Czech University of Life Sciences Prague

Faculty of Economics and Management

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Diploma Thesis

Carbon footprint of aviation

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DIPLOMA THESIS ASSIGNMENT

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Economics and Management
Economics and Management

Thesis title

Carbon footprint of aviation

Objectives of thesis

This diploma thesis deals with the issue of the carbon footprint of aviation, more precisely the emissions produced by aircrafts during LTO cycle and CCD phase.

The first objective is to provide information on what emissions are generated during the flight or ground movement of an aircraft, to outline the methods by which emissions can be calculated and to provide information about aircraft fuel and posibilities for its calculation.

The main goals of the thesis are:

to determine and compare the amount of carbon dioxide produced by aircrafts during the LTO phase at Prague Airport in a certain period,
to compare the carbon footprint of the LTO cycle of Prague Airport with competing airports,
to calculate the emissions of chosen aircraft type for a specific route,
to calculate the carbon footprint of Prague airport's regular airline routes within the summer flight schedule of 2021.

Methodology

The thesis consists of two parts – the theoretical and the practical part.

The theoretical part is based on research through literature review.

It includes the explanation of aircraft engine emissions in detail, the definition of carbon footprint, the methods for calculation, the aircraft operation including phases of flight and the calculation of aircraft fuel.

To calculate the carbon footprint of airports from LTO cycles of aircrafts and Prague's airline routes , it was necessary to obtain data about aircraft movements, aircraft types, schedules and emission factors. All data were collected from Eurocontrol, airports, ICAO and European Environmental Agency.

The proposed extent of the thesis

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Keywords

carbon footprint, CF, CO2 emissions, LTO cycle, CO2, emissions

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Expected date of thesis defence

2020/21 SS – FEM

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Electronic approval: 4. 4. 2021

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Prague on 06. 04. 2021

For calculations there were used methods of ICAO emission calculator and methodological tiers that are listed in the Chapter 3 of the IPCC Guidelines for National Greenhouse Gas Inventories.

Declaration

I declare that I have worked on my diploma thesis titled "Carbon footprint of aviation" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any their person.

In Prague on 6th April 2021 ______________________________

Acknowledgement

I would like to thank doc. Ing. Petr Procházka, MSc., Ph.D. , and my entire family, for their advice and support during my work on this thesis.

Uhlíková stopa letectví

Souhrn

Tato diplomová práce se zaměřuje na seznámení se s uhlíkovou stopou letectví. Teoretická část se zabývá emisemi vyprodukovanými leteckým motorem a vysvětlení pojmu uhlíková stopa.

Další část je věnována metodám výpočtu uhlíkové stopy, konkrétně metodám ICAO, 3 metodickým úrovním IPCC a nakonec operacemi letadel zahrnující fáze letu nebo letecké pohyby. Jsou zde vysvětleny pojmy jako LTO nebo CCD. Část je i věnována tématu výpočtu spotřeby paliva.

Analytická část obsahuje výpočet celkového množství uhlíkové stopy vyprodukované během LTO cyklu v období let 2014-2020. Dále použití tohoto výpočtu ke srovnání s jinými letišti. Další část se věnuje oblasti možností výpočtu emisí pro vybraný typ letadla a trasu. Poslední část je zaměřena na výpočet množství uhlíkové stopy vyprodukované na trasách z Letiště Praha v období letního letového řádu 2021.

Klíčová slova: Uhlíková stopa, CF, emise CO_2, LTO cyklus, CO_2, emise

Carbon footprint of aviation

Summary

This diploma thesis focuses on getting acquainted with the carbon footprint of aviation. The theoretical part deals with the emissions produced by an aircraft engine and an explanation of the concept of carbon footprint.

The next part is devoted to methods of calculating the carbon footprint, namely ICAO methods, 3 methodological levels of the IPCC and finally aircraft operations involving flight phases or aircraft movements. In this section are explained terms such as LTO or CCD. The part of this work is also devoted to the topic of fuel consumption calculation.

The analytical part contains the calculation of the total amount of carbon footprint produced during the LTO cycle in the period 2014-2020. Further use this calculation to compare with other airports. The next part deals with the possibility of calculating emissions for the selected aircraft type and route. The last part is focused on the calculation of the amount of carbon footprint produced on the routes from Prague Airport in the period of the summer flight schedule 2021.

Keywords: carbon footprint, CF, CO2 emissions, LTO cycle, CO2, emissions

Table of contents

1 Introduction

People always sought to conquer airspace. Over the centuries, we have gone from air balloons, through the first attempts of primitive aircraft, to jets. Thanks to our ancestors, today we have technologies and procedures that enables us to do things that people could not even have imagined hundreds of years ago.

One of these technologies that literally changed people's lives was the invention of the plane. Over the years, aircraft and aviation have gained unusual popularity among most human society. People began to move from place to place faster and faster, the demand for flights and tourism increased. Long distances stopped to be a matter of days but only took a few hours. Then after opening the air for new companies, the situation rapidly changed. The aviation together with air transport became available to a larger part of society. This resulted in that aviation, which people knew before, has completely changed.

Today, air transport is not perceived as something luxurious, but as a necessity or worse, as something noisy or annoying. All these views are related to the massive increase in air traffic, which also results in its negative effects. These impacts of aviation are felt by each of us, depending on where we live. Aviation has an impact on the environment through the extraction of minerals, the use of operating materials or the production of waste materials. The main negative effects are land occupation, fauna loss, noise, and emissions. And it is emissions in the form of carbon dioxide that are the focus of this work.

The title of this work uses the modern term carbon footprint. Under this term, each of us can imagine something different, therefore, I will state at the outset that the term carbon footprint in this work means only carbon dioxide.

This work deals in the theoretical part with an explanation of what emissions occur during fuel combustion, the term carbon footprint is explained in detail and finally the work focuses on methods of calculating the carbon footprint together with an explanation of individual phases of flight, which are necessary for calculation.

The main goal of the thesis is to determine and compare the amount of carbon dioxide produced by aircrafts during the landing and take-off phase (LTO) at Prague

Airport in a certain period, then comparing the carbon footprint produced by aircrafts during LTO cycle at Prague airport with other chosen airports. Also, the thesis includes the example of the calculation for all emissions of chosen aircraft for a specific route and finally the calculation of the carbon footprint of Prague airport's regular airline routes withing the summer schedule of 2021.

2 Thesis methodology and objectives

2.1 Objectives

The first objective is to provide information on what emissions are generated during the flight or ground movement of an aircraft, to outline the methods by which emissions can be calculated and to provide information about aircraft fuel and possibilities for its calculation.

The main goals of the thesis are:
to determine and compare the amount of carbon dioxide produced by aircrafts during the LTO phase at Prague Airport in a certain period,

to compare the carbon footprint of the LTO cycle of Prague Airport with competing airports,

to calculate the emissions of chosen aircraft type for a specific route,

to calculate the carbon footprint of Prague airport's regular airline routes within the summer flight schedule of 2021.

2.2 Methodology

The thesis consists of two parts – the theoretical and the practical part.

The theoretical part is based on research through literature review. It includes the explanation of aircraft engine emissions in detail, the definition of carbon footprint, the methods for calculation, the aircraft operation including phases of flight and the calculation of aircraft fuel. There were used methods induction and deduction.
To calculate the carbon footprint of airports from LTO cycles of aircrafts and Prague's airline routes, it was necessary to obtain data about aircraft movements, aircraft types, schedules and emission factors. All data were collected from Eurocontrol, airports, ICAO and European Environmental Agency (EEA).
For calculations there were used methods of ICAO emission calculator and methodological tiers that are listed in the Chapter 3 of the IPCC Guidelines for National Greenhouse Gas Inventories, Master emission calculator. For visualisation of results there were used graphs, tables and pictures.

3 Theoretical Part

3.1 Aviation

The word aviation comes from the Latin word avis "bird".[1] By aviation we mean "the branch of business, or technology that deals with any part of the operation of machines that fly through the air."[2]

Aviation is the youngest and fastest growing transport industry in the world. Air transport has grown tremendously over the last 30 years. From luxury transport and a certain romance, it has literally become a mass affair available to most of society of economically advanced countries and is commonly used for business and private trips. This was possible just thanks to a liberalization of the market that took place in many countries. Airlines were pushed to increase their productivity and to reduce ticket prices. On the other hand, market liberalization has led many carriers to bankruptcy (Alitalia. Swissair, Sabena), has given opportunity for establishing new low-cost companies but also has negatively increased effect on the environment. The most negative impact is caused by carbon footprint (CF). The term carbon footprint will be explained later, for the purposes of this work we will understand it as the amount of carbon dioxide (CO_2).

In the worldwide numbers emissions from the global aviation industry represents around 2% of all human induced carbon dioxide emissions in 2019. Aviation was at that time also responsible for about 12% of CO_2 emissions from all transport sources. In comparison to road transport where the emissions attack 74 %. Interesting number is that 80 % of CO_2 aviation emissions are produced by flights of over 1500 km. In these cases, however, there is no alternative mode of transport.[3]

In the Czech Republic, air transport is operated at 90 civil airports[4], of which 5 are international with regular traffic.[5] The main position is held by Prague Airport, that provides 94% of the total passenger transport. In 2009 the Czech capital airport produced 53824 t CO_2 while in 2016 the numbers were reduced to 46072 t CO_2 per year. The

[1] MABONGA, F.: Introduction to aviation. AUTHORHOUSE, 2015.
[2] CRANE, DALE. *Dictionary of Aeronautical Terms : Over 11,000 Entries*, edited by Editorial Team ASA, Aviation Supplies & Academics, Inc., 2017.
[3] Facts and figures. *ATAG - Air transport action group* [online]. 2020
[4] https://www.mdcr.cz/Dokumenty/Letecka-doprava/Pravni-predpisy/Letiste?lang=cs-CZ
[5] https://aim.rlp.cz/ais_data/aip/data/valid/a1-3-3.pdf

reduction was achieved by replacing airport equipment such as lights or replacing boilers. The highest number in total amount represents the emissions from aircrafts during landing and take-off cycle (LTO). Methods how to reduce CO_2 from LTO cycle will be described in a later chapter.

3.2 History of aviation

For a long time, humans desired to look into the clouds and to control the airspace and thus to get at equal level with the gods. The first person interested in aviation was Leonardo da Vinci. He became famous for his Codex on the Flight of Birds and plans for several flying machines, including a helicopter and a light hang glider. Then came the era of hot air balloons to which humans returned 100 years later in the form of rigid airship – Zeppelin.

One of the most important milestones was the first controlled flight with an engine aircraft realized by Orville and Wilbur Wright that was achieved on 17th December 1903. Even if the flight took just about 12 seconds[6], from this time we can start calculating the carbon footprint of the aircraft engines. Another hero of the history was undoubtedly the French aviator Louis Blériot. He was the first man who crossed the canal La Manche just after 37 min. of flying. Afterward the Daily Mail newspaper in connection with this came with a headline that went down in history: "England is no longer an island" ("L'Angleterre n'est plus une île").[7] On the territory of today's Czech Republic, the first emissions from air transport were created by a separate flight, which was taken by Jan Kašpar on May 12, 1911 from Pardubice to Prague and he also made a first flight with a passenger. It is also worth mentioning in 1914, air records reached a speed of 208.85 km / h and altitude 6120 m.

Pilot Charles Lindberg has also made a significant contribution to history. He was the first to fly from America to Europe in a plane called "Spirit of St. Louis. At that time, the aircraft was equipped with a nine-cylinder engine with an output of 225HP. It reached a speed of 180km / h. the total distance of 6000 km was flown by the pilot in an incredible 33h30min today.[8]

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[6] Alan P. Dobson, 'A History of International Civil Aviation: From its Origins through Transformative Evolution'. London and new York: Routledge, 2017.
[7] *Louis Blériot, il y a un siècle...* [online]. 2009.
[8] BÍNA, L., ŠOUREK, D., ŽIHLA, Z.: Letecká doprava II. VŠO v Praze, o. p. s., Praha, 2007..

The highest level of air transport is represented by supersonic aircraft – Concorde. It was in service from 1973 There were just 2 airlines that owned this plane. (Air France and British Airways). The aircraft was flown mainly on routes from Paris and London to New York. However, not everyone could afford the flight. The cost of the return ticket was about 8,000 $. In the near future, it is very unlikely that supersonic aircraft will meet current standards for commercial aircraft. It is estimated that in the most likely configuration, CO_2 limits will be exceeded by up to 70%. [9]

With the gradual development of aviation, it was also necessary to address issues of international civil aviation. In 1919 IATA (International Air Transport Association) was established. As trade association it represents 290 airlines or 82 % of all air traffic.[10] IATA members and industry stakeholders agreed on ambitious targets how to decrease CO_2 emissions from air transport:

- An improvement in fuel efficiency on average of 1.5% per year from 2009 to 2020.
- A decrease on net aviation CO_2 emissions from 2020 (carbon-neutral growth).
- A reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 levels.[11]

However, due to the current situation regarding COVID, IATA prognosed that emissions from year 2020 could decline to 250 million tonnes of CO_2. That would mean the level of emissions 25 years ago. [12]

Later on countries felt the need to agree on common rules covering aircraft registration, airspace, security, sustainability, details of the rights of the signatories in relation to air travel. It resulted in the signing of an agreement known as The Convention on International Civil Aviation on December 7, 1944. The convention established ICAO (International Civil Aviation Organization).

[9] KHARINA, Anastasia a Tim MACDONALD. *Environmental performance of emerging supersonic transport aircraft.,*
[10] The Founding of IATA. IATA [online].
[11] *Working Towards Ambitious Targets: Reducing climate change is a critical global challenge.* [online].
[12] *COVID-19 and CORSIA:: Stabilizing net CO2 at 2019 "pre-crisis" levels, rather than2010 levels* [online].

In the second half of the last century started serious debates about climate change at First World Climate Conference. There was adopted a declaration to take steps to prevent climate change and also acceptance of the World Climate Research Programme [13] The UN Environment Programme and World Meteorological Organization founded IPCC (Intergovernmental Panel on Climate Change) in 1988. IPCC is the important player concerning the climate regime, it regularly prepares assessment technical or special reports addressing key climate change problems.

In the early 1990s, an independent coalition of aviation industry organizations and companies around the world, called the ATAG (Air Transport Action Group), was formed. The members of this organization include representatives of airlines, airports, engine manufacturers, air navigation service providers, aircraft manufactures (such as Airbus or Bombardier) and many others. ATAG collects and shares a wide database of information and forecasts, such as the planning and development of environmentally friendly transport infrastructure.[14]

In 1992, the United Nations Framework Convention on Climate Change was written at the United Nations Conference on Environment and Development in Rio de Janeiro. But it began to be enforceable in 1994. The aim of the Convention was to create preconditions for the stabilization of greenhouse gas concentrations in the atmosphere at the global level.

