



OVERVIEW OF FACTORS RELATED TO AIRCRAFT OPERATION ASSOCIATED WITH A NEGATIVE IMPACT ON THE ENVIRONMENT

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Abstract

This paper presents the overview of the state of the science regarding factors related to aircraft operation that are associated with a negative impact on the environment as of early 2024. It lists the current status of science and remaining uncertainties as well as measures that have been lately undertaken to overcome aviation's unfavorable effect on our planet. The paper discusses aircraft noise pollution, exhaust emissions and contrails as examples of such factors based on trend analyses performed by the author.

Keywords: environment, aircraft, nitrogen oxides pollution, contrails, noise pollution, hydrocarbon pollution

1. Introduction

Nowadays, the world is trying to come up with a solution to one of its greatest challenges- climate change [1]. According to different studies, aviation is currently responsible for 2-3% of human-made CO₂ emissions and its impact could be compared with the production of methane by the global herd of cattle [2]. Aviation's impact on the environment is not only limited to CO₂, but also includes other forms of emissions like nitrogen oxides (NO_x), water vapor, soot and sulphate aerosols or noise [3]. While emitted greenhouse gases impact the climate and contribute to climate change [4], noise is expected to influence the health of people living in the vicinity of airports [5]. Many efforts are being pursued by various institutions and individuals to combat this problem.

Together with the long-term strategy of the European Commission, which has committed to achieving carbon neutrality by 2050 [6], the interest of companies producing both aircraft engines and aircrafts in this problem is constantly growing. The above-mentioned companies are competing with each other in new ideas and technologies that could eliminate the problem of emissions in aviation (e.g. the recently announced cooperation between GE Aerospace, Boeing and NASA, which resulted in the creation of an eco-demonstrator of the Boeing 737-10 aircraft with CFM LEAP-1B engines powered by SAF fuel [7]). There have also been many studies and works on optimizing the emissivity of an aircraft. Most of these works focus only on either optimizing the emission of an aircraft during flight or during operations on the airport runway, often taking into account the simultaneous optimization of operational costs.

2. Aircraft Noise Pollution

Noise is prevalent in everyday life and can cause both auditory and non-auditory health effects [8]. Examples of health issues produced by aviation are sleep disturbance, community annoyance, cardiovascular disease, and mental health problems [9]. Sleep is essential for life and optimal health as it plays an essential role in brain function and systemic physiology, including metabolism, appetite regulation, and the functioning of immune, hormonal, and cardiovascular systems [10]. Noise sleep disturbance has been measured in many studies, one of which conducted on participants living near 90 major US airports has shown that exposure to aircraft noise was associated with short sleep duration [11]. As far as the community annoyance is concerned it can be measured via surveys conducted systematically. However, numerous studies have shown that the results may vary depending on the selection criteria, such as a given airport or the age of the target group, among

others [12]. Long-term exposure to noise has been proven to increase the risk of coronary heart disease and incidence of stroke [13]. When it comes to the short-term subjection to noise, it has been observed for citizens living in the vicinity of the Heathrow airport and the results have shown that there is potentially an association between the aircraft noise in the late evening and night-time and the increased risk of cardiovascular hospitalizations and deaths in people living nearby the airport [14]. As for the impact of noise on the mental health, the findings of the study conducted in six European countries showed that a 10 dB increase in day-time or night-time aircraft noise was associated with a 28% increase in anxiety medication use [15]. The other cross-national study carried out on children going to schools in the Netherlands, Spain and the UK found that there is a relationship between exposure to chronic aircraft noise and children's cognition (i.e. impairment of reading comprehension and recognition memory) [16].

There have been several attempts made to mitigate the noise generated by aviation. One of which was the EU-funded project 'Community oriented solutions to minimize aircraft noise annoyance' (COSMA). The project worked out techniques to model the impact of aircraft noise on communities around airports. It also developed a database of noise including take-off and landing events for different aircrafts and developed a tool to generate sound files from recordings or simulations [17]. Furthermore, various authorities also tried to develop ways to control and certify noise emissions, for instance ICAO clarified its noise provisions in Annex 16, Volume I to the Convention on International Civil Aviation (the "Chicago Convention") [18]. Also, the FAA regulates the maximum noise level that an individual civil aircraft can emit through requiring aircraft to meet certain noise certification standards as defined in the Code of Federal Regulations (CFR) Title 14 Part 36 – Noise Standards: Aircraft Type and Airworthiness Certification (14 CFR Part 36) [19]. To counteract the abovementioned downsides of the noise, the European Union Aviation Safety Agency created the Aviation Noise Impact Management through Novel Approaches (ANIMA) project, funded under Horizon 2020, to work with airports and other authorities on methods which could help them implement the regulations designed to reduce noise adverse effects [20]. Yet, it is not only up to the biggest aviation authorities to regulate the noise pollution. As the community is getting increasingly aware of the danger, local authorities take it upon themselves to take some action and collect data that might be useful to take further steps. Let us take Poland as an example, Art. 118 of the Act of 27 April 2001, Environmental Protection Law (consolidated text of Dz. U. /Journal of Laws/ of 2022, item 2556, as amended) requires the heads of the major airports to prepare strategic noise maps based on the data collected during the previous calendar year [21]. This can help the airport management understand the current situation and undertake some countermeasures [22]. Besides all the above, aircraft and engine manufacturers also try to mitigate noise emissions by optimizing their designs. Figure 1 shows certification noise measurements for popular long range and short range airplanes produced by Boeing and Airbus over the years [23]. The gathered data proves that the newer the aircraft, the quieter its operation.

