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Review

The Contribution of Commercial Flights to the Global Emissions of Inorganic and Organic Pollutants

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Abstract: The aviation industry significantly contributes to global greenhouse gas (GHG) emissions, accounting for approximately 2–3% of total annual CO_2 emissions, with high-altitude operations amplifying radiative forcing effects. This study quantitatively examines aviation's contributions to global pollution compared to other transportation sectors, such as road and maritime, highlighting the substantial challenges in mitigating its environmental footprint. We focus on emissions of organic compounds, including polycyclic aromatic compounds and dioxins, and analyze key pollutants such as CO_2, NO_X, and ultrafine particles alongside the sector's indirect effects. Our estimation indicates that dioxin emissions from commercial flights are negligible, at only 0.76 g annually; however, the sector's broader impact on climate and air quality is significant. The analysis also evaluates current mitigation strategies, including the adoption of sustainable aviation fuels (SAFs), international initiatives like CORSIA, and advancements in aircraft technologies and operational efficiency. Despite these efforts, the projected growth in air traffic, estimated to increase annually by 5% over the next decade, underscores the urgent need for accelerated innovation and robust policy frameworks to achieve sustainable aviation. These findings emphasize the necessity of addressing aviation's unique environmental challenges through international cooperation, technological advancements, and targeted climate actions.

Keywords: aircraft; airplane; aviation; carbon dioxide; COVs; dioxin; flights; greenhouse gasses; PAHs; PCDD/Fs; pollution

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1. Introduction

In recent decades, the rapid expansion of the aviation industry has revolutionized global connectivity, enabling unprecedented mobility for people and goods. However, the environmental implications of this growth have become a critical area of concern, particularly regarding the contribution of commercial flights to global pollutant emissions. While much attention has been given to the aviation sector's role in greenhouse gas (GHG) emissions, its contribution to the release of inorganic and organic pollutants remains understudied, despite their profound impact on air quality, ecosystems, and human health.

Commercial aircraft emit pollutants both directly and indirectly through their operations. The combustion of jet fuel in aircraft engines generates primary emissions, including carbon dioxide (CO_2), nitrogen oxides (NO_X), carbon monoxide (CO), sulfur oxides (SO_X), particulate matter (PM), and unburned hydrocarbons (HC). These pollutants are discharged

at high altitudes due to nominal operational flight ceiling, where their environmental behavior and impact differ significantly from emissions released at ground level where they are generally measured. For instance, NO_X emissions in the upper troposphere and lower stratosphere can lead to ozone formation, a potent GHG, while simultaneously depleting methane, another GHG.

The release of particulate matter, specifically soot and secondary organic aerosols, has increasingly garnered scientific attention due to its implications in cloud formation and radiative forcing. Furthermore, aircraft operations at airports contribute to ground-level air pollution, exacerbating the exposure of surrounding communities to hazardous substances such as benzene, formaldehyde, and polycyclic aromatic hydrocarbons (PAHs).

Bendtsen et al. [1] studied the health effects associated with the exposure of set emissions in and around airports, showing an increased number of PAHs in airport personnel (4.61 $\mu g/m^3$) compared to a control group (3.84 $\mu g/m^3$).

In 2006, the global commercial aircraft fleet flew an estimated 31.26 million times, burned over 188 million metric tons of fuel, and emitted, primarily in the Northern Hemisphere, significant amounts of pollutants, directly affecting atmospheric composition and climate stability [2].

In addition to their primary emissions, commercial aviation indirectly contributes to secondary pollution through the chemical transformation of emitted compounds in the atmosphere. These include the formation of tropospheric ozone and secondary aerosols, which have far-reaching environmental and health consequences. Moreover, the aviation industry is a significant contributor of persistent organic pollutants (POPs), which can accumulate and persist over long periods of time in ecosystems, posing severe risks to biodiversity and food security.

The environmental impact of these pollutants is further complicated by the increasing growth of the aviation sector. Projections estimate that the number of commercial flights will continue to rise sharply in the coming decades, driven by increasing global demand for air travel and cargo transport. This growth underscores the urgency of quantifying and mitigating the sector's emissions in alignment with international climate and pollution abatement goals.