Already the year 1995 showed that not clearly specified commitments of the Convention would not have the effect expected. Two years later, the Kyoto Protocol was adopted at the Third Conference of Parties to the Framework Convention in Kyoto.[15] The Protocol required developed countries to reduce greenhouse gas emissions by 5.2% over the period (2008-2012) compared to 1990.

Since the beginning of 2000, international institutions and society have paid more attention to CO_2 emissions. Previously, international air transport was excluded from the national targets of the Kyoto Protocol. The problem was that the debate on reducing CO_2 emissions from flights remained controversial and unpopular due to green aviation for

[13] ZILLMAN, John W. Adaptation to a variable and changing climate: challenges and opportunities for National Meteorological and Hydrological Services 2009, Bulletin nº : Vol 58 [cit. 2021-01-05].
[14] *ATAG - Air transport action group* [online]. 2020
[15] Greenhouse Gas Emissions. *CHMI – Air Quality Information System* [online].

many reasons. The Kyoto Protocol mandated the inclusion of CO_2 emissions in the global climate commitment. But there was a slow progress in this task, so EU Commission decided to develop proposals to include aviation in its Emissions Trading Scheme (ETS)[16]

In 2015, the Paris Agreement was adopted. It set out the basic principles of climate protection measures and introduced strategy of voluntary reduction targets called Intended Nationally Determined Contributions. However, a major problem or shortcoming of the agreement is the lack of CO_2 charging.[17]

3.3 Air transport and the environment

Over the last decade, due to globalization, air transport has grown enormously. Since 1990, the number of passengers has tripled. This has brought with it a number of negative influences that are felt by residents living mainly in the vicinity of individual airports. The impacts of air traffic on the environment in the form of noise and emissions are the main reason preventing airport spread.

Aviation emissions

CF from aviation play a significant role in climate change. Today's modern aircraft fly at cruising attitude of 33 000 – 42 000 feet [18] (10000 feet equals 3050 m). At these heights there are 2 layers of the atmosphere: the troposphere as the lowest layer (it extends upward to about 33000 feet above sea level) and the stratosphere (extends from the top of the troposphere to about 50 km above the ground.[19] These layers of the atmosphere are most affected by air traffic. Some gases emitted by aircraft engine, together with the water vapor, give rise to a problem known as global warming. Gases that contribute to that are called greenhouse gases (GHGs). Among them are counted H_2O, NO_X and CO_2.[20] The last two pollutants are collectively measured in terms of CO_2e.

Emissions from aviation can be divided into 4 areas: the lifecycle of aviation technology, transport to the airport, airport operations and aircrafts.

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[16] BLOCKLEY, Richard a Ramesh AGARWAL. *Green Aviation*. 2016.
[17] *Paris Agreement to the United Nations Framework Convention on Climate Change, , T.I.A.S. No. 16-110*.
[18] MOHRMAN, Eric. *What Is the Altitude of a Plane in Flight?* [online]
[19] *Layers of Earth's Atmosphere* [online].UCAR, 2015.
[20] *European Commission: Causes of climate change* [online]

3.3.1 **Lifecycle of aviation technology**

The emissions of aviation begin with the manufacture of aviation technology, mainly construction of airplane. CO_2 and other gases are produced during the whole manufacturing process and other processes during the lifetime of an airplane until the aircraft is retired.

The lifecycle analysis of aviation contains emissions produced over the whole lifetime of an aircraft and other aviation equipment, including the stage of design, definition, development (increasing flight safety, increasing aircraft range and capacity, reducing aircraft emissions and fuel consumption), production, testing, maintenance, support, modernization, decommissioning and if necessary also a stage of extension of technical life. [21]

3.3.2 **Transport to the airport**

The transport network around the airport makes a significant contribution to environmental pollution. Potential passengers start from or arrive to the so called "airport catchment area" by using the surface access network. The size of the airport catchment area depends on airport geographical location or surface connecting transport system. Therefore, it is always important to consider the design of the whole ground transportation system when developing the airport project. The system is not only used by passengers but also by people that works at or around the airport. For achieving the smoothness of road traffic at the maximum level, it is important to build a quality and fast rail connection with the city center or transfer terminals.[22]

3.3.3 **Airport operations**

Infrastructure and ground airport operations also make a contribution to air pollution and to the creation of emissions. Airport operations include, for instance, the cars they supply aircraft with fuel, follow me cars, pushback tractors, ground de / anti-icing facilities, various loaders and equipment needed to transport passengers and luggage between the terminal and the aircraft.

[21] SZABO, Stanislav a Ivan KOBLEN. Aviation Technology Life Cycle Stages: Economy and society environment. *Exclusive e-JOURNAL* [online]. 2015.
[22] ČAPKOVÁ, Markéta. *Emission in air traffic* [online]. 2009.

Stationary sources, such as airport heating plants, are also a source of CF. It is important that they burn fuels that are environmentally friendly. Another goal at airports is also to reduce the proportion of particulate matter. That is why airports are looking for alternative fuels to traditional petrol and diesel engines in airport vehicles. This is due to the fact that in many cases the vehicles are operated even in enclosed spaces (cargo terminals, baggage sorting system) where it has a significant impact on the employee's work environment.

3.3.4 Aircrafts

Airplanes are significant source of CF. However, it is expected that CF will be reduced in the future due to new fuel types, crew operating procedures and air traffic control components, financial sanctions for exceeding standards and mainly due to new design of engines. The largest production of aircraft gasses occurs at airport during long taxing process including the waiting time for the take-off clearance or time for releasing a stand. Even if airports face a capacity problem, they still try to cooperate with airline operators to shorten the taxi time or to reduce fuel consumption by taxing with lower number of power units.

Flight emissions have the most visible impact on the environment. We divide emissions into:

National caused by aircrafts during take-off and landing - aircraft activities up to an attitude of 915 m (including taxing, take-off/ landing, climbing/descending).

International caused by aircrafts during activities above an attitude of 915 m (climbing/descending and cruising).[23]

As discussed before I will focus only on emission of CO_2 generated by aircrafts.

<u>Aircraft engine emissions</u>

Aircraft engines produce emissions similar to those produced by burning fossil fuels. However, aircraft engines are unusual in that some emissions are emitted at high altitudes and others have an impact on air quality at ground level.

[23] PRŮŠA, J. a kol.: Svět letecké dopravy. Praha: Galileo CEE Service ČR, 2007. 315 s. ISBN 978-80-239-9206-9.

Commercial aircrafts are powered by the combustion of kerosene in turbofan and turboprop gas turbine engines. The result of the aircraft engine combustion is shown in the figure below.

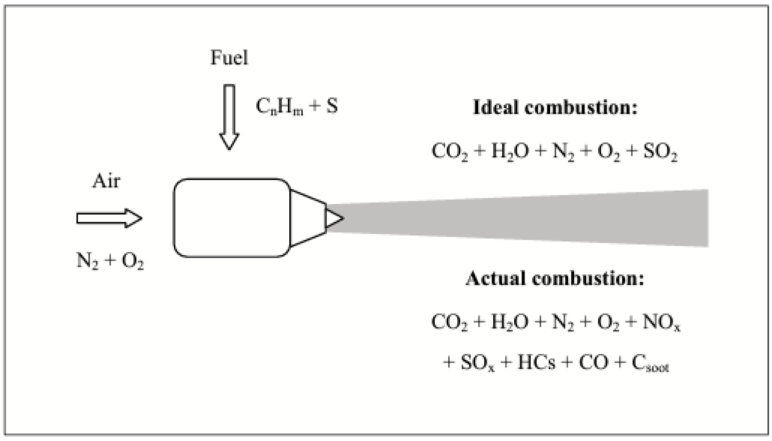

Figure 1 - Engine emissions[24]

In ideal conditions, kerosene pass complete combustion. Then the engine produces carbon dioxide (CO_2) and H_2O. The ratios of these gases depend on the ratio of carbon to hydrogen in the fuel. In addition, during the complete combustion, small proportion of SO_2 (sulphur dioxide) is produced as a result of the oxidation of sulphur containing compounds. On top of those combustion products, large quantities of air O_2 and N_2 (nitrogen) pass through the engine.

There exist other substances that are emitted due to the incomplete combustion of the fuel. These residuals include hydrocarbons (HCs), nitrogen oxides (NO_x), hydrocarbons (HCs), carbon monoxide (CO), sulphur oxides (SO_x) and soot particles.

[24] DALEY, Ben. *Air Transport and the Environment*. USA: Routledge, 2016.

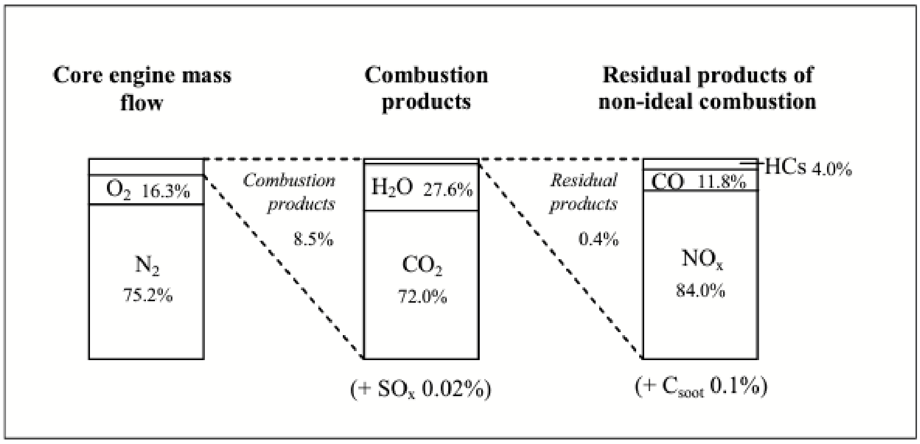

Figure 2 - Products of combustion - actual conditions[25]

As seen from the picture above, when the aircraft is flying, the combustion products make just about 8,5 % of the total mass flow coming out of the engine. From the percentage, the greater part (72%) is represented by the released CO_2 emissions into the atmosphere. However, aircraft engines are extremely effective in converting the fuel to kinetic energy.[26] Therefore when the airplane is cruising just 0,4 % by volume of the combustion products contains the residual products of non-ideal combustion.

Proportions and quantities of aircraft emissions differ quite widely. It depends on phase of flight and also on engine operating regime (Table 1). The table below shows that the combustion of 1 kg of kerosene produces a certain number of emissions. For explanation, the engine draws the air from the outside. Then oxygen and nitrogen react with fuel (combustion) to generate energy and emissions. For instance, 1 kg of fuel burned will produce 3160 g CO_2.

Species	**Idle**	**Take-off**	**Cruise**
CO_2	3160	3160	3160
H_2O	1230	1230	1230
NO_x Short haul	4.5	32	7.9-11.9
NO_x Long-haul	4.5	27	11.1-15.4
CO	25	< 1	1-3.5

[25] DALEY, Ben. *Air Transport and the Environment*. USA: Routledge, 2016.
[26] ROGERS, H.L. Lee, Raper. D.W. 2002. "Impacts of aviation on the global atmosphere", The Aeronautical Journal, October 2002.

HC (as methane)	4	< 0.5	0.2-1.3
SO_x (as SO_2)	1	1	1

Table 1 – Emissions (g) per (kg) kerosene burned[27]

The table above shows that major products of fuel combustion are carbon dioxide and water vapour.

Carbon dioxide (CO_2)

Carbon dioxide occurs naturally in the environment. It is produced by respiration of humans and other organisms. It is the odourless, colourless gaseous substance that is most abundant in fuel combustion. CO_2 is emitted by burning fossil fuels such as coal or kerosene in case of aircrafts. More precisely it is formed during combustion due to the reaction of carbon with oxygen. The amount of generated CO_2 depends on the total amount of carbon in the fuel.

Consumption of jet fuel (kerosene) produces carbon dioxide at a ratio 3160 grams of CO_2 per 1 kilogram of fuel consumed, regardless of the phase of flight. After emission, about half of a given amount of gas is removed from the atmosphere naturally over 30 years, another 50 % disappears within hundred years, and the remaining 20 % remains in the atmosphere for thousands of years.[28] Therefore, CO_2 is considered to be a major cause of global warming. In worldwide numbers, flights produced 915 million tonnes of CO_2 in 2019. In comparison humans globally produced over 43 billion tonnes of CO_2.[29]

Water vapour (H_2O)

Water vapour is the second most abundant compound in the atmosphere formed during the combustion of fossil fuels. H_2O is emitted by airplane in direct proportion to the quantity of fuel consumed, with around 1230 grams of H_2O released per kilogram of kerosene burned.

Most of airplane water vapour emissions are released in the troposphere. When emitted, they are quickly removed by precipitation within a maximum of 1 - 2 weeks. Therefore, the climate effects of water vapour emissions from aircrafts are small.

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[27] DALEY, Ben. *Air Transport and the Environment*. USA: Routledge, 2016.
[28] OVERTON, Jeff. *Fact Sheet | The Growth in Greenhouse Gas Emissions from Commercial Aviation: Part 1 of a Series on Airlines and Climate Change* [online]. 2019.
[29] Facts and figures. *ATAG - Air transport action group* [online]. 2020.

A smaller part of water vapour emissions is released in the lower stratosphere. There it can create higher concentrations. Because water vapour is a greenhouse gas, these increases tend to warm the Earth's surface. However, it is necessary to mention that for subsonic aircraft the effect is smaller than for other aircraft emissions (such as NO_x and CO_2).[30]

Other emissions from combustion processes

Nitrogen oxides (NOx)

Only a small portion of nitrogen oxides (NO_x) comes from aviation. They include nitrogen dioxide (NO_2) and nitric oxide (NO). The climate impacts of aircraft NO_x emissions are complex. They influence the climate by contributing a positive radiative forcing through the support of tropospheric ozone creation and a negative RF by decreasing the lifetime of CH_4. [31]

Carbon monoxide (CO)

Carbon monoxide is a colourless and highly toxic gas that is formed during the incomplete combustion of the carbon in the fuel.[32]

Hydrocarbons (HC)

Hydrocarbons like CO are formed due to incomplete fuel combustion. They are referred to as volatile organic compounds (VOCs). Many of these substances are also considered hazardous to the air.