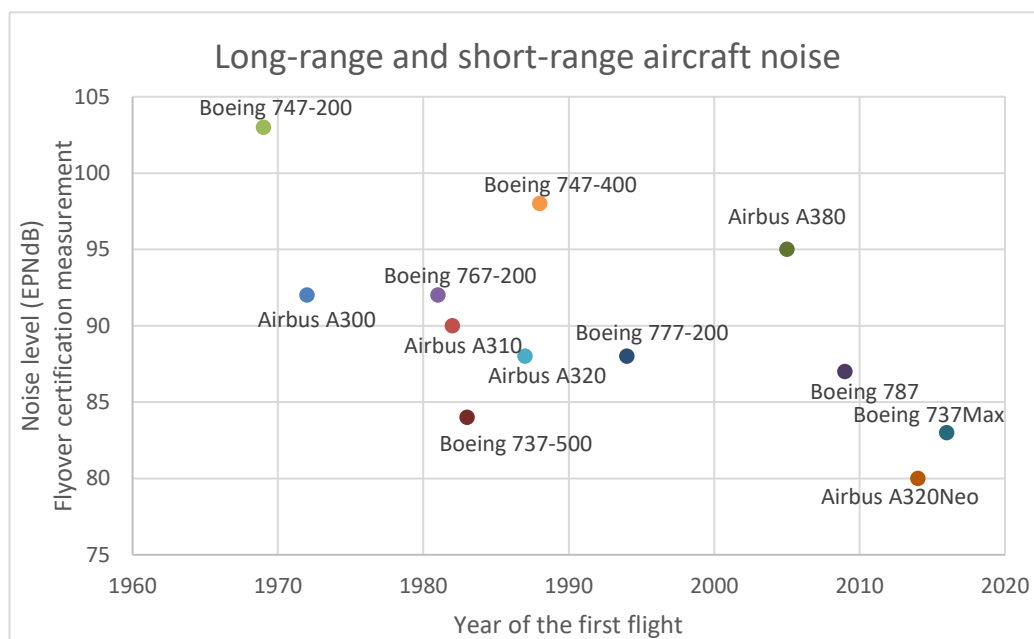


Figure 1 – Long-range and short-range aircraft noise.

3. Exhaust Emissions

The aviation sector emissions account to 2.1% of the global share, however if we include non-CO₂ effects, aviation contributes an estimated 4.9% to the global warming problem [24]. International aviation alone accounts for 1.3% of global CO₂ emissions. Even though a flight taken today would produce half the CO₂ than the same flight taken in 1990, the growth of the industry exceeds the speed and efficiency of the implemented improvements [25]. Moreover, passenger flights are responsible for ~85% of commercial aviation CO₂ emissions [26].

Other forms of non-CO₂ emissions such as ozone, water vapor, or aerosols also affect global warming. Aircrafts emit nitrogen oxides (NO_x), which form ozone and acid rain in the atmosphere and similarly to particulate matter emissions from aircraft turbine engines have a negative impact on health and climate. Particulate emissions formed at the exhaust mainly consist of ultrafine soot or black carbon emissions - such particles are called “non-volatile” (nvPM) [27]. NO_x and particulate matter presence in the air can have negative impact on human health leading to respiratory and cardiovascular diseases such as asthma, COPD (Chronic Obstructive Pulmonary Disease), hypertension, cardiac arrhythmias, acute coronary syndrome, atherosclerosis progression, ischemic stroke and formation of methemoglobin [28]. Furthermore, nitrogen oxide emissions and their contribution to the formation of acid rains lead to numerous environmental concerns such as water quality deterioration, disturbed vegetation of plants and trees and adverse effects on aquatic environments impacting wildlife and fish [29]. As far as particulate matter (PM) emissions are concerned, they might contribute to visibility impairment (haze), making lakes and streams acidic, damaging crops and depleting the diversity of ecosystems [30]. Standards limiting the LTO (landing and take-off) emissions of smoke number, nvPM (as maximum mass concentration), unburnt hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x) from turbojet and turbofan aircraft engines are contained in Annex 16 Volume II to the Convention on International Civil Aviation, Doc 7300 [31]. Regulatory levels for the mentioned gaseous emissions are clearly described in the abovementioned document and some of them might differ depending on the date of manufacture of the first individual engine, its pressure ratio and thrust.

3.1 Turbofan Engine Exhaust Emissions – Study

3.1.1 Gaseous Emissions in Different Flight Phases

The following sections of this article focus on the study performed by the author. The aim of this study is to perform a comparative analysis of exhaust emissions of a few chosen aircraft turbofan engines used on passenger aircraft. The chosen engines are used on most popular aircraft and all of them are still in production. The emission data was gathered from ICAO database with information submitted by engine manufacturers [32]. Selected engines are listed in Table 1.

