30,000 tons. Using an average fuel burn rate ranging from 5.4 gph to 11.4 gph for different aircraft models, these flight training CO_2 emissions of 30,000 tons can be reported with a range from 19,000 to 40,000 tons.

5.2. CO_2 Emissions Trend Analysis

The estimated CO_2 emissions from both PPL and CPL training have experienced considerable fluctuations over the years, detailed in Figure 2 and discussed below.

PPL emissions exhibited an initial period of fluctuation from 2000 to 2006, beginning at 13,567.84 tons of CO_2 in 2000 and experiencing variations, including a slight increase in the first two years, followed by a gradual decrease to reach 9993.98 tons in 2006. This period indicates a mixed trend with both increases and decreases, ultimately leading to a decrease in emissions by 2006. The year 2007 marked a turning point, with emissions rising to 10,749.02 tons, signaling the start of an erratic upward trend. This trend included fluctuations with slight increases and decreases, reaching a modest peak in 2009 at 12,355.2 tons before a decrease in 2010 to 11,073.92 tons, illustrating the variable nature of PPL emissions during this period. From 2010 to 2017, the emissions pattern remained variable, with a notable decrease following 2010, reaching a low in 2013 at 10,547.68 tons. The period then saw gradual increases, culminating in a more consistent upward trend through to 2019, peaking at 13,965.95 tons. This rise was marked by a gradual increase in emissions, reflecting a period of growth in PPL activities. The impact of the COVID-19 pandemic was significantly felt in

2020, with emissions plummeting to 10,026.02 tons—a sharp decline reflecting the global downturn in aviation activities. A partial recovery was observed in 2021, with emissions increasing to 11,719.14 tons, followed by a decrease in 2022 to 10,300.58 tons. This recent period highlights the challenges faced by the aviation sector, including PPL training, in the wake of the pandemic, with initial signs of recovery tempered by subsequent decreases.

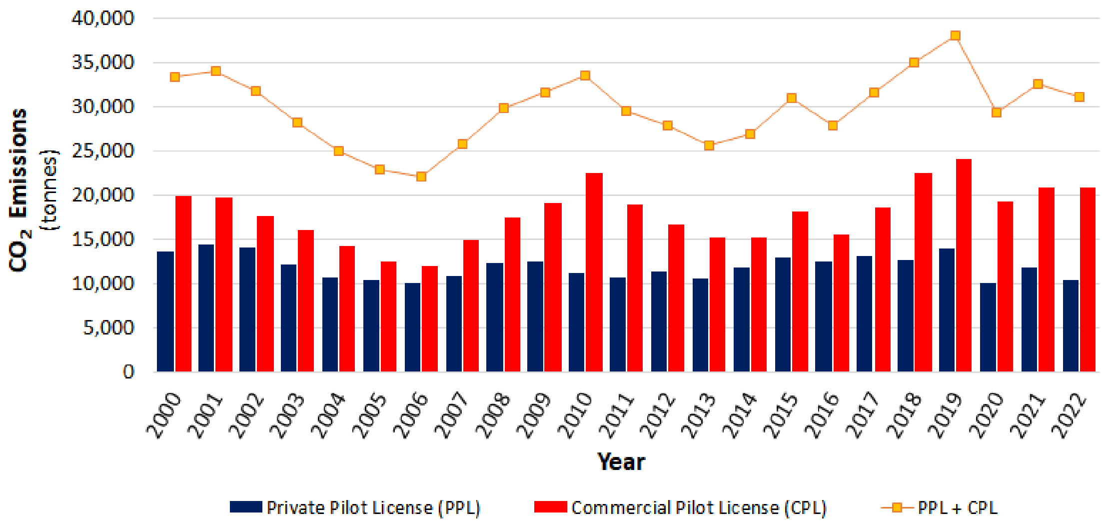

Figure 2. Estimated CO_2 Emissions for PPL and CPL Training.