Emissions from commercial aircraft contribute to atmospheric pollution through the release of various inorganic and organic compounds. While greenhouse gasses such as CO_2 and NO_X are well-known contributors to climate change, other pollutants, including particulate matter (PM) and organic compounds, can also impact air quality and human health. Ultrafine particles and certain organic pollutants emitted during combustion can be transported over long distances, potentially affecting populations near airports and at high altitudes. However, due to the high-altitude dispersion of emissions and the relatively low concentrations of bioaccumulative organic compounds, their direct impact on human exposure remains limited compared to other pollution sources. Understanding these implications is crucial for evaluating mitigation strategies, including the transition to cleaner fuels and the implementation of stricter emission regulations.

Existing regulations and mitigation efforts, such as the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), primarily target CO_2 emissions, often overlooking the broader spectrum of pollutants emitted by commercial flights. Furthermore, technological advancements in fuel efficiency and alternative propulsion systems, such as sustainable aviation fuels (SAFs) and electric aircraft, remain in nascent stages and face significant scalability challenges.

This review aims to provide a comprehensive overview of the contributions of commercial flights to the global emissions of both inorganic and organic pollutants. By synthesizing current scientific knowledge, we explore the chemical composition of aviation emissions,

their environmental pathways, and their potential impacts. In doing so, we aim to highlight the gaps in current regulatory frameworks and identify opportunities for advancing sustainable aviation practices. In particular, no previous study has estimated the global emissions of dioxins from commercial aircraft. In fact, there are very few studies reporting data on these emissions. Understanding the multifaceted pollution profile of the aviation sector is essential for developing targeted mitigation strategies that address not only climate change but also the broader spectrum of environmental and public health challenges posed by these emissions.

2. The Role of Aviation Emission Regulators

The International Civil Aviation Organization (ICAO) is a specialized agency of the United Nations, established in 1944 to promote the safe, efficient, and sustainable development of international aviation. Based in Montreal, Canada, ICAO works with 193 member states to set global standards and policies for aviation operations, air navigation, security, and environmental sustainability. By fostering international cooperation and innovation, ICAO aims to balance the growth of the aviation industry with its environmental and social responsibilities.

In the context of environmental protection, the ICAO plays a crucial role in addressing the aviation sector's contribution to climate change. Key initiatives include the development of policies to improve fuel efficiency, promote the use of sustainable aviation fuels (SAFs), and implement global measures like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

CORSIA is a global initiative established to mitigate carbon emissions from international flights. Its primary goal is to achieve carbon-neutral growth from 2020 onwards, requiring airlines to offset any emissions exceeding 2020 levels through the purchase of carbon credits from certified projects in other sectors.

CORSIA operates in three phases: a pilot phase (2021–2023), a voluntary phase (2024–2026), and a mandatory phase (2027–2035), with exceptions for the least developed countries and nations with minimal aviation activity. Airlines must monitor and report their emissions, with a verification process overseen by ICAO.

The scheme encourages the use of SAFs to reduce emissions at the source. While CORSIA represents a significant step towards decarbonizing aviation, it has limitations, such as its reliance on carbon offsets, its exclusion of domestic flights, and its primarily focusing on CO_2 rather than other pollutants.

The Intergovernmental Panel on Climate Change (IPCC) highlights the significant role of aviation in climate change through its direct and indirect emissions. Key contributions include carbon dioxide, nitrogen oxides, and particulate matter, which impact radiative forcing and atmospheric chemistry, particularly at high altitudes. Additionally, aviation-induced contrails and cirrus clouds amplify warming through non-CO_2 effects.

The IPCC projects significant growth in aviation emissions due to increasing demand, underscoring the need for mitigation strategies such as fuel efficiency improvements, use of SAFs, and optimized air traffic management. These measures, combined with global policies like CORSIA, are essential to limit aviation's environmental footprint.

The regulatory framework for reducing emissions in the aviation sector has been reinforced through initiatives such as the Fit for 55 legislative package and the RefuelEU Aviation initiative. The Fit for 55 packages, introduced by the European Union, aims to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, including measures to increase the adoption of sustainable aviation fuels (SAFs) and improve aircraft fuel efficiency. The RefuelEU Aviation initiative specifically targets the aviation sector by mandating a gradual increase in the share of SAFs used in commercial flights

departing from EU airports. These policies are designed to mitigate the environmental impact of air transportation by reducing carbon dioxide emissions and limiting the release of other pollutants associated with conventional jet fuel combustion.