Sulphur oxides (SO_x)

Sulphur oxides are formed as a result of oxidation of sulphur-containing compounds. These compounds are added to the fuel to improve its lubricity. Most of the sulphur is emitted in the form of SO_2. Sulphur dioxide is a toxic colourless gaseous substance. It is the primary source of acid rain.[33] After oxidation of SO_2 to H_2SO_4 it can become hazardous for aircraft engines and frames. Sulfuric acid aerosol particles can cause damage to the airframe and engine components as a result of sulfidation. Sulfuric

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[30] PENNER, Joyce E. a David H. LISTER. IPCC SPECIAL REPORT: Aviation and the Global Atmosphere. *Intergovernmental Panel on Climate Change* [online].1999.
[31] FREEMAN, Sarah a David S. LEE. Trading off Aircraft Fuel Burn and NO_x Emissions for Optimal Climate Policy: Aviation and the Global Atmosphere. *Environmental Science & Technology* [online].2018
[32] BLUMENTHAL, George, T. *Aviation and Climate Change*.
[33] *NASA's Earth Observing System: Sulphur dioxide* [online].

acid particles have the potential to cause corrosion and erosion of compressor blades and other engine components.[34]

Particles

Particles are very small with typical sizes between 3nm - 4 μm. They are divided into carbonaceous material (soot) and sulphates. [35]

It must be said that aviation produces various amounts of pollutants that have a negative impact on the environment. In the thesis I will only focus on carbon dioxide generated by flights because it makes the main negative effect of aviation on the environment.

3.4 Carbon footprint

Over the past 20 years the term carbon footprint (CF) gained its popularity. It happened due to the public that started to care about environmental issues. The popularity of CF is linked with the concern about the increasing levels of CO_2 in the earth's atmosphere. The term CF was derived from the concept of ecological footprint. That was first developed by scholars at the University of British Columbia, W. Rees and M. Wackernagel.

Today the term carbon footprint is widely used in the commercial world and media but there is no clear and uniform definition of this term. Therefore, there exist various definitions of carbon footprint.

<u>CF is explained as:</u>

- "a measure of the exclusive total amount of carbon dioxide emissions ." [36]
- „a measure of the amount of CO_2 emitted through the combustion of fossil fuels. In the example of organization, it is the amount of CO_2 emitted directly or indirectly as a result of its everyday operations."[37]

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[34] SCHMIDT, Sarah a Claire S. WITHAM. *Assessing hazards to aviation from sulfur dioxide* [online]. 2014
[35] DALEY, Ben. *Air Transport and the Environment*. USA: Routledge, 2016.
[36] PERTSOVA, Caroline C. *Ecological Economics: Research Trends*. NY: Nova Science Publishers, 2007.
[37] GRUBB, ELLIS. Meeting the Carbon Challenge: The Role of Commercial Real Estate Owners, Users & Managers, Chicago. 2007.

- “the estimated amount of GHGs that trap and retain Sun’s heat in the atmosphere produced by our day-to-day activities over a period of time measured by household or organisation.”[38]

Based on several definitions there is no consensus about the measurement or quantification of CF. It can be measured in tonnes of CO_2, C, CO_2 equivalent or in an or in an area-based unit.[39]

With usage of linguistic interpretation and analogy it can be concluded that CF represents amount of CO_2 or all carbon compounds emitted by human activity.

Although the unified definition of carbon footprint has to be formed yet, for the purpose of the thesis the term carbon footprint will be understood as the amount of carbon dioxide that is released into the atmosphere by a certain activity.

We divide CF into 2 types:

- The direct (primary) CF shows the amount of CO_2 that is produced by combustion of fossil fuels (also energy consumption or traffic). CF results from individual activities. [40]
- The indirect (secondary) CF represents amount of CO_2 that is produced during the product's life cycle. (It means from the production to its liquidation).[41] CF is emitted by those who produce the goods.

3.5 Calculation of CF

Carbon footprint of aviation can be calculated in many ways. One option is to choose an online CF calculator. These calculators allow users to enter their departure and destination airport, select their trip and number of passengers of the flight. The output of the calculation is in the form of fuel burned, CO_2 or CO_2e. The second option is to calculate CF using available data about aircraft engines, the time or distance of the flight and emission factor.

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[38] MENON, Ramesh. *Carbon Footprint: Reducing It for a Better Tomorrow*. Delhi: Energy and Research Institute, 2014.
[39] WIEDMAN, Thomas a Jan MINX. *A Definition of "Carbon Footprint"* [online]. Durham, UK: ISA UK Research & Consulting, 2007.
[40] ČÁSLAVKA, J., T. HÁK, V. TŘEBICKÝ a S. KUTÁČEK. *Indikátory Blahobytu*. Praha, 2010.
[41] FRANCHETTI, Matthew, J. *Carbon footprint analysis: Concepts, methods, implementation and case studies*. USA, 2013.

3.5.1 Three methodological tiers of IPCC

International Panel on Climate Change (IPCC) proposes 3 methodological tiers for estimating emissions of CO_2, CH_4 and N_2O. Tier 1 is based mainly on fuel, Tier 2 relates to LTO cycles and fuel use and the last Tier 3 uses movement data for individual flights. Domestic or international flights can be calculated in all tiers. The choice of right method depends on available data. The decision tree that is shown in Figure 3 should help to choose the right method.

Tier 1 method

This method gives an estimation of each gas emission without discrimination of the fuel use between LTO cycle and cruise phase. The emission factor remains the same for all stages of flight. The method should be used only in case of small aircrafts that use aviation gasoline.

Emissions = Fuel Consumption * Emission Factor

Tier 2 method

Method 2 divides operations into LTO cycle (below 914m) and Cruise phase (above 914m). It is necessary to have information about the number of LTO operations for domestic and international aviation and about used aircrafts types (at least on average) during these operations. The calculations are based on these equations:

Total Emissions = LTO Emissions + Cruise Emissions

LTO Emissions = Number of LTOs * Emission Factor LTO

LTO Fuel Cons = Number of LTOs * Fuel Cons per LTO

Cruise Emissions = (TF Cons – LTO Fuel Cons) * Emission Factor Cruise

Where „Cons“ stands for consumption

Cruise Fuel = Total fuel - LTO fuel

The last equation shows that the fuel used in the cruise stage of the flight is estimated as residual. In order to get the cruise emissions, the estimated fuel use for cruise is multiplied by aggregate emission factors (average or per aircraft type).[42] LTO data (fuel consumed and emissions) are estimated from statistics that are related to the number of LTOs (per aircraft type or aggregate), default emission factors or fuel use factors per LTO cycle (average or per aircraft type).

Tier 3 method is divided into 2 methods - Tier 3A and Tier 3B.

Tier 3A method

Tier 3A method is based on flight distances between origin and destination airport and on aircraft type. For a range of representative aircraft categories are considered: average fuel consumption, emissions for the LTO phase and cruise phase distances.

The data used by this methodology take into consideration that the emitted emissions of aircraft differ between phases of flight and that fuel burn is related to flight distance. The method shows that fuel consumed can be higher on short distances than on longer routes. That's because the aircraft uses higher amount of fuel per distance for LTO cycle in comparison to the cruise phase.

Tier 3B method

Tier 3B method is based on full trajectory of each flight segment using specific aircraft and engine- aerodynamic performance information. In order to use this method, sophisticated models are needed for all the equipment, performance and trajectory variables and calculations for all flights in a given year.[43]

These models can specify output in terms of aircraft, airport, engine, region, and global totals, as well as by coordinates (latitude, longitude), altitude and time, for fuel burn and emissions of CO_2 (and others such as CO, HC, H_2O, NO_x, and SO_x). The emissions of aircraft are calculated from input data that reflects changes in aircraft equipment or air

[42] MAURICE, Lourdes Q., Leif HOCKSTAD a David S. LEE. *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Chapter 3, Mobile Combustion* [online]. 2006.
[43] MAURICE, Lourdes Q., Leif HOCKSTAD a David S. LEE. *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Chapter 3, Mobile Combustion* [online]. 2006

traffic. Examples of models for TIER 3B method: AEDT/SAGE [44] (US/FAA), AEM (Advanced Emission Model - Eurocontrol) [45] or AERO2k (UK/QinetiQ).[46]

It can be concluded that due to simplicity of input data, the method Tier 1 should be used only for aircrafts that use aviation gasoline. This fuel is burned only by engines in small aircrafts that generally represents less than 1% of aviation. While Tier 2 and Tier 3 gives better output numbers and will facilitate estimating the emission factors in future. For estimating the cruise phase more accurate become using methodology of Tiers 3A and 3B.

IPCC proposed a decision tree that should help with the choice of the right method for estimating emissions.

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[44] KIM, Brian Y., Gregg G. FLEMING a Joosung J. LEE. *System for assessing Aviation's Global Emissions (SAGE), Part 1: Model description and inventory results* [online]. 2007.
[45] ICAO, International Civil Aviation Organization. *Guidance on EnvironmentalAssessment of Proposed Air Traffic Management Operational Changes* [online]. Montreal, 2014
[46] EYERS, C. J., P NORMAN a J MIDDEL. *AERO 2k Global Aviation Emissions Inventories for 2002 and 2025* [online]. QinetiQ, 2004.

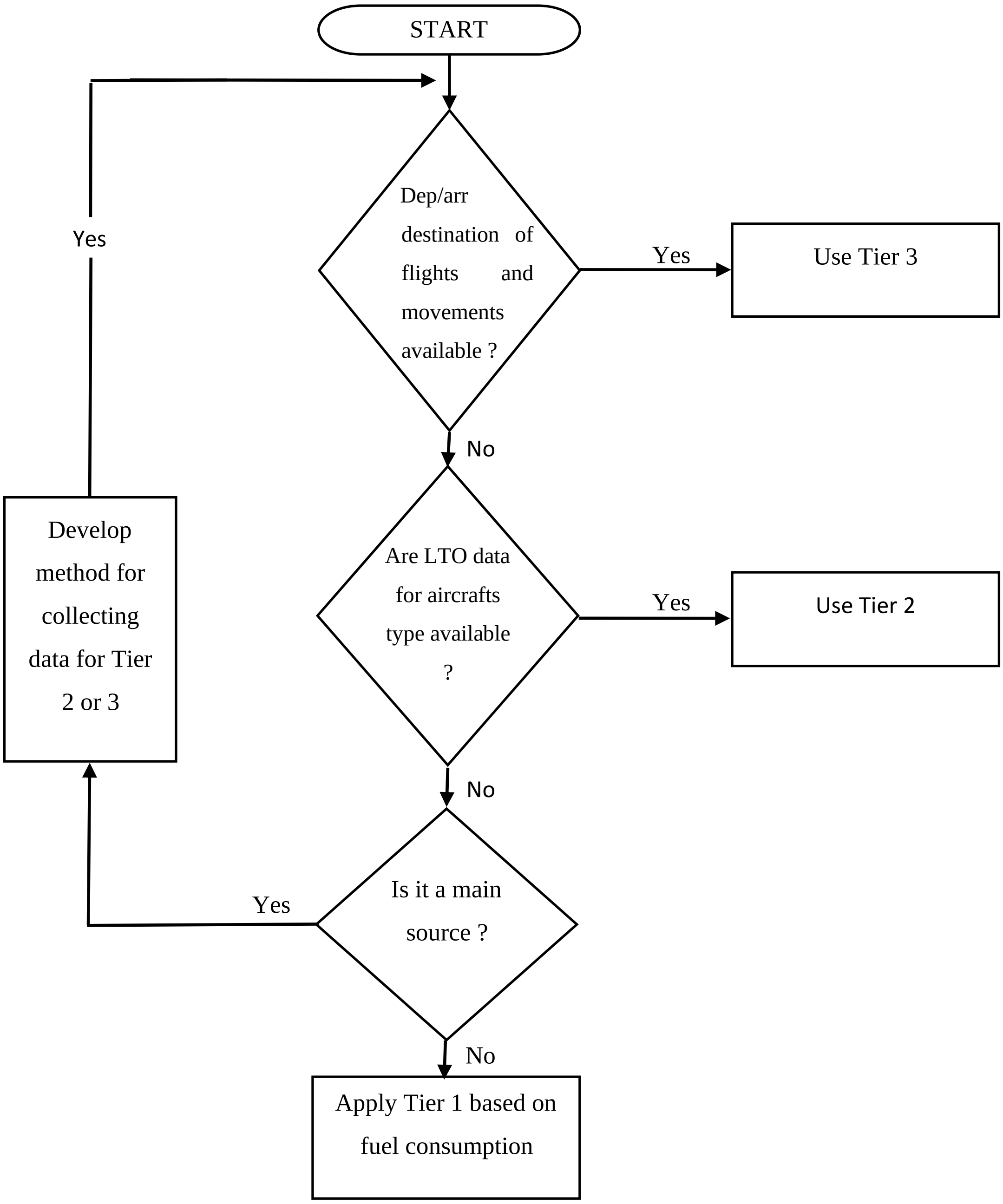

Figure 3 - Decision tree for estimating emissions

Each method requires certain data. The table 2 below summarizes the requirements for each of the tier proposed by IPCC.

Data – domestic and international	Tier 1	Tier 2	Tier 3A	Tier 3B
Aviation gasoline consumption	X			
Jet fuel consumption	X	X		
Total LTO				
LTO by aircraft type		X		
Origin and destination by aircraft type			X	
Full flight movements with aircraft and engine data				X

Table 2 - Data Requirements for methodological tiers

Reasons for choosing a higher tier include estimation of emissions with other pollutants and harmonisation of methods with other inventories. As we can see above in Table 2, in Tier 2 and higher, LTO emissions and emissions from cruise phase are estimated separately. The Tier 3A requires the flight data and Tier 3B requires to use sophisticated models.

Another option how to calculate CF is to use online calculators such as ICAO calculator, much more sophisticated Master emissions calculator or Atmosfair.

3.5.2 Master emissions calculator

Another option how to calculate all emissions of the aircraft during the entire flight, is to use Master emissions calculator. This method of calculating emissions was developed by Eurocontrol and the Environmental European Agency (EEA). The calculator is used to calculate all individual emissions (CO_2, NO_X, SO_X, H_2O, CO, HC) and fuel burned in kilograms during the flight of the aircraft in the LTO cycle and CCD phase.

<u>Master emissions calculator methodology:</u>

The master emissions calculator uses lots of aircraft types with associated data of most common engines. To these aircrafts the methodology checks the maximum range for each chosen aircraft (from PRISME database or manufactures). Then is modelled trajectory for each aircraft according to distance. For each stage length is applied a performance model. Afterwards is determined the mass of fuel burnt and the masses of emissions of each aircraft type, and for the different engines with which they can be equipped, for each stage length, and from gate to gate.