CPL emissions saw a downward trend from 2000 to 2006, starting at 19,798.73 tons in 2000 and decreasing each year to reach 11,975.48 tons in 2006, indicating a period of declining emissions. This was followed by an increase in 2007, with emissions rising to 14,917.80 tons, marking the beginning of a general upward trend that continued with fluctuations through 2010, which saw a significant increase, culminating in 22,356.07 tons—a 16.98% increase from 2009. From 2010 to 2017, the trend was more mixed. After reaching a peak in 2010, emissions dropped significantly by 2011, followed by further decreases until a low in 2013. Emissions then increased slightly in 2014, followed by a more substantial rise in 2015, leading to another period of growth that peaked in 2019 with 24,019.71 tons, highlighted by a 19.24% increase in 2017 compared to 2016. The year 2020 observed a pronounced decline, with emissions decreasing to 19,248.77 tons—a 19.86% decrease, reflecting the global impact of the COVID-19 pandemic on aviation activities. However, there was a partial recovery in 2021, with emissions increasing to 20,802.42 tons, an 8.07% increase, and stabilization in 2022 with a slight increase to 20,829.92 tons, representing a marginal 0.13% increase from the previous year. This period indicates a rebound and stabilization in CPL emissions after the pandemic's initial impacts.

The total emissions from PPL and CPL training from 2000 to 2022 show a trend of fluctuation, characterized by periods of both decline and growth. From 2000 to 2006, the data show a gradual decrease in total emissions, starting at 33,366.57 tons in 2000 and reaching a low of 21,969.47 tons in 2006. This period signifies a downward trend in total emissions from both PPL and CPL training. The year 2007 marked the beginning of a recovery phase, with emissions increasing to 25,666.82 tons. This recovery continued, with notable growth through to 2010, reaching 33,429.99 tons and indicating a resurgence in aviation training activities. However, from 2011 to 2013, a period of decline was observed once again, with emissions dropping to 25,644.21 tons by 2013. From 2014 onwards, a notable recovery and growth phase occurred, peaking in 2019 with emissions at 37,985.66 tons. This represents the highest level of emissions within the provided dataset, showcasing a period of increased training activity. The impact of the COVID-19 pandemic was clearly seen in 2020, with emissions dropping significantly to 29,274.78 tons. A partial recovery in 2021, with emissions rising to 32,521.55 tons, was observed, but a slight decrease in 2022 to 31,130.49 tons suggests that the recovery may be facing challenges.

The observed year-to-year changes in PPL and CPL emissions can be regarded as multifaceted, reflecting not merely changes in the issuance of licenses but can also intertwine with broader economic factors impacting the pilot training sub-sector. Fluctuations in fuel prices directly influence flight training expenses, challenging the affordability and accessibility of pilot training. The economic stability of aviation training institutions can play a role as well; their financial health determines the extent to which they can invest in modern training aircraft and other technologies. Such advancements not only enhance the quality and efficacy of training but also hold the potential for reducing CO_2 emissions. Furthermore, the COVID-19 pandemic has had a profound impact, with the noticeable downturn in 2020 predominantly linked to the widespread disruptions in flight training operations caused by travel restrictions and lockdown measures. This period stands out as a critical juncture, underscoring the vulnerability of the aviation training sector to global crises and emphasizing the importance of resilience and adaptability in the face of unprecedented challenges.

6. Discussion

6.1. Research Impact

The study provides a novel and significant insight into the environmental impact of ab initio pilot training in Canada, a previously underexplored area within general aviation's CO_2 emissions footprint. Establishing that each hour of flight training releases approximately 70.4 kg of CO_2, and with annual emissions estimated to be around 30,000 tons—ranging between 19,000 to 40,000 tons—it not only fills a gap in our understanding of the civil aviation sector's broader environmental effects beyond commercial flying but also emphasizes the need for integrating sustainable practices in the aviation education and training sub-sector. This research contributes to the discourse on aviation sustainability, urging a comprehensive view that includes all aviation activities in strategies to mitigate environmental impact. It highlights the importance of rethinking how pilot training is conducted as part of the industry's commitment to achieving net-zero emissions by 2050. Addressing this challenge necessitates overcoming technological, regulatory, and economic barriers, pointing towards an integrated approach that involves all stakeholders in the aviation ecosystem.

6.2. Comparison with Other Aviation Emission Sources

CO_2 emissions from flight training constitute a minor segment (<1%) of the overall aviation emissions in Canada, juxtaposed against the larger contributions from commercial flights, cargo transport, and military operations. The variation in yearly trends of flight training emissions diverges from other aviation sources, influenced by distinct operational demands and varying impacts from economic fluctuations. Within the broader context of general aviation's environmental impact, flight training emissions, while only a small fraction of overall aviation emissions, are integral to understanding the sector's total CO_2 footprint. Therefore, this research accentuates the imperative of incorporating flight training into the broader dialogue of general aviation sustainability, advocating for a comprehensive decarbonization strategy that emphasizes both current flying practices and training future pilots with eco-friendly practices.