3. Data on Emissions of Pollutants from Global Aircraft Activity

3.1. General View

From the chemical point of view, the reactions that take place on an airplane are imperfect chemical reactions, where products of incomplete combustion (PICs) as well as products of excessive combustion [3] are produced. Incomplete combustion occurs when there is not enough oxygen available for a fuel to react completely. This results in the production of carbon monoxide (CO), carbon (soot), and water, instead of CO_2 and water, which are the products of complete combustion. Excessive combustion, often referred to as "over-combustion", occurs when there is an excess of oxygen in the combustion process. Excessive combustion can lead to higher temperatures, which promote the formation of nitrogen oxides (NO_X). These are harmful pollutants that contribute to smog and acid rain. Among the various pollutants, NO_X was the most prevalent in China's aircraft emissions, both in terms of quantity and environmental impact. Meanwhile, PM2.5 had a widespread influence [4]. China's annual emissions of pollutants showed a rapid increase with economic and population growth, reaching significant levels by 2015 [5]. Emission intensities were higher in central and eastern China due to a high population density and economic activity. The cruise process was the dominant contributor to PM2.5, SO_2, CO_2, heavy metals, and NO_X emissions, while the landing and take-off (LTO) process contributed more to CO and HC emissions. Durdina et al.'s study [6] found up to 4 times less soot mass was being emitted from the standardized LTO cycle and up to 40 times less during taxiing. Depending on the fuel composition and flight distance, the mass emission indices (/kg fuel burned) were 6.2−14.7 mg.

The EDGAR (Emissions Database for Global Atmospheric Research) [7] provides comprehensive data on emissions from the transport sector, including road, maritime, aviation, and rail transport. Road transport is a major contributor of CO_2, CH_4, and N_2O emissions, alongside air pollutants such as NO_X, particulate matter (PM), and non-methane VOCs, primarily due to fossil fuel combustion in vehicles. Maritime transport accounts for significant CO_2 and NO_X emissions, while aviation contributes disproportionately through CO_2 and NO_X, especially at high altitudes where their climate impact is amplified. Rail transport, though a smaller contributor, emits CO_2 and NO_X from diesel locomotives.

The European Environment Agency (EEA) [8] provides detailed information on emissions from the transport sector in Europe, including aviation. According to recently published data, in 2023, the aviation industry in Europe generated 172 million tons of CO_2, representing a 16% increase compared to 2022.

The EEA highlights that while aviation and maritime transport account for only 8% of the EU's total GHG emissions, they are the fastest-growing sources of emissions. To address this challenge, the EU has implemented measures such as the 'Emissions Trading System', which operates on the "polluter pays" principle. Airlines must surrender emission allowances to cover their emissions, currently applying to flights within the European Economic Area.

Additionally, the EU collaborates with the CORSIA project from the ICAO, which aims to limit GHG emissions produced by international air transport.

The EEA also reports on initiatives to promote the use of sustainable aviation fuels. Since 1 January 2025, the EU has mandated a 2% blend of sustainable aviation fuels with kerosene [9], aiming to reduce emissions from the aviation sector.

These actions reflect the EU and EEA's commitment to monitoring and reducing emissions from the transport sector, including aviation, to meet the climate targets established under the European Green Deal.

3.2. Data on Emissions

Early studies by Spicer et al. [10] reported emissions of nitrogen oxides, carbon monoxide, hydrocarbons, and particulate matter from jet aircraft turbine engines. These pioneering studies have led to a large body of scientific literature, which generally concludes that aircraft exhausts significantly contribute to emissions of various gaseous, semi-volatile, and non-volatile species.

Non-volatile emissions, produced in the combustion chambers, include refractory materials like soot, which are emitted as particulate matter even at high engine exit temperatures. These emissions also contain many organic compounds. Volatile emissions, which exist as vapor at engine exit temperatures and pressures, include pollutants such as CO_2, CO, NO_X, SO_2, O_3, and various organic compounds like alkanes, alkenes, carbonyls, and aromatic compounds. The least volatile fraction, which makes up 10–20% of total organic emissions, can react in the atmosphere and condense in exhaust plumes, forming aerosol particles or volatile coatings on pre-existing particles.