Engine	Company	Certification year	Rated Thrust (kN)
CFM56-7B26E	CFM International	2010	117
LEAP-1B28	CFM International	2016	130.4
CF6-80C2B1F	GE Aerospace	1989	254.3
GE90-115B	GE Aerospace	2003	513.9
GENx-1B64/P2	GE Aerospace	2013	298
CF34-8E5	GE Aerospace	2002	59.7
PW1524G	Pratt & Whitney	2016	108.5
PW1921G	Pratt & Whitney	2016	100.3
PW4062	Pratt & Whitney	1998	275.8
Trent 972E-84	Rolls-Royce	2017	345.9
Trent 1000-D3	Rolls-Royce	2016	334.7
Trent7000-72	Rolls-Royce	2018	327.9
Trent XWB-79	Rolls-Royce	2010	355.2
TAY 611-8C	Rolls-Royce	2002	61.6

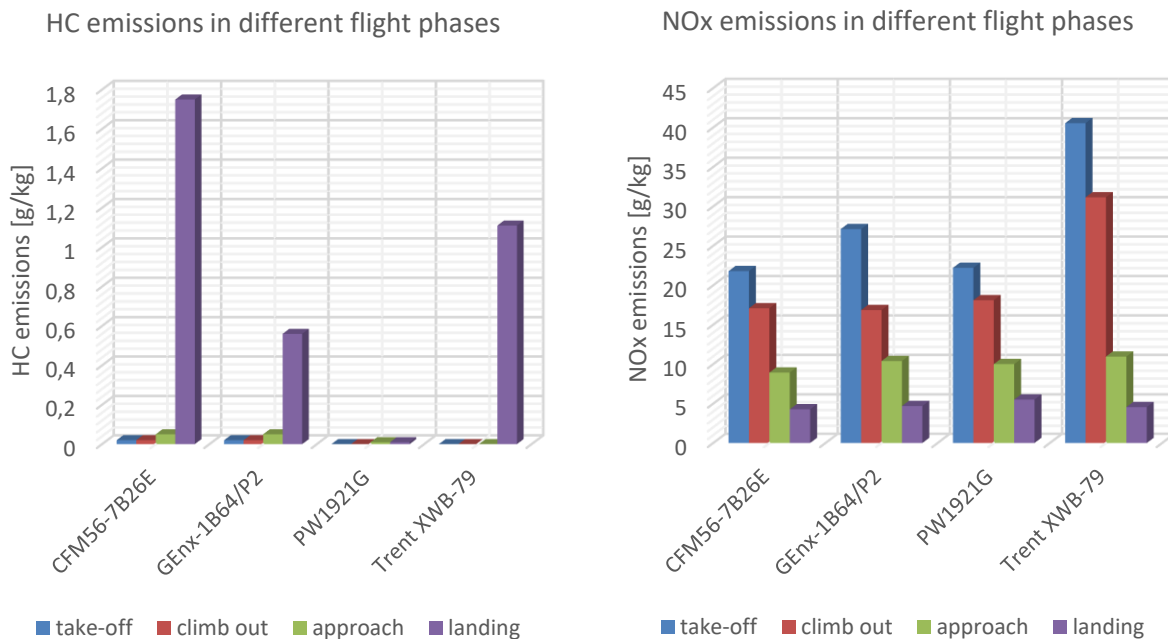
Table 1 – Selected turbofan engines.

Firstly, four engines were chosen as representative to depict the emissions of HC (hydrocarbons), NO_x (nitrogen oxides), CO (carbon monoxide) and nvPM (non-volatile particulate matter) in four flight phases: take-off, climb out, approach and landing (idle). Figure 2 shows the comparative bar charts. Based on the selected examples, a conclusion might be drawn that as far as emissions of hydrocarbons are concerned, the biggest amount is emitted in the last phase of the flight (landing/idle) and in the case of the CFM56-7B26E engine reach the maximum value of 1.75 g/kg. Nitrogen oxides, however, are emitted in greatest amounts at take-off – maximum of 40.55 g/kg for Trent XWB-79. It is not clear which flight phase is prone to the biggest carbon monoxide emissions, yet landing might be taken as a representative phase and thus it will be analyzed in the further study. Maximum CO emissions account to the CFM56-7B26E engine with the emission of 30.94 g/kg. Lastly, when it comes to the non-volatile particulate matter, it is also not easy to conclude which phase is mostly exposed to the nvPM emissions but in the further study take-off will be taken into account as a representative. Maximum nvPM emissions account to 44.9 mg/kg for Trent XWB-79 at climb out.

Based on this comparative analysis of gaseous emissions in different flight phases, one can come to a conclusion that there is no phase that could be considered emission-free and if there are some future efforts to reduce any kind of the mentioned emissions, all phases should be considered equally to ensure most efficient solution.

3.1.2 Gaseous Emissions – Trend Analysis

The second part of the performed study focuses on trends in gaseous emissions of turbofan engines which produce different levels of thrust and were certified between 1985 and 2018. As mentioned above, all factors were analyzed for one selected flight phase in order to illustrate trends in emissions.