The CCD length was defined as the GCD to be flown between the end of the LTO departure phase and the start of the ICAO LTO arrival phase. The trajectory of a flight is based on performance data of BADA. It is an aircraft performance model developed and maintained by EUROCONTROL, in cooperation with airlines and aircraft manufacturers. The BADA uses a kinetic approach to aircraft performance modelling. It enables to predict aircraft trajectories and the associated fuel consumption. And finally, for calculating the emissions is used the advanced emission model (AEM). [47]

The Calculator works in program EXCEL[48], where the user must input these data: aircraft type and the CCD phase. Then he will get results in the form of fuel burned and all emissions per LTO cycle and, per CCD and also the total for the whole flight.

To conclude this method is very sophisticated and works based on external models. It provides the user with quite relevant information on the number of emissions and fuel burned for a particular aircraft type and engine. The only disadvantage is that the model works with the standard ICAO time for the LTO cycle or the average time for European airports. Therefore, it is not appropriate to use it for a detailed calculation of the LTO cycle for a given airport but on the other hand it provides a relatively accurate picture of the number of emissions and fuel burned for the whole flight. Therefore, this method will be used to calculate the carbon footprint of all scheduled passenger flights from Prague airport's summer flight schedule 2021.

3.5.3 The method of ICAO

The ICAO calculator was created by The International Civil Aviation organization (ICAO) and is used to calculate CO_2 emissions in aviation. The calculator can be found on the ICAO website where person can also find detailed methodology and information on how the calculator works.

ICAO calculator methodology

[47] *Method for estimating fuel burnt and emissions: EMEP/EEA air pollutant emission inventory guidebook 2019*. 2019.
[48] *Environmental European Agency: 1.A.3.a Aviation 2 LTO emissions calculator 2019*. 2019.

The methodology of ICAO employs the distance-based approach in order to estimate passenger emission based on data available including a range of aircraft types. The calculator uses average values for various factors that contribute to the calculation of emissions associated with passenger aviation. The methodology was designed to require a little data from the user: departure airport and arrival airport, cabin class, number of passengers and if the flight is one way or round trip.

The entered data of the airports origin and destination are compared with the scheduled flights to get the right aircraft type. Each airplane is then matched with one of the 312 equivalent aircraft types for the calculation of the fuel consumption of the trip. The length of the journey is based on the great circle distance (GCD) between the airports. All other data such as passenger load factor (PLF), passenger to cargo ratios is collected from traffic data and then applied to get the proportion of total fuel used for passengers. Afterwards is calculated the average fuel burn for the trip weighted by the frequency of departure of each airplane type. Then the number is divided by the amount of economy class passengers. It gives an average fuel burn for passenger in economy class. To get the CF attributed to each passenger the result was multiplied by 3.16. [49]

The equations for calculating CO_2 emissions on a given route per passenger or per passenger kilometre are then as follows:

$$CO_2/pax = 3.16 * \frac{(Total\ fuel * \text{pax–to–freight factor})}{(number\ of\ y\text{–}seats * pax\ load\ factor)}$$

$$CO_2/pax/km = 3.16 * \frac{(Total\ fuel * \text{pax–to–freight factor})}{(number\ of\ y\text{–}seats * pax\ load\ factor * distance)}$$

Where

3,16 – is constant (emission factor) representing the number of tonnes of CO_2 that is produced by burning a tonne of fuel.

Total fuel – represents the average amount of fuel consumed by all aircrafts of equivalent types between 2 chosen airports.

Pax-to-freight factor – is the ratio (calculated from statistical database) based on the number of passengers and the tonnage of mail and freight.

[49] *ICAO Carbon Emissions CalculatorMethodology: v11* [online]. 2018 [cit. 2021-01-11].

Number of y-seats – is the total number of economy seats available for the equivalent aircraft type. To simplify, the number means the maximum capacity of the aircraft in the economic configuration.

Pax load factor (PLF) – measures the utilization of capacity of an aircraft. The ratio comes from the statistical database and is based on the number of passengers transported and the number of seats available on the given route.

Distance - the database searches for all flights serving the city pair. The distance between airports is based on coordinates of the airports and then calculated using GCD (Great Circle Distance) with a distance correction factor (displayed below the text). The correction factor is needed because aircrafts do not fly directly. Flights are affected by traffic situation, stacking or weather conditions.

GCD	Correction to GCD
< 550 Km	+ 50 Km
550 – 5500 Km	+ 100 Km
> 5500 Km	+ 125 Km

Table 3 - Great Circle Distance correction factor[50]

The fuel consumption of aircraft depending on the distance of the flight is obtained from the CORINAIR database. If a specific aircraft is missing, then the most similar aircraft is selected.

3.5.4 **Atmosfair**

Atmosfair is an online emission calculator used to calculate CO_2e per passenger of the certain flight. The calculator may be used for free on the website of Atmosfair. Also it is possible to get there detailed methodology and all information concerning the calculations.

Atmosfair methodology

The Atmosfair calculator is based on 32 million flights, more than 200 airlines, 22,300 city pairs worldwide and 119 aircraft types and 408 engines. The calculator accounts for flight distance and flight profile. At first it calculates the flight distance as the great circle route and afterwards it calculates fuel usage as a function of distance based on fuel consumed during three simplified altitude profiles: CCD (Climb, Cruise and Descent).The total number

[50] *ICAO Carbon Emissions CalculatorMethodology: v11*. 2018.

of emissions counted as CO_2 emissions are simulated using a computer model PIANO X[51] with usage of the fuel consumption of an airplane on a given journey. The result of carbon emissions is then divided by passenger numbers minus the cargo. Atmosfair also uses the seating classes as fuel consumption multiplier 0.8, 1.5, 2.0 (Economy, Business, First class).[52]

The Atmosfair requires these data from the user: departure and destination airport, flight class (economy, premium, business, first), flight type (Charter, scheduled), aircraft type and number of passengers. In conclusion it can be said that this calculator is not suitable for detailed calculation and therefore won't be used.

The fuel consumption and emissions also depend on the aircraft operation and phases of flight.

3.6 Aircraft operation

A flight can be defined as a trip made by in an airplane or spacecraft.

We distinguish between scheduled x non-scheduled flights, domestic x international flights and lastly according to rules under which the aircraft is flown.

- **The scheduled flights** are flights according to the approved flight schedule, these flights occur always, regardless of whether they are filled with passengers or not. [53]
- **non-scheduled flights** occur irregularly, they are performed on a direct order. According to the requirements of the customer, the flight is operated on time and the route which he sets. These flights include cargo flights, charters.

- **Domestic flights** represent air transport from one airport to another within one country. Usually, they are shorter than international flights but not every time cheaper.
- **International flights** represent air transport connection between two airports that are placed in different countries.

[51] *Atmosfair Flight Emissions Calculato: Documentation of the method and data* [online]. Berlin, 2016.
[52] *Atmosfair: Calculate Flight Emissions* [online]. 2016.
[53] JECHUMTÁL, Jaroslav; HYXOVÁ, Andrea. Obchodně přepravní činnost v letecké do-pravě. Pardubice: Univerzita Pardubice, 2000.

In principle flights can be divided into 4 categories: IFR flights, General aviation flights, Civil helicopters, Military flights.

- **IFR flights** - the IFR symbol indicates flights that are performed so-called by instruments. [54] The most emissions actually originate from these flights. Flight movement data are often recorded and may be found on internet. The aircrafts in this category are equipped with turbojet, turboprop or piston engine.
- **General aviation flights** (Civil VFR) are flight performed in accordance with the rules for visual flight. This category includes mostly small aircrafts that are used for leisure, trainings, or taxi flights. Therefore data about VFR flights are not accurate.
- **Civil helicopters** – is a category that contains all types of rotorcraft. Important is to say that helicopters are operated mostly under VFR and exceptionally under IFR rules. Therefore it's harder to get information about their flight movements.
- **Military flights** are the last category that is rarely seen in the air. It's hard to estimate these data because these flights are mainly operated from military airports and their data are not accessible for public.

From reasons mentioned above the thesis will reflect only international scheduled passenger flights under IFR rules that are publicly accessibly.

3.6.1 The phases of flight

All phases of the flight count together for the term the duration of flight that in general says that it is a measurement of the time taken by an object to travel a distance through a medium. In aviation it means the total time from the moment the aircraft started to move with the intention to take off until the moment when the aircraft stops for the last time (Off blocks – in blocks). [55] In blocks mean the aircraft arrived in the parking position while off blocks mean the aircraft started to move. Important is also to point out the term operating hours (operating time) It is the time from the moment the aircraft leaves the surface of the ground until the time of the first contact with the ground during the landing.[56]

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[54] *Letecký předpis: Pravidla létání, L2* [online]. Praha: MDCR, UCL, 2019.
[55] WANG, Guoqing. *Flight Phase: The requirement organization of the avionics system* [online]. 2020.
[56] SOLDÁN, Vladimír. *Sdělení ředitele sekce letové a provozní UCL k pojmu doba letu* [online]. UCL, Sekce letová a provozní, 2014.

As described in Figure 4, the phases of flight include:

Taxi-out, take-off, climb-out, climb, cruise, descent, final approach, landing and taxi-in.

The flight for passengers begins when the pilot gets the clearance to leave its stand by pushback, that is a procedure in which the aircraft is pushed backwards from the stand by external power – pushback tractors or tugs. Then comes starting the engines and the consumption of fuel begins.

The first step for the aircraft is **taxi-out**. This phase basically means the controlled movement on the grounds under its own power. The movement continues on taxiways until the holding point of the runway. After ATC (Air Traffic Control) clearance from the tower the aircraft enters the runway to the point from where taking-off operation will occur.

Afterwards the pilot receives ATC clearance for **take-off**, and he moves the thrust levers into take-off position (usually 100% power). The aircraft starts to move and the take-off phase begins. When the aircraft reaches speed V1, the pilot must decide if he continues with the flight or the take-off roll will be aborted. When the airplane reaches Vr speed (rotate) the pilot applies control inputs to make the aircraft nose to pitch up, after which the airplane leaves the ground. (In theory also appears V2 that is expressed as the speed at which the aircraft can safely climb only with 1 engine in operation.) At this stage the fuel consumption and engine emissions reach the highest numbers.[57]

After take-off the aircraft must climb until certain attitude. This phase is divided into **climb out** phase (until 3000ft) and **climb** (above 3000ft). The aircrafts flying under IFR rule must follow the flight plan SID route (Standard Instrument Departure) and can change the direction only with the approval from ATC controller. Usually it's due to the weather, turbulences, traffic separation or shortcutting the route. These changes must be taken into consideration when the pilot plans the amount of the fuel that he will need for the entire route. In order to get better precise data for calculation of emissions, adding correction factor is needed.

After the aircraft reaches a certain attitude the **cruise** phase starts. It occurs exactly between the climb and descent phase. It is usually the longest part of the entire journey except cases when the departure and destination airport stands too close. During the cruise

[57] Did You Know about Aircraft Take-off Speeds: V1, Vr and V2?: BA Training - Aviation center. *BA Training* [online]. 2017.

phase, because of the ATC, airplane can climb or descent from one FL (Flight Level) to another FL that is higher or lower. During very long flights, aircrafts fly higher because the weight of the fuel aboard decreases. It’s a common practice that pilots ask the ATC for an optimal FL. The Flight level depends on type of aircraft, the weight of the aircraft and also on the distance of the flight. For most of the aircrafts the cruise phase of a flight uses most of the fuel and therefore has higher impact on the environment.

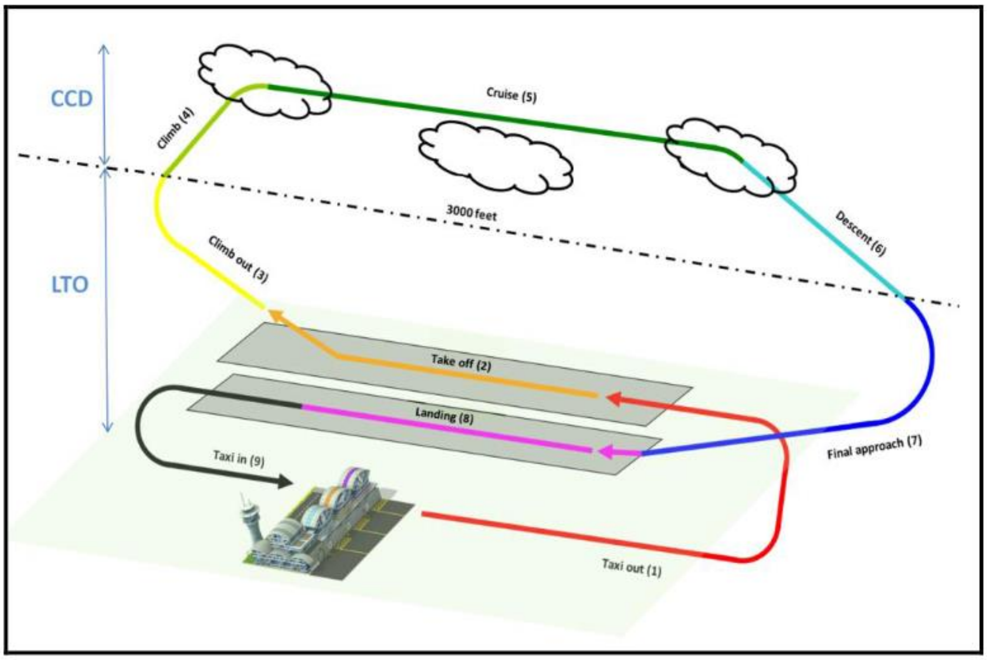

Figure 4 - Phases of a flight, LTO x CCD[58]

After cruise comes **descent** phase. During this stage aircraft decreases its attitude and the pilots start to prepare the aircraft for landing depending on the version of approach at the airport. Usually, the airplane descends in several steps according to the agreements among countries at which level the aircraft should fly over the borders in order being able to land at certain airport. When airplane under IFR rules reaches a last point on the flight plan then the plane flies according STAR (Standard Terminal Arrival Route) for concrete runway in operation. The STAR continues until the point IAF (Initial approach fix) from where the initial precision approach segment begins. Then the aircraft follows the approach chart for

[58] WINTHER, Morten a Winther RYPDAL. *EMEP/EEA air pollutant emission inventory guidebook 2019*. 2019.

concrete runway. The second phase of approach is Intermediate Approach Segment that is used to descend to intermediate altitude - ends in the so-called final approach fix (FAF).