Masiol and Harrison [11] show that between 99.5 and 99.9% of the molar mass of gas produced in an aircraft is composed by nitrogen, oxygen (from the excess air), carbon dioxide, and water. From all the gas emissions, 70% are generated at altitude and 30% during LTOs and ground operations.

The global picture for the emission in aircraft activity is described by Masiol and Harrison [11], shown as a graph in Figure 1.

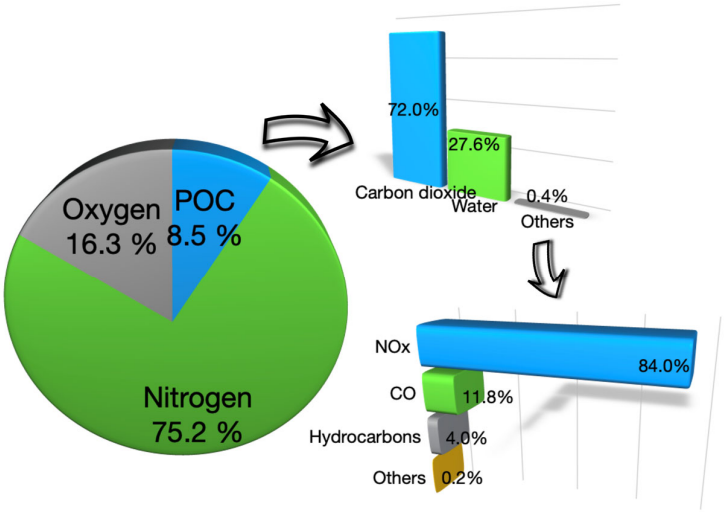


Figure 1. Combustion products from an aircraft engine (POC = products of combustion), adapted from Masiol and Harrison [11]. Data in weight percent.

The amount of exhaust emissions depends on factors such as the combustion chamber temperature, pressure, fuel-to-air ratio, and fuel atomization mixed with inlet compressed air. Emissions can vary significantly with engine technology, model, and thrust. For example, hydrocarbon emissions can depend not only on engine type, but its usage, maintenance history, and fuel composition.

Masiol and Harrison [11] indicated that the maximum permitted amount of sulfur in fuels is 3 g/kg fuel, i.e., 3000 ppm. A typical value of S content in a Jet A-1 fuel is between 550 and 750 ppm. The low sulfur content in fuels generally results in very low sulfur oxide emissions.

Other minor compounds with a special relevance can also be formed due to their high toxicity. Polychlorinated dioxins (PCDDs), polychlorinated furans (PCDFs), polychlorinated biphenyls (PCBs), and polyaromatic hydrocarbons (PAHs) are formed in combustion processes. They are all considered as POPs (Persistent Organic Pollutants) in the Stockholm Protocol [12].

The general term 'dioxin' is applied to a set of aromatic substances and usually refers to the derivatives PCDDs and PCDFs. There are 75 chemical congeners for PCDDs and 135 congeners for PCDFs. Of all these compounds, there are 17 that develop toxic effects, and they are those that have chlorine atoms in positions 2, 3, 7, and 8. These compounds are of no industrial interest, and are only obtained as unwanted by-products. The toxicity of the 17 compounds is measured with an equivalent toxicity factor with respect to the most toxic (2,3,7,8-TetraChloroDibenzoDioxin or 2378-TCDD) [13].

Their formation in combustion processes can occur through several chemical routes (Figure 2):