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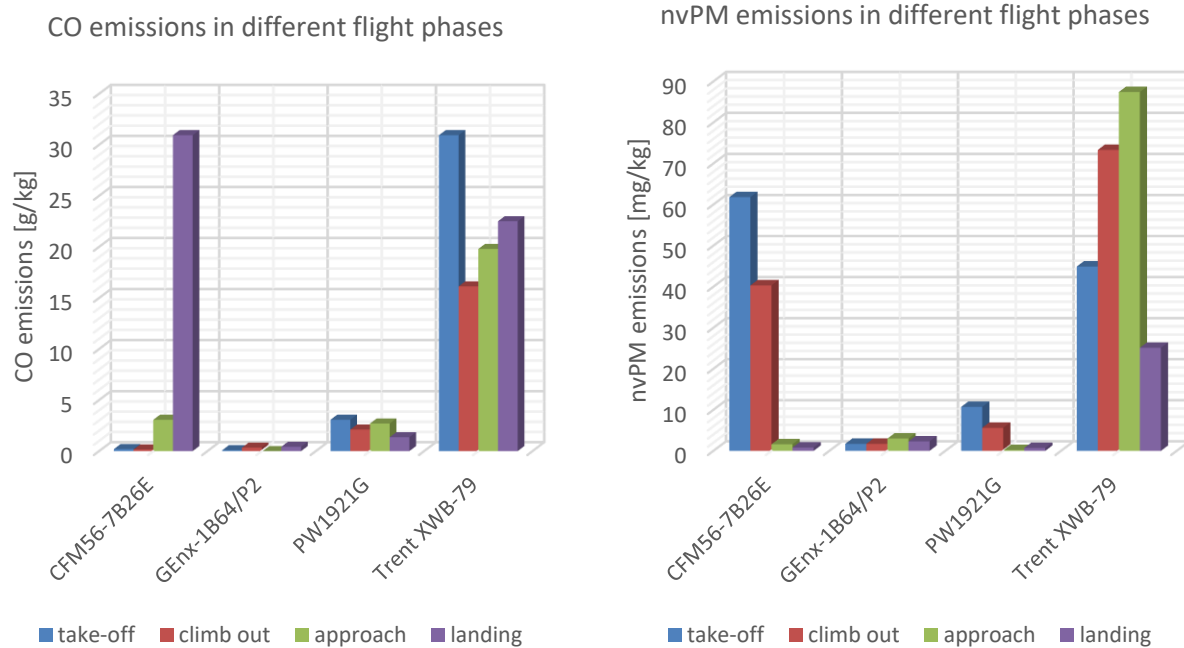


Figure 2 – HC, NO_x, CO and nvPM emissions of exemplary turbofan engines in different flight phases.

Figure 3 and Figure 4 depict trends in NO_x emissions for the chosen set of turbofan engines. The general trend is that the bigger the thrust the engine is able to produce, the bigger the nitrogen oxides emissions. Yet, it is worth noting that there are some exceptions that are placed away from the trend line – an example of such an exception might be the LEAP-1B28 engine which is capable of producing the thrust of only 130.4 kN but produces the NO_x emissions of 60.7 g/kg at take-off which is more than 51 g/kg produced by GE90-115B engine that produces 514 kN of thrust. It is important to point out that Figure 4 shows that there is an upward trend in the emissions of newer engines. Interestingly, even though the engines fulfill the emission level requirements, they produce bigger amounts of nitrogen oxides than older engines.

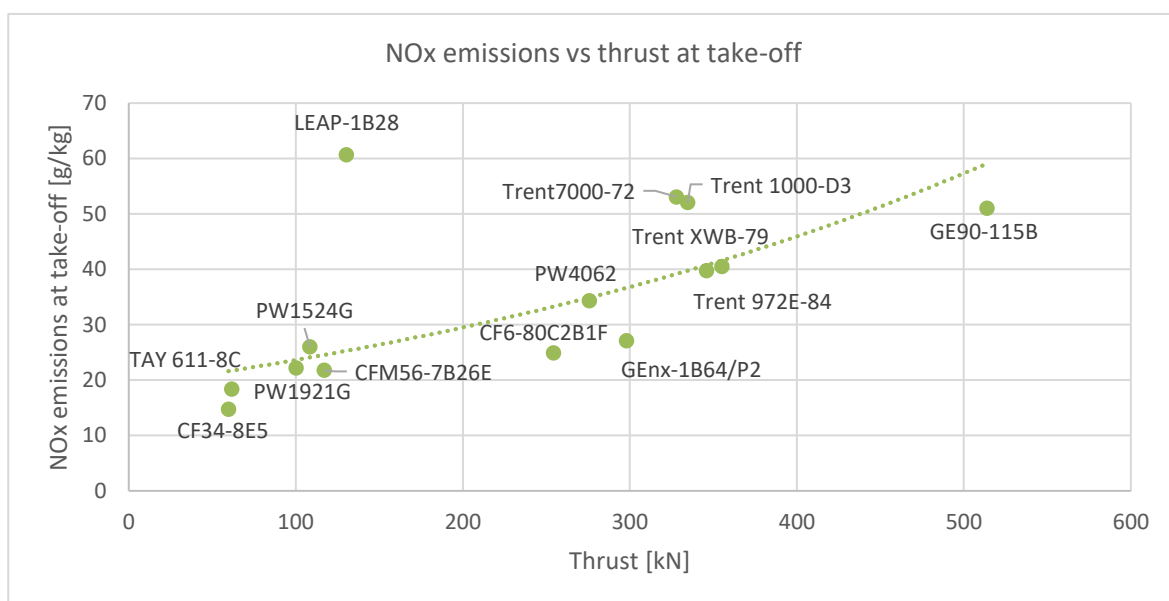


Figure 3 – Nitrogen oxides emissions at take-off versus thrust for the selected group of turbofan engines.