And finally comes the **final approach** that is the last leg of an aircraft's approach to landing. The aircraft is in line with the runway and from the point FAF (Final approach fix) in case of instrument ILS approach, starts descending for landing. This procedure ends in the point MAP (Missed approach point). At the latest at the decision height (DH), the pilot must decide whether he will land or not.

Then comes **landing** that is the part of the flight when the aircraft returns to the ground, uses brakes and reverse engine thrust and reduces the speed to taxi. Aircraft leaves the runway by crossing the holding point of the runway. Then the pilot is instructed by ATC to taxi through taxiways to the concrete stand, where the pilot set the parking brake and shuts down the engines.

3.6.2 Flight movements

The theory also points out several other terms such as a flight movement. Flight movement can be explained differently. The first meaning says that it begins when the aircraft starts taxing out and finishes when the aircraft comes to a complete stop.[59] According to Eurocontrol a flight movement is when "An aircraft take-offs or lands at an airport. For airport traffic purposes one arrival and one departure is counted as two movements.“ [60] On the other hand statistical data of airports work with the term flight movement as departure and arrival together. For instance, Prague airport uses the same meaning in its statistics.

<u>There are several activities related to flight movements:</u>

Pre-departure activities (fuelling and handling), departure activities (Taxi-out, Takeoff, Climb out), CCD activities (Climb, Cruise, Descent), emergency activities (Fuel dumping), arrival activities (Final approach, landing, taxi in), post-arrival activities (service vehicles), maintenance activities (maintenance of aircraft engines, paintings).

[59] WINTHER, Morten a Winther RYPDAL. *EMEP/EEA air pollutant emission inventory guidebook 2019*. 2019.
[60] *Eurocontrol ATM lexicon: Aircraft movement* [online]. 2019.

From flight movements listed above, it's possible to obtain fuel usage and emission inventories for activities: departure, arrival and CCD (Climb, Cruise, Descent).

Departure contains all activities that occur near the airport and take place below the altitude of 3000ft. It includes taxing from the stand to the departure point on the runway (taxi – out), take-off and also climb-out. On the other hand, figure 4 also describes CCD as activities that take place above 3000ft. CCD includes the climb phase right after the climb-out phase up to the cruise altitude. There isn't set any limit of height. Then comes descent to 3000ft from where begins the arrival activity, that means all activities below a heigh of 3000ft, including the final approach, landing and taxi-in phase of the flight.

In context it's important to explain the term LTO and cruise stage.

The term LTO is an abbreviation for landing take- off cycle. As we can see above in figure 4, LTO cycle includes all activities near the airport that take place below the altitude of 3000 feet (1000 m). It means that it includes departure and arrival activities (taxi-out, take-off, climb out, descent, approach, landing and taxi in)[61] While cruise stage is just another word for CCD. The number of LTO cycles is based on the number of statistical movements, where, as mentioned above, 1 movement = departure + arrival activity. Therefore the sum of departure and arrival is equal to one LTO cycle.

3.6.3 **Fuel of aircraft**

The amount of fuel in aircraft consists of taxi fuel, trip fuel, reserve fuel and commander extra fuel. The fuel for taxing consists of starting the engines, taxing, and de-icing procedure. The trip fuel simply consists of the total fuel for the flight from take-off to landing. The reserve fuel is used for circumstances the pilot can't control, for a flight to an alternate airport, final reserve fuel and additional fuel. Extraordinary fuel is at the captain's discretion, for instance due to the weather forecast at the destination. And finally the sum of all these items therefore gives the weight of fuel required on board.

Aircraft fuel consumption depends on many factors, from engine types and year of manufacture, through load and number of passengers, the effect of wind or the flight attitude. However, one of the important factors that applies to each flight is the setting of engine

[61] RYPDAL, Kristin. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories: Aircraft emissions* [online]. 2011 [cit. 2021-02]. Dostupné z: doi:Kristin Rypdal

thrust in the individual phases of flight. ICAO has established the general engine thrust settings at the various stages of the LTO cycle.

From the table below the text, it is clear that the largest thrust of the engine is in the take-off phase (100%) and in contrary, the lowest 7% is when the aircraft is taxiing or standing in the airport area. The table also shows the times for which the aircraft is in the individual phases of the LTO cycle. It is important to mention that these are average times, as there are different conditions at each airport. At some airports, the aircraft travels over the area for more than 12 minutes, and at others, the aircraft travels from the stand in units of minutes.

Operating mode	Thrust setting	Time (minutes)
Take-off	100 %	0.7
Climb-out	85 %	2.2
Approach-landing	30 %	4
Taxi, ground idle	7 %	26

Table 4 - LTO cycle - engine thrust setting and times[62]

The amount of fuel needed for a flight can be obtained simply by calculating the distance (flight length) between two airports. For this purpose, can be used the ICAO method that uses Great Circle Distance (shortest distance between two points on the surface) and the correction factor. This distance is then compared with the average fuel consumption tables for each aircraft type. Averaged from the reason, that each type of aircraft has x types of engines and is still manufactured for the decades. For instance, the engine for the A320 has a different fuel consumption today and a different one at the beginning of production.

The second way to calculate the flight distance is based on the flight plan. The flight plan is submitted by the captain of the aircraft for approval to the air traffic controller. The ATC adjusts it by adding the departure route. The flight plan determines the route of the aircraft on which the aircraft will fly. This route can be found in the route maps, where both the distances and directions (in which the aircraft can fly along the route) are listed.

[62] DICKSON, Neil. *Local Air Quality and ICAO Engine Emissions Standards: Environment BranchICAO Air Transport Bureau* 2014.

As an example, below is given the map of 2 STARS (LOMKI 7S, GOSEK 4S) for rwy 24 at Prague airport (LKPR). The map shows distances in nautical miles (1nm = 1.852 km), courses, minimal attitudes, and other and other necessary data for the pilot. For instance, the distance between point PR511 and PR512 is 17.5 nm with minimum attitude 5000ft and course 049°. The problem with this method for calculating the distance is that the flight plans for specific flights are not publicly available and change frequently.

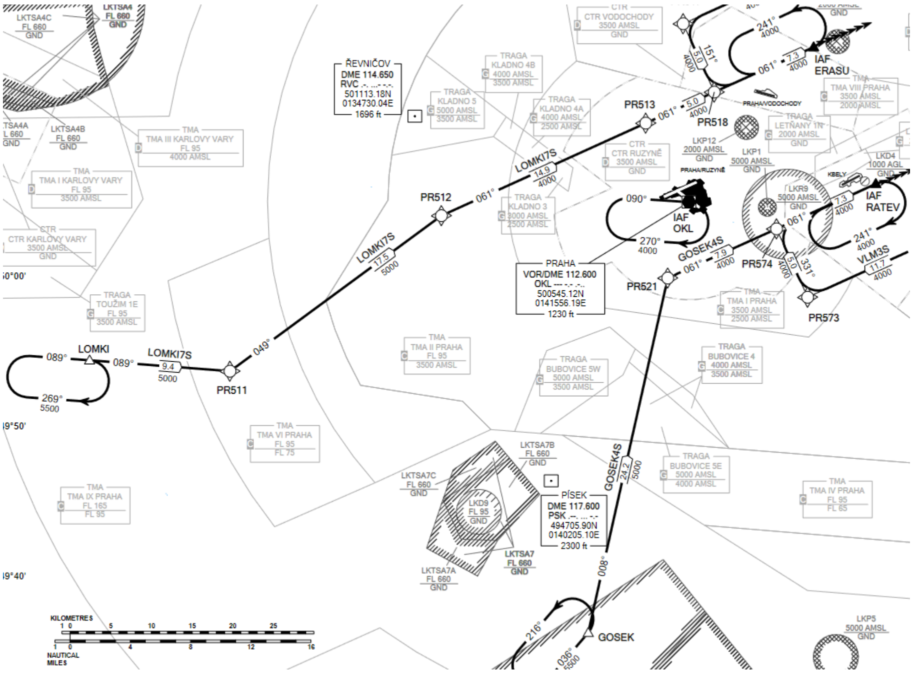

Figure 5 - Map of 2 STAR routes for LKPR rwy 24[63]

Another way how to calculate the amount of fuel needed for the route is based on data about a particular engine that is assigned to a particular aircraft.

The picture below the text shows the fuel consumption of the specific A320 engine in various engine modes (flight phases), the time (in minutes) for which this phase of flight takes place (standard according to ICAO) and the last column shows the engine fuel flow in kg /s. The total amount of fuel required for the entire LTO cycle is calculated in the figure. It should be emphasized that there is only one engine, so the total amount of fuel needs to be multiplied by two.

[63] *RNAV STANDARD ARRIVAL CHART - INSTRUMENT (STAR) - ICAO: AD 2-LKPR-RNAV STAR RWY 24* [online]. Praha: Air navigational services of the Czech Republic, 2021.

MODE	POWER SETTING (%F_{oo})	TIME (minutes)	FUEL FLOW (kg/s)
TAKE-OFF	100	0.7	1.132
CLIMB OUT	85	2.2	0.935
APPROACH	30	4.0	0.312
IDLE	7	26.0	0.104
LTO TOTAL FUEL (kg) or EMISSIONS (g)			408

Figure 6 - Aircraft A320 – 1 engine CFM56-5B4/P, 3CM026. fuel flow with standard ICAO times[64]

The advantage of this method is greater accuracy of the calculation of fuel consumption and the possibility of adapting the time of individual flight phases to a specific airport. The disadvantage is that each specific aircraft must be assigned to the right engine, which is not possible in real. Therefore, averaged data of all engines or engine representatives for each aircraft type are used in the calculations.

[64] *Edb - emissions data sheets: ICAO Aircraft Engine Emissions Databank* [online]. 2020.

4 Analytical Part

4.1 Comparison of the amount of CO_2 produced by aircrafts on scheduled flights during LTO cycle at Prague airport

The amount of CO_2 emitted by aircrafts during the LTO cycle in the airport area negatively affects the environment and burdens the inhabitants living in its immediate surroundings. The same situation is in the case of Prague Airport.

In the following section, I would like to present and describe Prague Airport, its statistics with the number of flights, passengers, and aircraft types. Based on data, I will perform a calculation for the carbon footprint of Prague Airport from the operation of aircrafts on scheduled flights during the LTO cycle. Finally, I will compare the CF between aircrafts.

4.1.1 Prague airport

The airport is the largest international airport in the Czech Republic. In terms of the number of passengers, it is one of the largest airports in the Central European region after Vienna and Warsaw airports. The airport is located on the north western edge of Prague near the villages of Hostivice, Jeneč, Dobrovíz and Kněževes. It is also located near the city districts of Prague 6.

The interesting thing relates to airport's name. According to all aerial maps, this airport is correctly called as Prague / Ruzyně airport. While for passengers it has been renamed for Václav Havel Airport Prague in 2012. It's up to everyone how the airport will call however the name remains the same for pilots. The airport is designed for handling international, domestic, scheduled and non-scheduled flights. It serves as a hub for Czech Airlines (ČSA) and Smartwings, and as a base for Ryanair.

Prague Airport is considered as a gateway to the region. The great advantage of this airport is its proximity to the city centre, the disadvantage is the still lack of quality transport to city centre, which not only prolongs the journey but also negatively contributes to the air quality around the airport. The airport offers a total of 4 passenger terminals; where Terminal 1 is used for departures to countries outside the Schengen area, Terminal 2 for the Schengen area, Terminal 3 for private flights, Terminal 4 for the needs of the army and 2 cargo terminals.

For the needs of aircrafts, the airport has 2 runways - the main runway 06/24 in the length of 3715m and the side runway 12/30 in the length of 3250m.[65] However, these runways cannot be in the operation at the same time. With increasing the traffic numbers, the construction of a parallel runway is considered. That would make possible to cancel the side runway, on the other hand the new runway will bring worse living conditions to residents in its vicinity.

Before pandemic situation, Prague Airport has had the status of the airport with the fastest growing number of passengers in the category of 10-25 million handled passengers in Europe. The airport handled over 15 million passengers a year. The airport offered of almost 70 airlines connecting Prague with a direct line to more than 160 destinations around the world. There were also 8 regular cargo carriers operating here and dozens of other companies then provided charter transport.[66]

4.1.2 Calculation of the CF of aircrafts at Prague airport

In order to calculate the CF of aircrafts it was first necessary to set methods that will be used for the calculation. I decided to use knowledge of methods Tier 2, Tier 3A and ICAO and then I developed my own sophisticated calculation procedure whose steps are described below.

To calculate the amount of CO_2 produced by aircrafts on scheduled flights during LTO cycles, it was first necessary to get information about number of movements (departures and arrivals). The table below summarizes all movements of Prague airport during years 2014 to 2020. For the purposes of calculation, there are relevant only data about international flights and the number of scheduled flights. During years 2014-2018 there was a scheduled domestic service to Ostrava, but this number is already included in the number of scheduled flights.

	2014	2015	2016	2017	2018	2019	2020
International	118703	120827	129338	141261	148360	148753	48318
Domestic	3608	4223	4035	3980	4150	2962	3144
Others	3126	2968	3393	3042	3022	3062	2701
Total	125437	128018	136766	148283	155532	154777	54163
Scheduled	**99931**	**103127**	**113461**	**125448**	**131842**	**130500**	**37855**
Non- scheduled	22380	21923	19912	19793	20668	21215	13607

[65] AIM Letecká informační služba. *AERODROME CHART - ICAO, PRAHA/ RUZYNĚ*. 2020.
[66] *Prague airport: Facts about the company*. 2018.

Others	3126	2968	3393	3042	3022	3062	2701
Total	125437	128018	136766	148283	155532	154777	54163

Table 5 – Aircraft movements at Prague airport 2014 – 2020[67]

From the table above we can also read that scheduled flights with passengers cover most of the movements at the airport and therefore are the main goal of the study.

The second step in calculations was to get the number of LTO cycles from scheduled flights (for the reasons mentioned above, these flights are mainly international). Due to statistics of Prague airport, I directly got the number of LTO in the form of movements (departures + arrivals). In other situations, it would be needed to get the amount of LTO as it's seenable from the equation below: calculating the total number of departures and arrivals and then divide it by two.

$$\sum \text{LTO} = \frac{\sum departures + arrivals}{2}$$

Where

LTO is landing take-off cycle

The equation gave us results (Table 6) for the total number of LTO cycles and possibly the number of cycles for individual months. From the table is possible to also read a huge drop in the number of LTO cycles (37855) during a coronavirus pandemic in 2020.