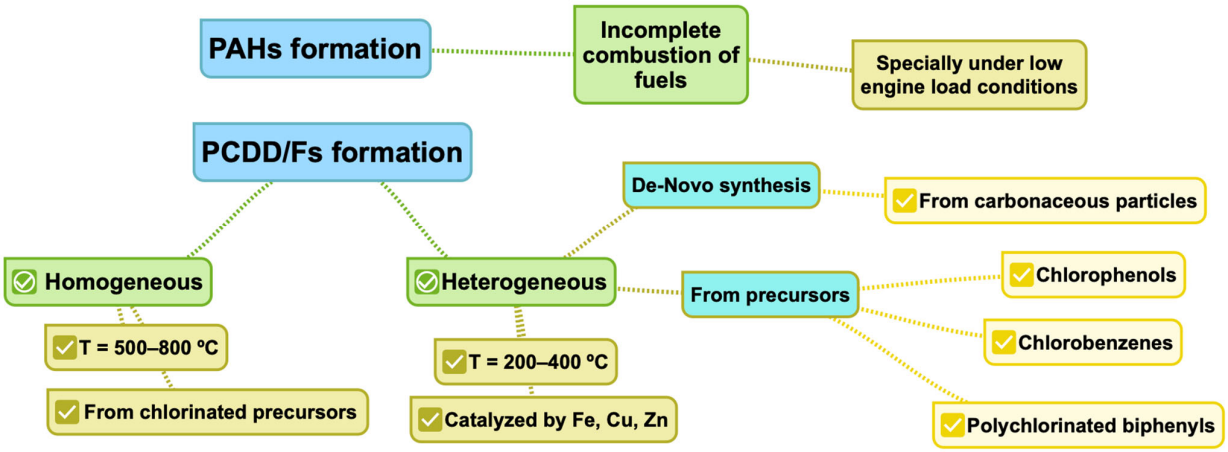


Figure 2. Formation pathways for dioxins and furans (PCDD/Fs) and origin of PAHs.

- Homogeneous Formation: This occurs in the gas phase at high temperatures (500–800 °C). It involves the pyrolytic rearrangement of chlorinated precursors like chlorophenols and chlorobenzenes [14].
- Heterogeneous Formation: This takes place at lower temperatures (200–400 °C) on the surface of particles such as ash or soot. It is a catalyzed reaction involving the oxidation and chlorination of unburned carbon in the particulates [14].
- De Novo Synthesis: This mechanism involves the formation of dioxins from carbonaceous particles in the presence of chlorine. It typically occurs at temperatures between 200 and 400 °C and is catalyzed by metals like copper. The process includes the oxidation and chlorination of carbon structures, leading to the formation of PCDD/Fs [15].

The formation of dioxins is influenced by several factors, including temperature, the presence of chlorine, the type of combustion process, and the nature of the fuel and materials being burned. Controlling these factors can help minimize dioxin emissions.

Agrawal et al. [16] indicate that 13.9 teragrams of fuel were burned in 2005 for aviation purposes; this accounts to 13.9 million tons. Considering an annual growth of 5% (according to Masiol and Harrison [11]), the current amount of fuel as of 2025 should be as high as 36.9 million tons. According to previous data, this represents the emission of 2.26 million tons of CO_2 annually.

Wilkerson et al. [2] estimated that for 188.2 teragrams of fuel, the consumption for 2006, applying a 5% annual growth would represent 475.5 million tons per year today. However, other organizations estimate the consumption of fuel at 7.42 million barrels per

day (bpd) during the first seven months of 2024 [17], which corresponds to approx. 344.5 million tons a year.

To shed more light on the environmental impact of commercial aviation, we present Table 1, featuring the ten most used commercial aircraft [18], along with their key characteristics. This information is essential for contextualizing the discussion on pollutant emissions, as these aircraft collectively contribute significantly to global emissions. By analyzing their specifications, including fuel efficiency, passenger capacity, and operational range, we can better assess their individual and cumulative roles in the sector's environmental footprint.

Table 1. Some characteristics of the most used aircrafts currently.

Ranking	Maker	Model	Production Years	Number of Passengers (Approx.)	Fuel Capacity (L)	Maximum Speed (Mach)	Autonomy (km)
1	Boeing	747	1969–2005	366	243,120	0.92	14,816
2	Boeing	777	1995–now	440	181,283	0.84	17,370
3	Boeing	737	1967–now	170	29,660	0.78	7223
4	Boeing	787	2009–now	350	101,350	0.84	14,075
5	Boeing	757	1982–2004	270	43,400	0.80	7222
6	Boeing	767	1982–now	375	61,800	0.69	11,093
7	Boeing	727	1963–1984	190	15,000	0.67	5000
8	Airbus	A320	1984–now	220	27,200	0.71	6100
9	Boeing	707	1954–1978	190	90,290	0.71	10,500
10	Airbus	A380	2005–2021	853	320,000	0.96	15,200

The most used aviation fuels are Jet A and Jet A-1, which are types of refined kerosene. These fuels are primarily used in commercial jet aircraft due to their high energy density, low freezing point, and reliability at high altitudes. Jet A is typically used in the United States, while Jet A-1 is more widely used globally, particularly in Europe and other international regions, due to its lower freezing point, which is crucial for flights at even higher altitudes. Both fuels are derived from crude oil and are processed to meet stringent quality standards set by aviation authorities to ensure both safety and performance.