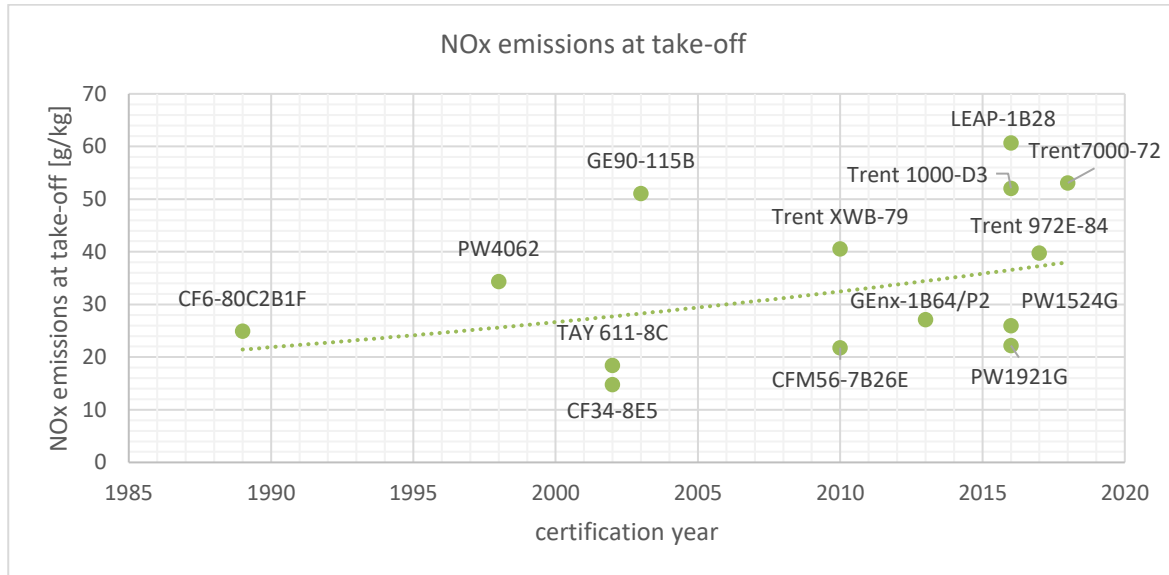


Figure 4 – Nitrogen oxides emissions at take-off versus engine certification year for the selected group of turbofan engines.

Next, carbon monoxide emissions are to be analyzed based on Figure 5 and Figure 6, it might be observed that although the engine with the biggest thrust (GE90-115B) has one of the biggest emission scores of 35 g/kg, the general trend says that the bigger the produced thrust, the smaller the CO emission level. Also, the newer the aircraft engine, the smaller the emissions. Figure 5 presents the emissions of hydrocarbons and proves that most of the selected engines have the emission level below 4 g/kg, moreover, there are several engines which almost do not emit HC. Figure 6 also shows a very comforting trend of HC emissions getting to neutral level of 0 g/kg for the newest engines. Lastly, nvPM emissions might be investigated. Trend line in Figure 9 intelligibly shows that the amount of produced thrust does not necessarily have a correlation with the emissions. For example, GE90-115B (514kN) engine emits 14.9 mg/kg, whereas Trent 972E-84 (346 kN) emits 64 mg/kg which is over 4 times as much. Figure 10, however, shows that even though the trend line indicated a downward trend in the nvPM emissions, some of the newest engines have the highest levels of nvPM emissions at take-off.

The performed analysis may lead to the conclusion that the ICAO regulatory limits had a positive influence on drawing the attention of turbofan engine manufacturers to the reduction of gaseous emissions that was achieved through design improvements of combustion chambers, among others. However, it is also evident that even though fulfilling the regulatory requirements some of the most recently certified engines still have relatively high levels of emissions of certain gases and leave some room for improvement for the design engineers. Please note that the gathered data comes from the test with conventional aviation fuel. Currently Sustainable Aviation Fuel (SAF) is ramping up and there are plans to use it in great amounts in the upcoming years. SAF can be produced from a number of sources, including waste oil and fats, agriculture and municipal waste, and non-food crops [33].