6.3. Technologies for Sustainable Ab Initio Training

Canada's existing pilot licensing and flight training standards are based on specific hour requirements. Student pilots must amass a prescribed number of flight hours for their flight test qualification. However, this approach may not encompass the full training necessary for proficiency, including exposure to diverse scenarios such as in-flight emergencies, equipment malfunctions, or severe weather conditions. Flight schools lack incentives to embrace innovative training methods such as FSTDs since the regulations do not mandate their use, thus preventing flying schools from incurring the financial burden of acquiring FSTDs, which can cost hundreds of thousands of dollars. The underutilization of FSTDs by student pilots can result in extended flight training periods to meet proficiency standards, consequently resulting in additional CO_2 emissions. Therefore, a more cohesive integration of FSTDs into pilot licensing and training standards is recommended to enhance training quality.

Battery-powered electric aircraft provide a solution to reduce CO_2 emissions from general aviation flight training. They also eliminate the use of leaded fuel, which can have adverse health effects, especially on children exposed to lead emissions. Electric aircraft, such as the Velis Electro, can provide cost-effective short-distance flight training with reduced maintenance [56]. Although electric aircraft face challenges with battery life, ongoing developments are expected to improve their performance. In addition to electric aircraft, alternative fuel solutions like sustainable aviation fuel (SAF) can be considered to reduce CO_2 emissions. These biofuels can cut emissions by up to 80%, and their use in small piston-engine planes is being explored [57–60]. Despite challenges, such as limited production and high costs, SAF has the potential to reduce the environmental impact of flight training as the industry develops further.

6.4. Limitations

The analysis in this study is conducted in accordance with the general aviation flight training standards for private and commercial pilot licenses currently being practiced in Canada. While both private and commercial pilot license training primarily utilize single-engine aircraft for flight training, the curriculum at different flight schools may integrate the option for a multi-engine rating as part of the commercial pilot license training. The analysis presented in this study assumes aspiring pilots opt only for the single-engine rating; thus, the analysis exclusively considers single-engine flight training aircraft. Attaining a multi-engine rating generally necessitates up to 10 h of additional dual-flight training for adequate preparation [35]. This would have led to an increment in the total flight training hours associated with CPL, resulting in additional CO_2 emissions.

The cruise flight fuel burn rates utilized in this study are based on aircraft performance data provided by airplane manufacturers. Typically, these rates are ascertained from staged testing on new engines and may not wholly reflect the performance of operational aircraft. Furthermore, the fuel burn rates utilized pertain to specific standard cruise operation conditions, such as maintaining a constant altitude and speed, adhering to nominal weight, observing standard temperature, experiencing favorable weather conditions with no cross-winds, employing ideal pilot flying techniques, receiving optimum flight management from Air Traffic Control (ATC), maintaining a set rated power settings, among others. However, in real-world scenarios, an airplane may encounter continuous variations in fuel burn rate as the fuel consumption rate could be influenced by a multitude of factors.

The analysis in this study leverages the most commonly utilized aircraft to depict flight training activities across Canada, yet it recognizes that it does not cover the entire array of aircraft used by flying schools, especially those that employ unique or less common types. Furthermore, the analysis is based on a specific variant for each identified aircraft type and model, despite the fact that many models have multiple variants with distinct fuel consumption rates. This means flying schools might use a variety of aircraft variants, which could differ from those analyzed in our study. However, we derived an average fuel consumption rate of 8.4 gph from a wide range of fuel burn rates, spanning from 5.4 to 11.4 gph. While the precise variation can depend on the specific model differences and operational settings, it is generally understood that fuel burn rates for Cessna aircraft variants typically fluctuate by $+/-0.5$ to $+/-1$ gph [46–48]. In contrast, Diamond and Piper variants may experience a larger variation of $+/-1$ to 2 gph [49–52]. When considering these best and worst performance variations, using different variants of the aircraft models used in this study could theoretically adjust the estimated average fuel consumption rate of 8.4 gph by approximately ± 0.8 gph. Consequently, the selected average of 8.4 gph can be considered a reasonable estimate, suggesting that our conclusions should remain relevant even when taking into account a broader spectrum of aircraft types and their variants.