The amount of gasses produced during the combustion of a kilogram of fuel depends on the chemical composition of the fuel. In the case of aviation fuel (usually kerosene or Jet-A1), it can be approximated by considering its average composition as $C_{12}H_{23}$ [11].

Assuming a complete combustion of the fuel with oxygen, we have the chemical reaction as follows:

$$4C_{12}H_{23} + 71O_2 \rightarrow 48CO_2 + 46H_2O \quad (1)$$

This means that a kilogram of fuel (5.97 moles) would produce 140.45 moles of gas, i.e., 3.136 m^3 of gas in normal conditions. Bearing in mind that these compounds represent 8.5% of the total gas emitted (Figure 1), we can take an average value of 36.9 Nm^3 gas emitted per kg of fuel burned.

In the study carried out by Masiol et al. [19] on air quality in an operational air base in Iraq during the war, the emitted dioxins and furans were measured, determining a profile where no TCDD or TCDF (tetra-chlorinated congeners, which are the most toxic) were found in aircraft exhausts. Going through the main data shown in this paper, a total toxicity due to dioxins of 0.06 pg WHO-TEQ/m^3 can be calculated. Other authors [16] did not detect dioxins or furans in the emitted fumes from aircraft engines. On the contrary, a toxicity of 0.48 pg WHO-TEQ/m^3 is detected in the same study in diesel combustion within an operating air base.

All previous calculations indicate that the total amount of dioxins emitted by aviation can be estimated to be as below:

$$\left(344.5\ \text{Tg}\cdot 10^{9}\frac{\text{kg fuel}}{\text{Tg}}\right)\cdot 36.9\frac{\text{Nm}^3}{\text{kg fuel}}\cdot\left(0.06\frac{\text{pg TEQ}}{\text{Nm}^3}\cdot 10^{-12}\frac{\text{g}}{\text{pg}}\right)=0.76\ \text{g TEQ} \quad (2)$$

This accounts to a minimal number of dioxins produced by aviation globally. Quab et al. [20] show the dioxin inventory in air corresponding to the European Union, and mention that road transport contributed with 262 g TEQ (equivalent toxicity) of dioxins and furans in 1995, decreasing this amount to 41–60 g by 2005. The TEQ for dioxins is calculated by multiplying the concentration of each dioxin congener by its respective Toxic Equivalency Factor (TEF) and summing the results.

Figure 3 schematically shows the emissions expected from a single kilogram of Jet-A1 for comparison purposes, according to the proposed model.

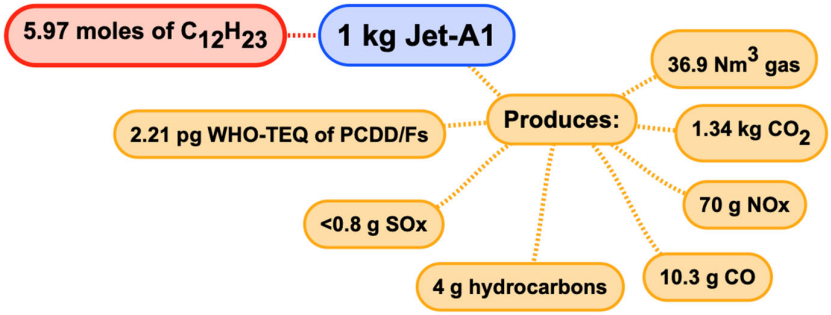


Figure 3. Expected emissions from Jet-A1 fuel.

Tesseraux [21] evaluates the risk factors of jet fuels combustion products but does not mention the halogenated compounds nor heavy metals findings. Gao et al. [22], on the other hand, observed a sharp decrease in the emitted dioxins in the ambient air of China during the period 2003 to 2020, but does not consider aviation.

On the website of ICAO [23], an emissions calculator for different types of aircrafts and routes can be found. With this tool, the average consumption of fuel for a standard aircraft can be estimated. For example, considering a trip from Barcelona (BCN) to Denver (DEN), 58,065 kg of fuel are normally used, this is, for a total distance of 7491 km, i.e., an average of 7.75 kg of fuel are being used per kilometer traveled. Bearing in mind the previous calculation, 285.9 Nm^3 of gas is emitted per km.