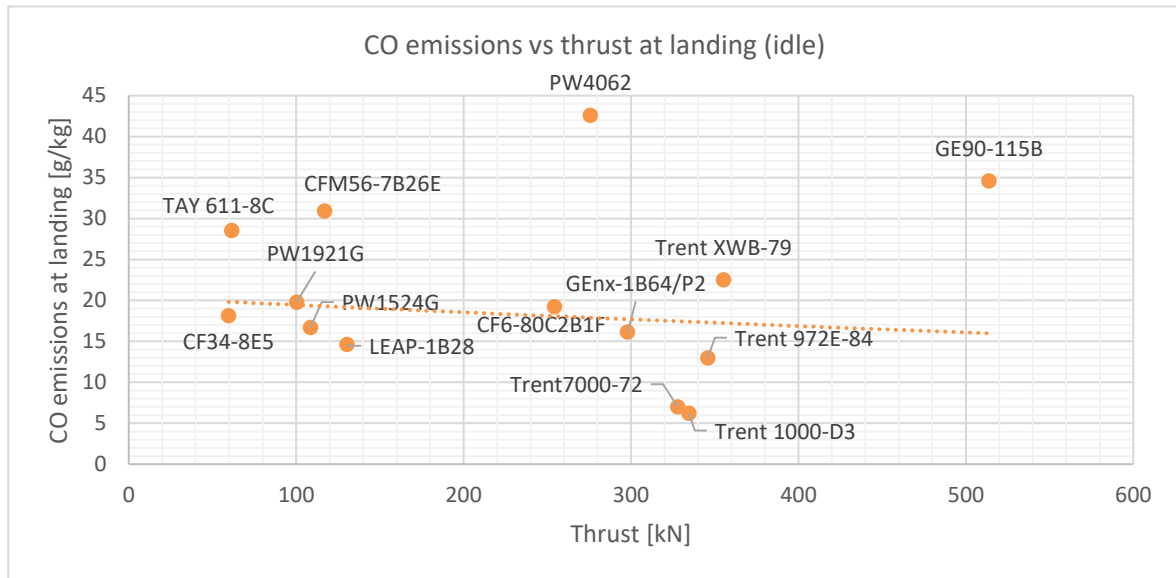


Figure 5 – Carbon monoxide emissions at landing versus thrust for the selected group of turbofan engines.

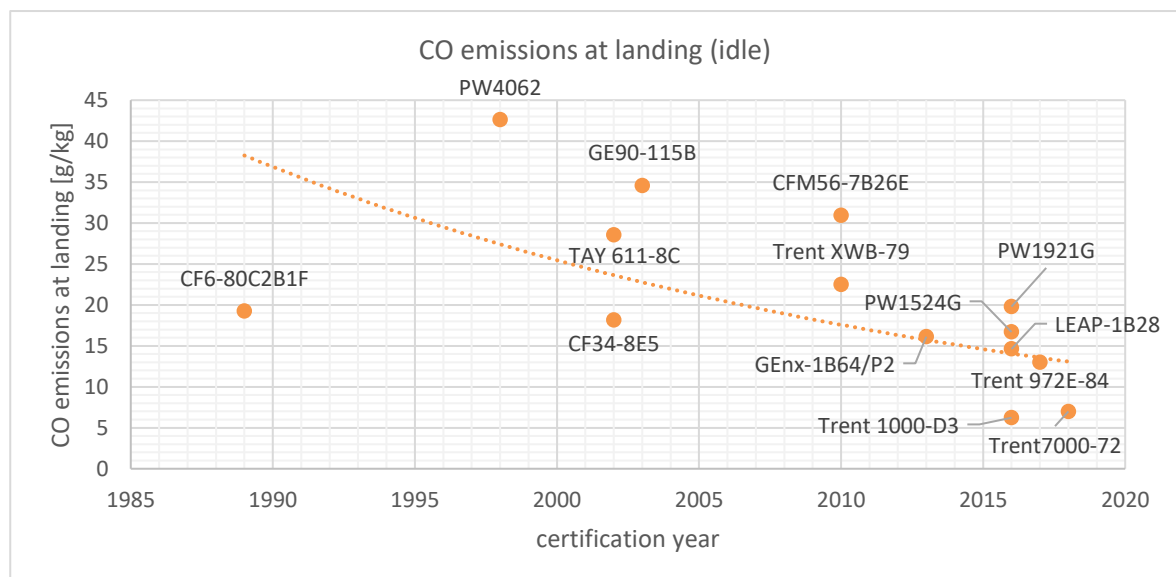


Figure 6 – Carbon monoxide emissions at landing versus engine certification year for the selected group of turbofan engines.

In July 2021, the European Commission published its proposal ReFuelEU Aviation for the introduction of a SAF blending mandate as part of the “Fit for 55 package” under the European Green Deal. This proposal stipulates that a growing share of SAF, from initially 2% in the year 2025 up to 70% in the year 2050, must be used by all aircraft operators present at European airports [34]. As such, the greenhouse gas emissions associated with the use of a particular amount of SAF fuel may vary by feedstock and production process thus it has to be meticulously selected and certified by authorities. Also, more and more extensive application of SAF in aviation is believed to contribute to bigger reductions in gaseous emissions without significant changes in engine design. Thus, when SAF is more widely used in the analyzed engines, their emission test results might improve.