	2014	2015	2016	2017	2018	2019	2020
∑ LTO = 742164	99931	103127	113461	125448	131842	130500	37855

Table 6 - Number of LTO cycles per year, total LTO cycle

The next step was to assign aircraft representatives to LTO cycles. This can be done by dividing airliners into 4 weight categories (<33t, <80t, <136t, >136t).

From these categories, the most common passenger aircraft was identified. In our case there were chosen: ATR 72 as a representative of a small turboprop aircrafts (such as Bombardier Dash) up to 33t, the airbus A320 as a representative of jet a narrow-body aircraft (B737, Avro, Embraer, Fokker), Airbus A321 as a selected example of an aircraft up to 136t (B739, B752) and for the last category Airbus A333 as a representant of jet

[67] *Prague airport: Prague Airport Traffic Reports*.2021., own work.

widebody aircrafts with a weight exceeding 135t (A310, B777, B767, B788, B747, A380).

Then based on maintaining the proportions between the categories and the percentages, the missing percentages from categories (military, sports, and other small aircraft) were added. These aircrafts are not included in numbers, because they do not appear on the scheduled routes and at the same time, they do not have such an impact on the environment in total numbers as regular air transport has.

Finally, I got aircraft percentages for years 2014-2016. The missing years were averaged from the last 2 previous years except for year 2020. I had to take into consideration that year 2020 was affected by the coronavirus crisis, and therefore, based on the available data on the number of long-distance routes and of their frequencies,[68][69] I adjusted the number of wide-body aircrafts to 1 movement (LTO cycle) per day. Then the percentages of aircraft representatives of years 2014 – 2020 were multiplied by the number of LTO cycles per each year.

The results are shown in the graph below showing 4 aircraft types representatives with the number of their LTO cycles in certain years. From the figure 7 is possible to read that the presence of widebody aircrafts at Prague airport moved up from year 2014 until 2019 practically 2 times while the number of LTO cycles for ATR72 (turboprops) increased only by about a third. For A321 we can see more than 150 percent increase in numbers from 2013 – 2019. All numbers for year 2020 are hit by a pandemic situation so therefore are not entirely relevant for future development.

[68] HAMPL, Tomáš. *Airways.cz: Emirates obnovily pravidelné lety do Prahy* 2020

[69] *Prague airport: Letecká společnost Korean Air obnoví linku do Soulu* [online]. 2020.

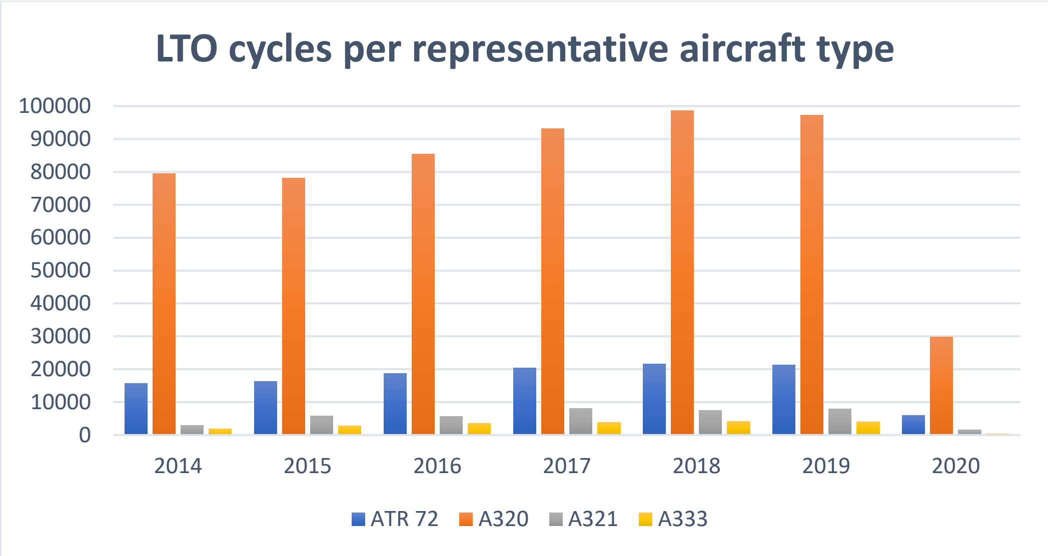

Figure 7 - Number of LTO cycles per representative aircraft types (ATR72, A320, A321, A330)

The next step was about to find out the most common engine type for a given aircraft and the average times of LTO cycle at the airport. For the chosen aircrafts there were allocated these most common engines: [70]

ATR72 – engine ID: none identification: PW124B

AIRBUS A320 – engine ID: 3CM026; identification: CFM56-5B4/P

AIRBUS A321 – engine ID: 3IA008; identification: V2533-A5
AIRBUS A333 – engine ID: 01P14RR102; identification: Trent772

Data limitations:

For ATR aircraft is available only the amount of burned fuel for LTO cycle and the number of emissions burned during LTO cycle and the fuel flow for 30% thrust (cruise or approach phase), while for airbuses all data are available.

Taxi times at Prague airport were taken from Eurocontrol[71] as a sum of taxi-in (5,6min) and taxi-out (12,4min) from winter 2018. Other times of LTO cycle were taken from document of Dr.Majer.[72] All times are summarized in the table below.

[70] *EDB - emissions data sheets: ICAO Aircraft Engine Emissions Databank* 2020.
[71] *Taxi times - winter 2018/2019* [online]. Eurocontrol, 2019.
[72] MAJER, Tomáš a Martin ŠÁRA. *PARALELNÍ RWY 06R/24L LETIŠTĚ PRAHA – RUZYNĚ Rozptylová studie* 2010.

A320/ 1 ENG	POWER	TIME ICAO (MIN)	TIME ICAO (s)	**LKPR** (MIN)	**LKPR**(s)
TAKEOFF	100	0,7	42	0,83	49,8
CLIMB OUT	85	2,2	132	1,25	75
APPROACH	30	4,0	240	4	240
IDDLE	7	26,0	1560	18	1080
	Tot LTO Time	32,9	1974	24,08	1444,8

Table 7 - ICAO x Prague LTO times

Now it was necessary to obtain data about fuel flow and emission factors. All these data were taken from emissions databank for each chosen available aircrafts.[73] As an example of these data I'm giving an airbus A320 table that describes the amount of emission factors and fuel consumptions per second at different stages of flight.

			EMISSION FACTORS (g)				
A320/ 1 ENG	FUEL FLOW kg/s	CO_2	NO_X	SO_X	H_2O	CO	HC
TAKEOFF	1,132	3160,0	28	1	1230	0,9	0,2
CLIMB OUT	0,935	3160,0	23,2	1	1230	0,9	0,2
APPROACH	0,312	3160,0	10	1	1230	2,3	0,5
IDDLE	0,104	3160,0	4,3	1	1230	23,4	4,6
LTO FUEL KG	**313,7**						

Table 8 - A320 - fuel flow, emission factors

Then I calculated emissions per each aircraft using these equations:

FTO = (TMTO*60)*FFTO*NE

FCO = (TMCO*60)*FFCO*NE

FAP = (TMAP*60)* FFAP*NE

FID = (TMID*60)*FFID*NE

LTO FUEL = FTO + FCO + FAP + FID

Where

FTO … fuel for take-off, FCO… fuel from climb out, FAP… fuel for approach, FID… fuel for taxi

[73] *EDB - emissions data sheets: ICAO Aircraft Engine Emissions Databank* 2020.

TMTO … time for take-off, TMCO… time for climb out, TMAP … time for approach, TMID…time for taxing

FFTO…fuel flow for take-off, FFCO…fuel flow for climb out, FFAP…fuel flow for approach, FFID…fuel flow for taxing, NE… number of engines

Carbon dioxide and also other emissions can be calculated for each phase of LTO cycle Below is given an example for amount of CO_2 produced during take-off phase:

$CO_2TO = (TMTO *60) * FFTO* NE * EFCO_2$

Where, $EFCO_2$ represents emission factor of CO_2

As an example of my calculations is given the table below, where were calculated emissions of Airbus A320 during different phases of LTO cycle. The number 1982,58 represents the total amount of CO_2 in kilograms per 1 LTO cycle and 1 airbus A320 in Prague times. As we can see I also calculated the same emissions using ICAO times (2579,09kg in case of CO_2) for comparing the total difference for 1 aircraft. In case of CO_2 the difference is quite significant therefore I will apply Prague times for complete result.

EMISSIONS FROM PHASES OF LTO CYCLE (ICAO TIMES) (g)						
A320	**CO_2**	NO_X	SO_X	H_2O	CO	HC
Take-off	150239	1331,232	47,544	58479,12	42,7896	9,5088
Climb out	390007,2	2863,344	123,42	151806,6	111,078	24,684
Approach	236620,8	748,8	74,88	92102,4	172,224	37,44
Iddle	512678,4	697,632	162,24	199555,2	3796,416	746,304
SUM /1000	1289,545	5,641008	0,408084	501,9433	4,122508	0,817937
2 ENG (kgs)	2579,09	11,28	0,82	1003,89	8,25	1,64
EMISSIONS FROM PHASES OF LTO CYCLE (PRAGUE TIMES) (g)						
Take-off	178140,6	1578,461	56,3736	69339,53	50,73624	11,27472
Climb out	221595	1626,9	70,125	86253,75	63,1125	14,025
Approach	236620,8	748,8	74,88	92102,4	172,224	37,44
Iddle	354931,2	482,976	112,32	138153,6	2628,288	516,672
SUM/1000	991,2876	4,437137	0,313699	385,8493	2,914361	0,579412
2 ENG (kgs)	**1982,58**	8,87	0,63	771,70	5,83	1,16

Table 9 - Emissions from different phases of LTO cycle per aircraft A320

The last step in calculations was to allocate the number of CO_2 emissions per each aircraft to the number of LTO cycles. The total number of CO_2 produced by 1 aircraft cycle was multiplied by the number of LTO cycles of each aircraft. Then these numbers were converted to tonnes and the graph was created.

It shows us the total amount of t CO_2 for each selected aircraft produced during all LTO cycles in certain years. Also, the graph shows the total amount of CO_2 in tonnes produced in the LTO cycles each year.

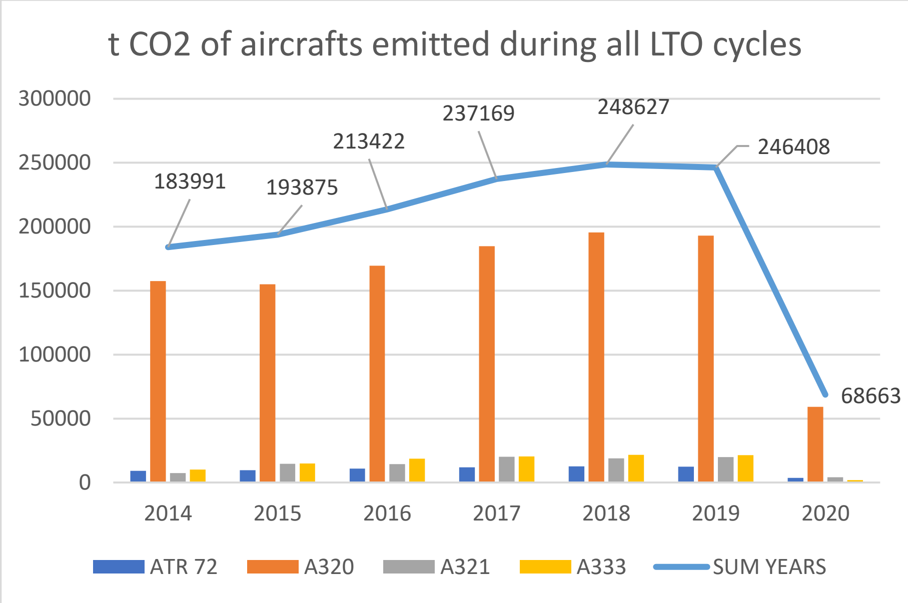

Figure 8 - Tons of CO_2 of aircrafts produced during all LTO cycles during 2014-2020

To better show how the total amount of CO_2 in the vicinity of Prague Airport changed, we must look at the initial value of year 2014. From 183,991 tons of CO_2 produced during LTO cycles in 2014, the value reached 246408 tons of CO_2 per year in 2019. This represents an increase of 33.9 %. The following year 2020 massively contributed to the improvement of the environment around the airport due to the pandemic. The total value of tons of CO_2 was only 68663 tons per year. Compared to 2014, it was an overall decrease in tCO_2 by 37.3%.

The table 'Aircrafts t CO_2 Total Prague Times, LTO' below the text gives us the exact complete numbers of t CO_2 in the years 2014-2020 and individual data on the amount of t CO_2 for each aircraft per year from LTO cycles. Also, we can see there the total sum of all tCO_2 1 392 155 that are highlighted in red.

	2014	2015	2016	2017	2018	2019	2020	SUM AIRCRAFT
ATR 72	9121	9512	10907	11843	12561	12377	3521	69842
A320	157504	155005	169457	184792	195560	192901	59079	1114297
A321	7330	14580	14325	20208	18942	19885	4120	99389
A333	10035	14779	18733	20326	21565	21245	1943	108627
SUM YEARS	183991	193875	213422	237169	248627	246408	68663	**1392155**

Table 10 - Aircrafts t CO_2 TOTAL Prague Times, LTO

For better approximation of year on year increases we will look at another chart - the figure “Year on year percentage changes of total t CO_2.

It shows us a gradually increasing amount of tCO_2 based on year-on-year percentage increases. From around 5% in 2015, the amount increased by up to about 10% each year. The year 2018 represented a reduction in the year-on-year increase in the number of CO_2 emissions, but still maintained the growth trend at the level of 2015. The year 2019 brought stagnation in the number of CO_2 emissions and, as I already mentioned, 2020 brought an improvement in CO_2 emissions in the air by 27.9% compared to the previous year.