The HC emission can be estimated as 0.004 g of HC per gram of fuel consumed [11]. Janicka et al. [24] also analyzed the volatile organic compounds (VOCs) from a small turbojet engine, such as n-pentane, 2-propanol, benzene and xylenes, showing emissions of approximately 33, 31, 5, and <1 mg/m^3, respectively. The same study compared Jet A-1 emissions with those produced by the blend of Jet A-1 with 25 vol. % of biobutanol, showing an important decrease in emissions by using the biofuel mixture.

4. Comparing Aviation Emissions with Other Transport Sectors

Although aviation accounts for only 2–3% of global CO_2 emissions, its environmental impact is unique due to the altitude of its emissions and their amplified radiative effects. To better understand aviation's role, it is crucial to compare it with other transport sectors, including road and maritime transport, which contribute significantly to global emissions.

4.1. Total Emissions by Sector

Road Transport is the largest contributor to global transportation emissions, responsible for approximately 75% of the sector's total emissions. These emissions primarily

result from the combustion of fossil fuels in cars, trucks, and buses, releasing significant amounts of CO_2, NO_X, PM, and VOCs. Road transport is a major source of urban pollution, disproportionately impacting air quality in densely populated areas.

There is extensive research concerning dioxin emissions associated with road traffic, reflecting its significant contribution to environmental pollution and its impact on human health. Studies have delved deeply into the mechanisms of dioxin formation, the role of combustion engines, and the influence of different fuel types and emission control technologies [25–27], the most relevant of which can be found in Figure 4.

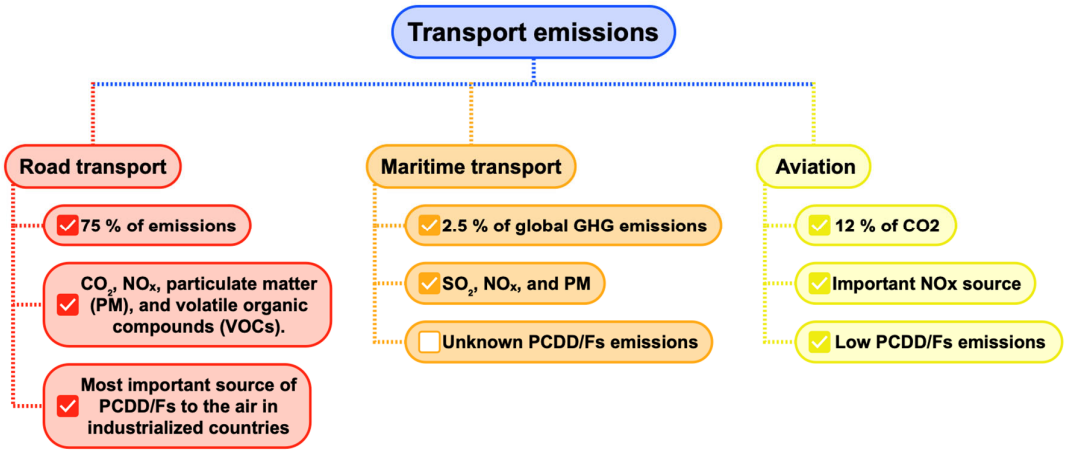


Figure 4. Pollutant emissions in road, maritime, and air transport industries.

Maritime transportation, specifically the shipping industry, accounts for about 2.5% of GHG emissions, with a significant portion derived from the use of high-sulfur heavy fuel oil. Maritime transportation produces substantial amounts of SO_2, NO_X, and PM, contributing to the air pollution of port cities. While it is more energy-efficient than aviation on a per-ton-kilometer basis, the sheer volume of goods transported makes its carbon footprint substantial.

Aviation is responsible for 12% of transport-related CO_2 emissions globally, according to the IATA. Although its absolute emissions are lower than road transportation's, aviation's total operational forcing—the warming impact of its emissions, including CO_2, NO_X, and contrails—is estimated to be 2 to 4 times greater than CO_2 alone. This amplified impact, coupled with the steady growth of air travel, makes aviation a significant contributor to climate change.