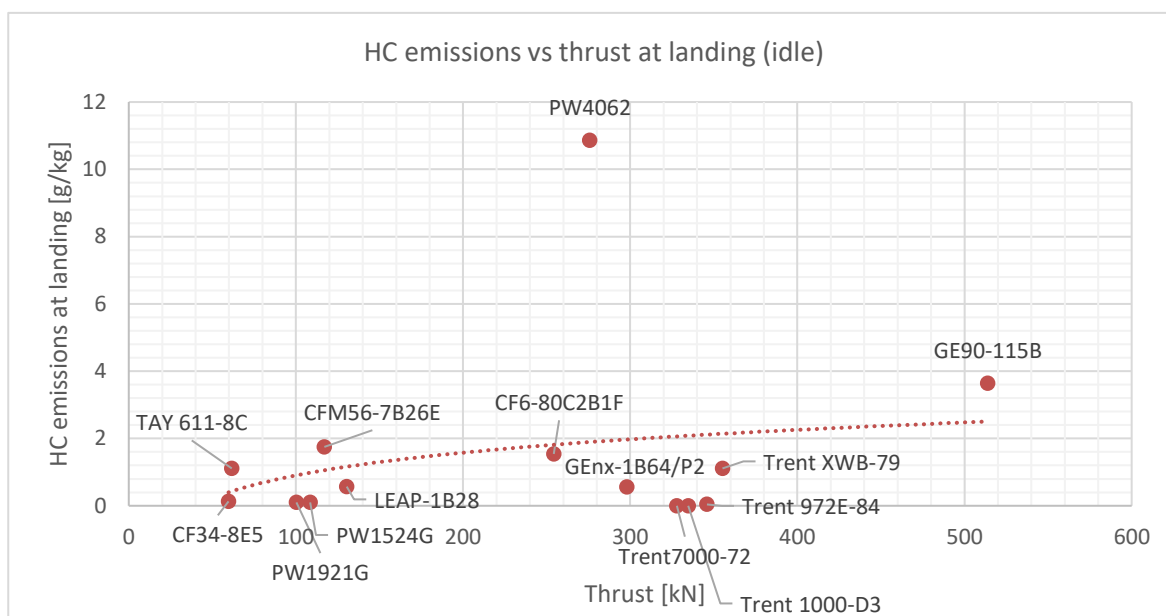


Figure 7 – Hydrocarbons emissions at take-off versus thrust for the selected group of turbofan engines.

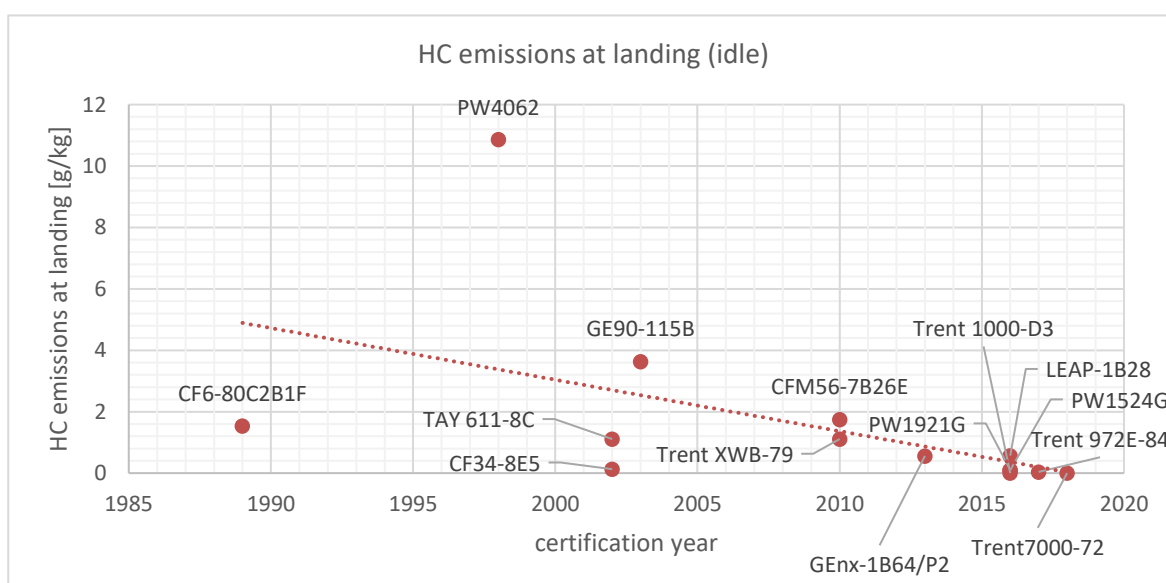


Figure 8 – Hydrocarbons emissions at take-off versus engine certification year for the selected group of turbofan engines.