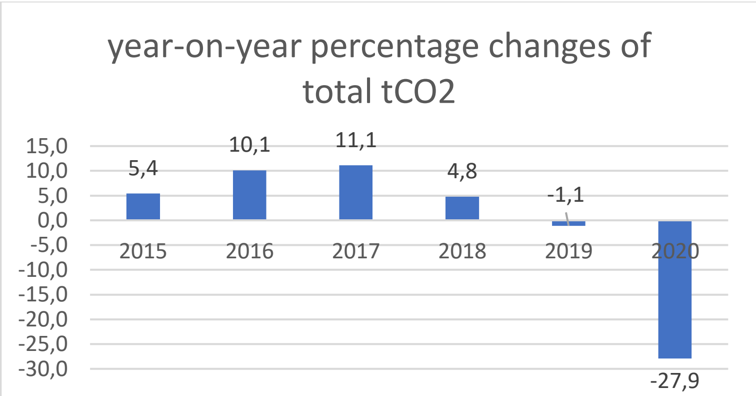

Figure 9 - Year on year percentage changes of total tCO_2

4.1.3 Carbon footprint between aircraft types at Prague airport

To compare the carbon footprint between 4 individual aircrafts at Prague Airport during LTO cycles, it was first necessary to select the required aircraft and then obtain data on individual types of aircraft. For the needs of this work, the same types of aircraft were selected: ATR72, A320, A321 and A333. After obtaining the data it was necessary to use this equation for each phase of LTO cycle:

$CO_2TO = (TMTO * 60) * FFTO * NE * EFCO_2$

Then using the same procedure for other phases with different numbers: CO_2CO, CO_2AP, CO_2ID.

After processing all the calculations, we will get the results in grams. So, in order to get kilograms, we need to convert the final results.

From table “ICAO x Prague LTO times” we already know that phase times of LTO cycle at Prague airport differs significantly in comparison to average times from the ICAO organization.

Therefore, the times corresponding to the traffic at Prague Airport will be used again. The aircraft takes the least time to take off, namely 0.83 min. This is followed by a climb out phase with a flight time of 1.25 minutes. When returning to the airport, the aircraft must pass through the approach phase, which has a duration of 4 minutes. The longest time for the aircraft will be the total taxiing before take-off and after landing. This time includes - waiting for the taxiways to be cleared, the taxiing itself, defrosting, time for to obtain a permit. All taxi-idle phase takes approximately 18 minutes at Prague Airport. When we put all the times together, we reach the number 24.08 min.

Based on the knowledge of the aircraft phases times within one LTO cycle at the Prague airport, we can look at the following graph. The figure below shows us results of CO_2 emissions for 4 individual aircrafts representing 4 weight categories during different phases of LTO cycle (Take – off, climb out, approach, iddle – taxi). From the figure we read that the amount of CO_2 depends on the length of each phase (from calculations we already know that it depends also on fuel flow and emission factor, that isn’t the case here because it is 3.16 kg in all phases of flight).

The graph and the calculations show that the greatest CO_2 pollution emitted by all aircraft types is caused by taxiing at the airport, even if during this time the engine runs at only 7%. The second largest pollution phase is paradoxically the approach, even if people would call take-off as a bigger polluter, due to the fact that the engines run at 100% and therefore they generate much more noise emissions. The 3rd in the numbers of CO_2 is the climb out phase and the last is represented by take-off phase.

Based on the 2 graphs below the differences between aircraft types are following:

There is a small difference between the A320 and the A321 in terms of the number of emissions per aircraft. For take-off, climb out and landing there is a difference of about 100 kg between these aircrafts. An exception is the taxi phase, where the A321 produces about 200 kg of extra CO_2. There is a big difference in the number of emissions between the A333 and ATR aircraft. The amount of CO_2 produced by the A333 during take-off is de facto equal to 890% CO_2 produced by ATR during take-off. A321 is expressed during the taxi phase 551% while A330 1093% of CO_2 produced by ATR. This means that the A330 produces 2x more emissions when taxing than the A321, when we look closer to graph below, we can generally say that A330 produces 2x more emissions of CO_2 than A321. When we compare airbus A320 with A330 the difference is about 2,5 – 3x in emissions of CO_2 depending on the phase.

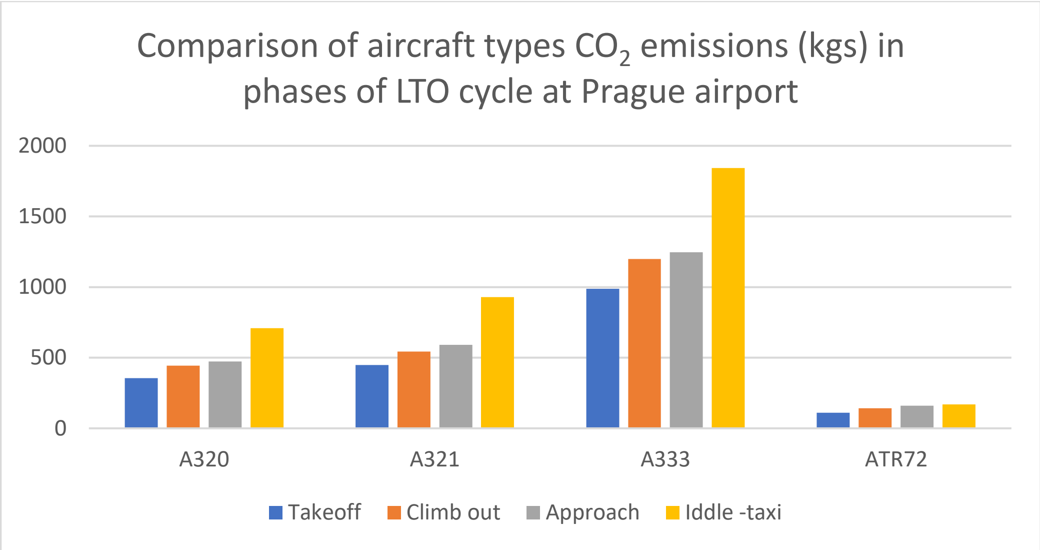

Figure 10 - Comparison of aircraft types CO_2 emisisons in phases of LTO cycle at Prague airport

To better understand the differences between CO_2 emissions of aircraft types that occur at Prague airport and for comparison purposes, I prepared a graph that represents amount of CO_2 produced by aircraft types A320, A321 and A333 as a percentage of the amount of CO_2 of the aircraft ATR72. Then is easier to imagine how many emitted carbon dioxide emissions of aircrafts A330, A321, A320 represents for ATR emissions.

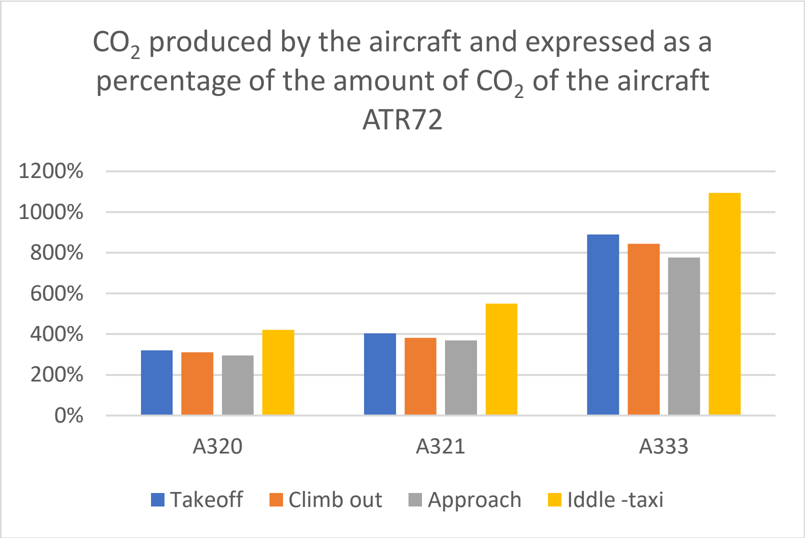

Figure 11 - CO_2 of aircrafts A320, A321, A333 expressed as a percentage of CO_2 of aircraft ATR72

4.2 Comparison of the CF LTO cycle of Prague airport with competing airports

The next part of the practical part will deal with the comparison of the carbon footprint from the LTO cycle of Prague airport and competing airports.

At first we have to decide with which airports will be Prague airport compared.

We can decide which airports to choose based on the number of passengers or based on the distance from Prague airport. If we look at the number of passengers, we find that Prague Airport handled 17 804 900 passengers in 2019. The nearest airports from Prague with comparable traffic are: Vienna, Munich or Berlin. In terms of passenger numbers, the most comparable is the airport in Budapest, which handled around 16 million people in 2019, or the airport in Warsaw with similar numbers, while the airport in Vienna around 27 million passengers.

According to these facts I decided to choose Wien, Munich and Budapest airport for comparison with Prague airport, because for passengers the most important is the time for getting to the airport and secondly Budapest airport has similar passenger numbers so therefore is a good candidate for the calculation.

4.2.1 Calculation procedure of the CF of LTOs for Vienna and Munich airport

The first step was to obtain data on the number of aircraft movements from statistics. Due to the lack of accurate data on the number of movements of scheduled airport routes, I used data from Eurocontrol. They contain the number of departures and arrivals as well as the numbers of departures and arrivals according to IFR rules for most of airports from year 2016. Thanks to this procedure all small light aircrafts and aircrafts flying under VFR rules won't be included.

The next step involved finding out the taxi timesfor the airports, concretely taxi-in and taxi out (Eurocontrol database of winter 2018/2019)[74], so that we do not have to use ICAO taxi times, which are overestimated. ICAO times will be only used for approach, takeoff and climb out because are similar to those used for Prague calculations.

Based on the assumptions mentioned above I went through calculations. The table below shows the number of departures, arrivals and finally the number of LTO cycles that are needed for calculation of CF.

WIEN /IFR	DEP	ARR	TOTAL
2016	120 586	120 587	241 173
2017	119 943	119 964	239 907
2018	128 131	128 109	256 240
2019	140 740	140 748	281 488
2020	54 099	54 076	108 175

Table 11 - Wien airport, total movements

Then it was necessary to calculate the LTO cycle for a given airport. Due to the fact that it was not possible to find exact data on the types of aircraft for the given airports, the A320 aircraft was used for the calculation. It is selected as an representative aircraft that stays between small and wide-body airplanes and also is one of the most common ones at the airports.

The calculation procedure is the same as for the calculation of the LTO cycle for Prague airport:

[74] *Taxi times - winter 2018/2019.*Eurocontrol.2019.

The figure below shows the comparison of carbon footprint emitted by LTO cycles at different airports during years 2016 to 2020 in tCO_2. We can see that the highest impact on the environment has Munich airport. On the other hand, Budapest airport produces from LTO cycles the lowest amount of CF. The carbon footprint of Prague slowly stagnates between years 2018 to 2019. When we compare the airport with the other ones, we get that in year 2018 the amount of tCO_2 of Prague airport is approximately half of the CF of Munich airport. The year 2017 means for Prague airport changement from slow growth to stabilization of the amount of CF. This year also the airport gets little closer to Wien airport in terms of CF. The reason of growth between 2016 and 2017 may be caused by new widebody routes that produces much more CF than other aircrafts. All 4 airports were hit by the coronavirus crisis in year 2020. The most hurt airport was Munich followed by Wien, Prague and Budapest but this airport did not suffer as much as the others. The reason for that is quite clear, because Budapest airport isn't a hub, it works more as point to point than as a stop for connecting flights, also it misses the regular traditional airline that would use that kind of services.

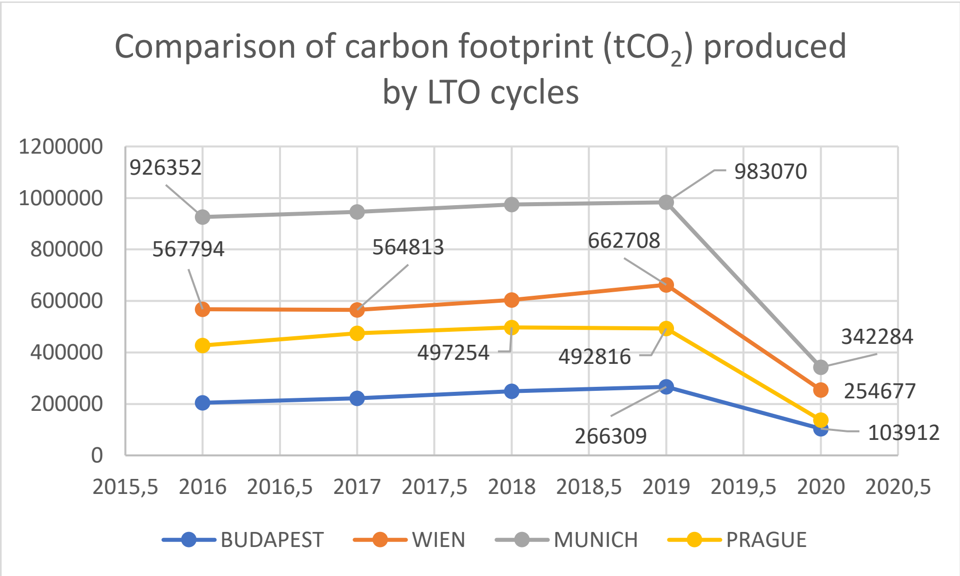

Figure 12 - Comparison of CF (in form of CO_2) from LTO cycles of different airports

4.3 Calculating the emissions of chosen aircraft type for a specific route

In this section I would like to show different methods how to emissions on one specific route. For calculating emissions and based on available data I decided to choose route from Prague to Stockholm with an aircraft airbus A319 with an engine type ID: 3CM027; identification: CFM56-5B5/P

4.3.1 Calculation based on concrete flight plan route Prague - Stockholm

The first step in order to calculate the CO_2 emissions for the certain route was to get a real flight plan. This was obtained from the website of "real world flight plan",[75] where pilots voluntarily upload them.

Flight plan: ARTUP DCT TOMTI P733 DIMEX DCT RIVDI M607 PENOR DCT ROGMI Z229 NILUG

In order to calculate the total flight route, it was necessary to check the aerial maps of areas withing individual states[76], to obtain a departure map and taxiway map of Prague Airport and an arrival, an approach and a taxiway map for Stockholm Airport.

Based on a real flight of Czech airlines OK490 which flew on April 1, 2021[77] I decided for the runways in use, SIDS, STARS, taxiways and stands.

Data decision:

Taxiways: from stand 17, J-Blue, H, A

Departure: Prague Ruzyně (LKPR, PRG) RWY 24

SID: ARTUP 4A, RWY 24

Route: ARTUP DCT TOMTI P733 DIMEX DCT RIVDI M607 PENOR DCT ROGMI Z229 NILUG

STAR: NILUG2V

APPROACH: via EKDAS, ILS ILS RWY 26

Arrival: Stockholm (ESSA, ARN) RWY 26

Taxiways: to stand 17, X2, ZP, Z

[75] *Real world flight plan database*. 2021.
[76] *Skyvector: Aeronautical charts.* 2021.
[77] *Flightradar24: Live Air Traffic* 2021.

Based on decisions above I calculated the distances from maps and also times of the real flight OK490 which flew on 1st April 2021 and then I summarized the data in the table below. It's important to add that for taxing at airports I converted metres to nautical miles (1nm = 1.852 km).