In contrast to the huge number of studies on the emission of PCDD/Fs on road transportation, very little is known about the emissions of such pollutants from other modes of transportation, such as ships and airplanes. Despite their global relevance, these sectors have received limited scientific attention, creating a gap in understanding their role in the overall dioxin emissions inventory. This lack of data is particularly concerning for aviation and maritime transport, which are significant contributors to long-range atmospheric pollution. Airplanes, for instance, emit pollutants at high altitudes, potentially enhancing their atmospheric persistence and transport. Similarly, ships, often powered by heavy fuel oils, are associated with high pollutant loads in coastal and marine environments. Addressing these knowledge gaps is crucial for developing comprehensive strategies which lead to reducing dioxin emissions across all transportation sectors, particularly as international shipping and aviation continue their growth. Further research is needed to quantify these emissions and assess their environmental and health impacts, ensuring informed policy decisions in the fight against global pollution can be made.

Following data presented by Song et al. [22], Canada has a very important contribution of dioxins and furans due to transport compared to other countries. In terms of global data, 2.3% of dioxins are due to transport (data corresponding to 2018) but the amount turns out to be 26.6% in Canada. This could be due to several country-specific factors. Some possible reasons include how the climatic conditions in Canada, such as extremely cold winters, could influence the type of fuels (and additives) used in vehicles. In cold climates, more polluting fuels might be used, or additional fuel might be burned to heat vehicles, leading to increased emissions of dioxins. We must also consider the fact that some countries may have other significant sources of dioxins, such as industrial activities or waste incineration processes, that might be more prominent than in Canada, reducing the share of emissions attributable to traffic.

4.2. Trends and Future Projections

Road transport is leading the transition to low-carbon technologies, with electric vehicles (EVs) and hybrids becoming increasingly popular. Many countries have implemented ambitious policies to phase out internal combustion engines in favor of EVs.

While progress in decarbonization has been slower in maritime transport, the industry is exploring innovative solutions, including alternative fuels, improved vessel designs, and operational efficiencies, to reduce emissions. Examples include optimized flight routing, continuous descent approaches, and single-engine taxiing. Wider adoption requires regulatory and infrastructure support.

The aviation industry faces significant challenges in reducing its emissions due to technical constraints and the projected growth due to air travel demand, which is expected to increase by 3–4% annually. Without substantial mitigation efforts, the sector's emissions could double by 2050.

While road transportation has the largest absolute emissions and the most direct impact on urban air quality, aviation's disproportionate impact on radiative forcing makes it a critical focus for climate action. Similarly, maritime transport's emissions, though more energy-efficient, remain significant due to the vast scale of global trade.

5. Conclusions

The article reviews the contribution of commercial flights to global emissions of both inorganic and organic pollutants, highlighting several key points. Commercial aircraft emit pollutants both directly and indirectly. Primary emissions include CO_2, NO_X, CO, SO_X, particulate matter (PM), and hydrocarbons (HCs), while secondary emissions result from the atmospheric transformation of these compounds, leading to the formation of tropospheric ozone and secondary aerosols.

Aircraft emissions have significant impacts on air quality, ecosystems, and human health. Pollutants such as polycyclic aromatic hydrocarbons (PAHs) and persistent organic pollutants (POPs) can accumulate in ecosystems and persist for long periods of time, posing risks to biodiversity and food security. Although current regulations, such as the ICAO's CORSIA scheme, primarily focus on CO_2 emissions, they often overlook other harmful pollutants. While there are technological advancements in sustainable fuels and alternative propulsion systems, these innovations face considerable scalability challenges that must be properly addressed.

Although aviation currently accounts for only 2–3% of global CO_2 emissions, its environmental impact is substantial due to the altitude of its emissions and their amplified radiative effects. In comparison, road transportation remains the largest contributor to the transportation sector's emissions, followed by maritime transportation. With the number of commercial flights expected to rise sharply in the coming decades (5% yearly), it is urgent

to quantify and mitigate the sector's emissions and align them with international pollution and climate goals.

To effectively address these challenges, it is essential to develop targeted mitigation strategies that not only tackle climate change but also consider the broader spectrum of environmental and public health issues associated with aviation emissions. Future research should focus on enhancing our understanding of the full impact of these emissions, as well as exploring innovative solutions that can lead to a more sustainable aviation industry.

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