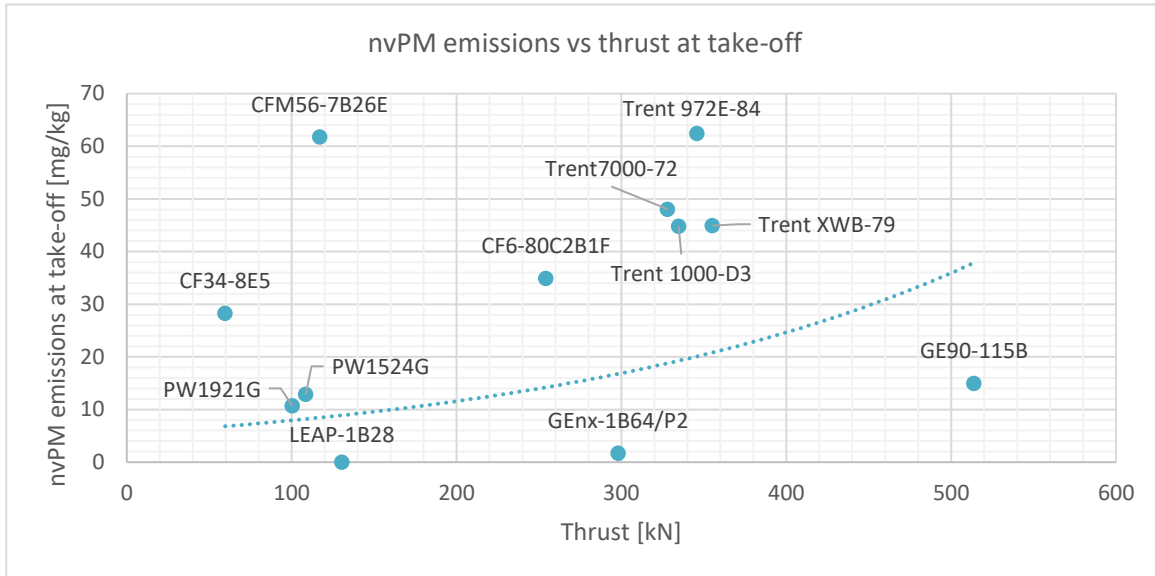


Figure 9 – Non-volatile particulate matter emissions at take-off versus thrust for the selected group of turbofan engines.

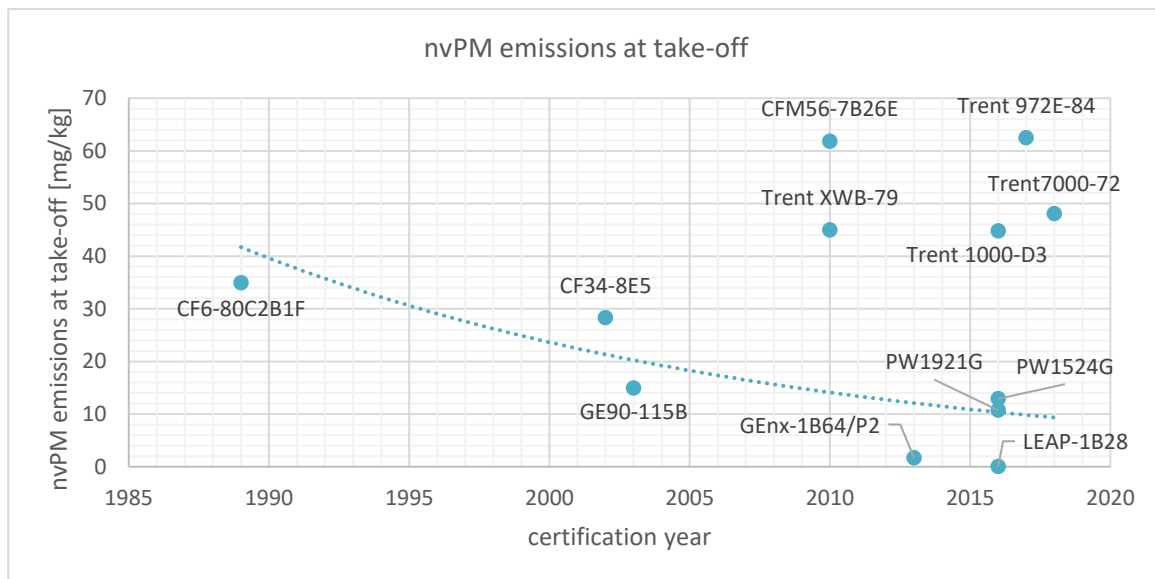


Figure 10 – Non-volatile particulate matter emissions at take-off versus engine certification year for the selected group of turbofan engines.

4. Contrails

The last environmental factor considered in this article are contrails shown in Figure 11. These are a type of cloud that forms in the wake of an aircraft at high cruise altitudes under specific temperature and humidity conditions when water vapor condenses onto emitted aerosols and then freezes to form ice particles [35]. Contrail cirrus, the cirrus clouds that form within the aircraft plume, account for aviation's largest radiative forcing, larger than the forcing from aviation CO₂ emissions. The impact that a contrail has on the climate depends on numerous factors and might be hard to quantify, however it is undisputable that persistent contrails have a warming or cooling climate impact (depending e.g. on the part of the day). In contrary to CO₂ effect on the environment which may last for many years, the climate impact of contrails would normally last a few hours [36]. It is not surprising that there is interest in the potential of contrail avoidance to reduce aviation radiative forcing while accounting for potential tradeoffs such as increased fuel burn thanks to the flexibility in aviation operations to change routing not to enter ice-supersaturated regions [37] [38].



Figure 11- Contrails over Europe on June 8, 2024, source: map.contrails.org

5. Conclusions

This paper discusses some of the factors that are related to aircraft operation and have adverse effect on the environment. These factors include aircraft noise pollution, contrails and CO₂, nitrogen oxides (NO_x), hydrocarbons, CO (carbon monoxide) and nvPM (non-volatile particulate matter) emissions. The overview proves that setting new rules and directives by authorities is an efficient way of implementing new regulations that are aimed at reducing aviation's negative impact on our planet. These official documents motivate both aircraft operators and manufacturers to change their designs and standard works in order to reduce pollution. Moreover, the trend analysis of the turbofan engine emissions of NO_x for engines that are currently in operation might encourage researchers to take a deeper look at these trends and understand why most modern engines have an increased level of emissions.

To sum up, this overview of the abovementioned aspects and currently taken countermeasures might lead to future research and development of new optimization projects as well as indicate which of the factors are being more successfully mitigated than the others.

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