Pilots are required to participate in recurring flight training [35] at regular intervals. However, the frequency of this training can fluctuate based on each pilot's individual circumstances. Experienced pilots who regularly engage in flying activities to maintain their skills may not need additional recurrent training. On the other hand, less active pilots or those whose skills have deteriorated may necessitate more recurrent training, potentially involving dual-instruction flight training to maintain safety and proficiency in their flying activities. Because of the unavailability of adequate data to estimate CO_2 emissions stemming from recurrent flight training, we have chosen to exclude it from our CO_2 emission calculations.

6.5. Future Research

Simulation training has been a staple in pilot training programs and has been utilized by aviation schools for several years [61]. Despite its evident benefits [62–64] to teaching and learning, simulation training in general aviation training often is not exploited to its fullest potential. Alongside this, simply accumulating the regulatory minimum number of flight hours should not be seen as the only measure of true competence. Thus, to evolve beyond the traditional hour-based in-aircraft training requirements, a re-evaluation of training time distribution between in-aircraft and FSTD training is essential. This re-evaluation should prioritize maximizing the use of FSTDs. Although real aircraft flying remains the gold standard for pilot training and licensing, directly replacing an hour of in-aircraft training with an hour of FSTD training may not be a suitable approach. The potential substitution of FSTD training for in-aircraft flight training within the current PPL and CPL regulatory requirements needs thorough examination. For instance, it must be determined whether an hour of FSTD training could equate to an hour of in-aircraft training or if multiple hours of FSTD training are needed to replace a single hour of in-aircraft training. Finding the optimal balance between FSTD and in-aircraft training will ensure the full advantages of simulation training are realized without compromising on training quality or safety.

Electric aircraft and SAF have also been highlighted as means to mitigate CO_2 emissions. However, the widespread adoption of these technologies demands interdisciplinary collaboration, encompassing a diverse range of stakeholders, including government, industry, research institutions, and the public. While their implementation seems promising, further research is essential to address any associated challenges.

7. Conclusions

In light of the rapid growth in the global aviation sector and the associated surge in CO_2 emissions, achieving sustainability remains a paramount challenge. The unanimous goal across international aviation agencies to reach net-zero emissions by 2050 highlights the urgency of the situation. Central to this endeavor is the critical understanding and reduction of CO_2 emissions from all facets of the sector. The findings of this study underscore the urgent need for policy interventions to mitigate the environmental impact of pilot training in Canada's general aviation sector. Our estimation that each hour of ab initio flight training emits about 70.4 kg of CO_2, cumulating to approximately 30,000 tons annually, highlights a potential area for emissions reduction within the aviation sector. This revelation underscores the necessity of adopting measures aimed at reducing emissions, thereby contributing to the global aviation community's objective of attaining net-zero emissions by 2050. Policy implications derived from these findings suggest a multi-faceted approach towards sustainability. Firstly, there is a strong case for regulatory support in favor of flight simulation training devices (FSTDs). By recognizing additional FSTD hours towards licensing requirements, actual flight hours and emissions could be reduced. Secondly, the transition to electric aircraft for training purposes emerges as a viable path to decarbonization, with policy mechanisms such as tax incentives and subsidies proposed to hasten their adoption. Similarly, the promotion of SAF could offer immediate reductions in carbon emissions, albeit its current limited adoption due to cost and availability challenges necessitates supportive policies for development and distribution. Additionally, the establishment of a comprehensive emissions reporting policy for flight schools would foster transparency and encourage the adoption of greener practices, potentially supported by a public registry of emissions data. Finally, achieving sustainable aviation training mandates a collaborative effort among all stakeholders, including regulators, training institutions, and aircraft manufacturers, to share innovations and best practices. In essence, while the study primarily zeroes in on Canada's aviation training emissions, its findings and recommendations hold broader implications, advocating for a global shift towards more sustainable pilot training practices. This aligns with the wider aviation industry's sustainability goals, emphasizing that the sector's growth should not compromise environmental integrity. Moving forward, a concerted effort involving innovation, commitment, and collaboration is paramount to actualizing these sustainable practices across the aviation ecosystem.

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