	Distances from charts (nm)	Source of charts	Times flightradar[78] (min)
TAXI DEP	0,86	*AIM*[79]	4
Take-off	1,2	*AIM*	1
Climb out	0,79	*AIM*	1
SID - CLIMB	73	*AIM*	14
reach FL - CLIMB	----		
Route - CRUISE	510,7	*Skyvector*[80]	59
DESCENT	-------	-	16
STAR - DESCENT	59	*AROWeb*[81]	
Approach	6,86	*AROWeb*	2
Final Approach	3,43	*AROWeb*	4
Landing	1,35	*AROWeb*	1
TAXI ARR	0,65	*AROWeb*	4
SUMA	657,85		106

Table 12 - Flight distances and times for route Prague - Stockholm

From the table above we can see that flight plan route has 510,7nm[82] (calculated by the website skyvector, containing aerial maps of areas within individual states), STAR= 59nm, SID = 73nm. Also the table distinguishes by colour LTO cycle and CCD. The next step was to divide LTO cycle into departure part for Prague airport and arrival part for Stockholm airport. From these sections of flight, there were used times to calculate the fuel burned during departure and arrival with usage of equations already explained before. I'm giving here an example for calculation of fuel burned during takeoff:

78 *Flightradar24: Live Air Traffic* 2021.
79 *AIM - Letecká informační služba: AIP - LKPR Prague Ruzyne* [online]. 2021.
80 *Skyvector: Aeronautical charts.* 2021.
81 *AROWeb – AIS MET and Flight Planning Flight planning centre: IAIP – ESSA STOCKHOLM/Arlanda* 2021.

82 *Skyvector: Aeronautical charts.* 2021.

FTO = (TMTO*60)*FFTO*NE

Finally I calculated also the CCD phase based on engine databank, its emissions and thrust 30% for CCD[83] (table below).:

A319/ 1EN	PRG+ARN(min)	PRG+ARN(s)	FUEL FLOW kg/s	CO_2	NO_X	SO_X	H_2O	CO	HC
TAKEOFF	1	60	0,891	3160	22	1	1230	0,9	0,2
CLIMB OUT	1	60	0,742	3160	19	1	1230	1	0,2
APP	4	240	0,260	3160	8,7	1	1230	3,4	0,7
IDDLE	9	540	0,094	3160	3,8	1	1230	30	6,2
CCD	91	5460	0,260	3160	8,7	1	1230	3,4	0,7
		FUEL BURNED:	1630,7						
		TOTAL 2 ENG	**3261,48**						

Table 13 - Fuel burned for departure, arrival and CCD on route Prague - Stockholm

From the table above, we obtained the amount of fuel consumed on the OK490 flight by the A319 aircraft by equation: FUEL 2engines = 2* (FTO+ FCO+FAP+FID+FCCD)

Where,

FTO … fuel burned during take-off, FCO… fuel from climb out, FAP… fuel for approach, FID… fuel for taxi, FFCD… fuel burned during CCD phase

The next step was to calculate the emissions for the flight to Stockholm

For calculating emissions of this flight this equation was used similarly for all emissions:

$CO_2TO = (TMTO *60) * FFTO* NE * EFCO_2$

After proceeding all calculations, we finally got the table of all emissions from the flight to Stockholm (table below):

EMISSIONS FROM ROUTE PRAGUE STOCKHOLM (g)						
	CO_2	NO_X	SO_X	H_2O	CO	HC
Takeoff	168933,60	1170,77	53,46	65755,80	48,11	10,69
Climb out	140683,20	823,62	44,52	54759,60	44,52	8,90
Approach	197184,00	542,88	62,40	76752,00	212,16	43,68
Iddle	160401,60	192,89	50,76	62434,80	1522,80	314,71
CCD	4485936,00	12350,52	1419,60	1746108,00	4826,64	993,72
SUM/1000 (g->kg)	5153,14	15,08	1,63	2005,81	6,65	1,37
2 ENGINES (kg)	10306,28	30,16	3,26	4011,62	13,31	2,74

[83] *EDB - emissions data sheets: ICAO Aircraft Engine Emissions Databank.* 2020.

Table 14 - Emissions from route Prague - Stockholm

The table of emissions from route Prague – Stockholm shows the huge amount of CO_2 emissions produced in a single flight, namely 10306,28 kilograms. The second largest emission is the amount of water 4011,62 kgs and the third is the amount of NO_x. In principle, it can be said that the order confirmed the information contained in the theory.

When we compare the individual phases, we find that most of the emissions come from the CCD phase. For better comparison of other 3 emissions, I prepared a graph below showing only SO_x, CO and HC in 4 different stages. As we can see, from these 3 the most impact on environment has CO especially during approach, iddle (taxi) and CCD while emissions from the takeoff and climb out phases are negligible.

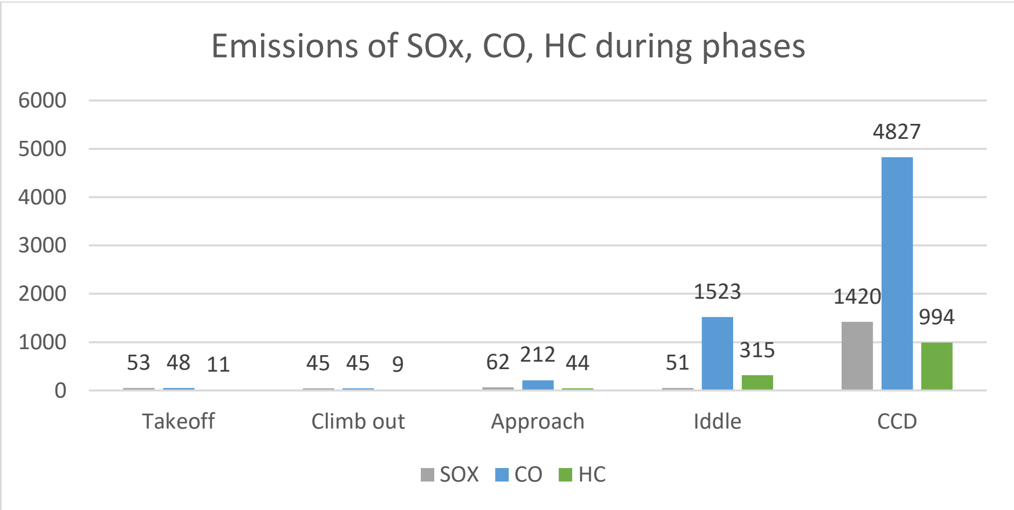

Figure 13- Emissions SOx, CO, HC during phases of flight to Stockholm

It can be concluded that on the flight OK490 to Stockholm was produced:

10306 kg CO_2, 30 kg NOx, 3,26 kg SO_X, 4012 kg H_2O, 13 kg CO and 3kg HC.

4.3.2 Calculation based on ICAO carbon calculator – route Prague-Stockhom

Another way to calculate emissions for a given route is to use an online emissions calculator. The best of the calculators that offer the possibility to enter departure and arrival to a certain destination and at the same time calculate the amount of fuel for a given route is from the ICAO organization. However, this calculator has the disadvantage that it is not possible calculate other emissions than CO2 and that there is also no possibility to select an aircraft, it is assigned automatically according to the flight database.

<u>Calculation procedure:</u>

On the website I filled in the data: departure: Prague (PRG), Arrival: Stockholm (ARN), trip: one way, cabin class: economy, number of passengers 100. After performing the operation, the calculator gave me these results (figure below):

Total						
Dep Airport	Arr Airport	Number of passengers	Cabin Class	Trip	Aircraft Fuel Burn/journey (KG)[ab]	Total passengers' CO2/journey (KG)[c]
PRG	ARN	100	Economy	One Way	5400.5	11123.7

Flight Stage Detail					
Dep Airport	Arr Airport	Distance (KM)	Aircraft	Aircraft Fuel Burn/leg (KG)[a]	Passenger CO_2/pax/leg (KG)
PRG	ARN	1086.0	319, 320, 737, 738, 739, 73G, 73H, CR9	5400.5	111.2

a. Fuel Burn information provided are for 1 aircraft per leg

b. Aircraft Fuel Burn/journey = ∑Aircraft Fuel Burn/leg

c. Total passengers' CO2/journey = ∑Passenger CO2/pax/leg×Number of pax

Figure 14 - ICAO Carbon emission calculator Prague - Stockholm

In order to calculate the amount of CO_2, it is necessary to multiply the amount of fuel burned by the emission factor of carbon dioxide:

CO_2 = Fuel burned * $EFCO_2$ $CO_2 = 5400{,}5 * 3{,}16 = 17\ 065{,}58$ kg ,

From ICAO calculator methodology we get these numbers for intra Europe flights:

PLF = 82,3%; Passenger to freight factor = 96,12%[84]

In the figure of ICAO calculator, we can see also an amount of CO_2 per pax/leg that is for our route: 111,2 kg

Then based on equations below we calculate number of y-seats rounded to tens that uses the calculator… 180 and also the amount of CO_2 per pax/km

[84] *ICAO Carbon Emissions CalculatorMethodology: v11*.2018.

$$CO_2/pax = 3,16 * \frac{(Total\ fuel * \text{pax-to-freight factor})}{(number\ of\ y\text{-}seats * pax\ load\ factor)}$$

$$CO_2/pax/km = 3,16 * \frac{(Total\ fuel * \text{pax-to-freight factor})}{(number\ of\ y\text{-}seats * pax\ load\ factor * distance)}$$

$$CO_2/pax/km = 3,16 * \frac{(5400,5 * 96,12)}{(180 * 82,3 * 1086)} = 0,102 \text{ kg pax/km}$$

Using the emission calculator, we calculated for the route from Prague to Stockholm that, the aircraft will emit a total of 17 065,58 kg of CO_2, one passenger accounts for 111.2 kg of CO_2, and for one pax km flown, there is 0,102 kg of CO_2.

4.3.3 Calculation based on Master emissions calculator – route Prague Stockholm

The next calculation for the chosen route is based on the Master emissions calculator with usage of aircraft A319.

As first we needed to get the distance between these two airports. For this case I used 2 methods:

1) The length between airport obtained using great circle distance. For this purpose, I used the gcmap page[85], which calculates the entire distance after entering both airports. Thanks to this website I got a distance of 588 nm between Prague and Stockholm airports. 4.2.1.

2) Calculation of the entire route based on aerial maps charts. This has been already calculated in the chapter 4.2.1, where the total distance is 657,85 nm, of which CCD phase equals after rounding 650 nm.

<u>1) distance- based method – great circle distance</u>

For this method we had to calculate the great distance between the airport as it is mentioned above. Then the aircraft type was selected from the list and we got these results: The total amount of fuel burn is according to the calculator 3860 kg. For this amount of fuel corresponds about 12282 kg CO_2 and 4796 kg H_2O.

[85] *Great Circle Mapper.* 2021.

		Estimated parameters (based on year 2015)											
Aircraft type	A319 AIRBUS INDUSTRIE	Most frequently observed cruise flight level (100 ft)	Duration (hh:mm:ss)	Fuel burn (kg)	CO_2 (kg)	NO_x (kg)	SO_x (kg)	H_2O (kg)	CO (kg)	HC (kg)	PM non volatile (kg)	PM volatile (organic + sulphurous) (kg)	PM TOTAL (kg) (3)
Default LTO (1) cycle	Default for a busy European airport, year 2015		0:27:00	622,26	1 960,12	7,21	0,52	765,38	7,49	1,55	0,0033	0,0488	0,0521
	ICAO default		0:32:54	650,00	2 169,76	7,46	0,58	847,24	9,49	1,96	0,0035	0,0546	0,0581
Enter a CCD (2) stage length (NM)	**588**	320	1:22:49	3 210,40	10 112,77	46,45	2,70	3 948,79	10,48	2,19	0,0413	0,3708	0,4121
TOTAL LTO + CCD 588 nm.			1:55:43	3 860,40	12 282,53	53,92	3,28	4 796,03	19,97	4,15	0,0448	0,4254	0,4701

Figure 15 - Master emission calculator, Prague – Stockholm (method 1)

<u>2) distance-based method - charts</u>

		Estimated parameters (based on year 2015)								
Aircraft type	A319 AIRBUS INDUSTRIE	Most frequently observed cruise flight level (100 ft)	Duration (hh:mm:ss)	Fuel burn (kg)	CO_2 (kg)	NO_x (kg)	SO_x (kg)	H_2O (kg)	CO (kg)	HC (kg)
Default LTO (1) cycle	Default for a busy European airport, year 2015		0:27:00	622,26	1 960,12	7,21	0,52	765,38	7,49	1,55
	ICAO default		0:32:54	650,00	2 169,76	7,46	0,58	847,24	9,49	1,96
Enter a CCD (2) stage length (NM)	**650**	320	1:31:19	3 468,45	10 925,62	49,24	2,91	4 266,19	11,09	2,32
TOTAL LTO + CCD 650 nm.			2:04:13	4 118,45	13 095,38	56,70	3,49	5 113,43	20,58	4,28

Figure 16 - Master emission calculator, Prague – Stockholm (method 2)

After selecting the parameters, the master calculator calculated the amount of fuel burn and estimated emissions for the LTO cycle based on ICAO time, for the entire route and for the CCD phase of 650 nm. From the results we found that for the entire length of the flight 2h4min, the aircraft burned 4118 tons of fuel and produced 13095 kg of CO_2. If we look at the other results, we find that the values of SO_x and HC are practically negligible, in units of kilos. a large share of emissions is also represented by H_2O in the total number of 5113 kg. It is clear from the data that CO has an impact on the environment, especially during the LTO cycle, during the flight itself the values are negligible.

For both methods, it is necessary to look at the time spent in the LTO cycle from the ICAO organization. As we can see in the figure of master emission calculator, the time the aircraft spends in the LTO cycle is almost 33 minutes. If we compare the measured data from real operation, it is obvious that this value is quite overestimated. This is because the ICAO organization is based on the average of all flights at all airports and therefore does not consider smaller airports or traffic. The data measured by me from the previous calculation for the route Prague - Stockholm give a value of 15 minutes, which is practically half compared to 33 minutes. The difference can make about 70-80 kg.

If we look at the individual values, they are interesting for CO and HC in terms of how much they are produced at a certain stage. During the LTO cycle the aircraft emits almost the same amount of harmful substances CO and HC in 33 minutes as in the CCD flight phase, which according to the calculator lasts 1 hour and 22 minutes. From above we can conclude that these substances are dangerous for people around the airport area, while during the flight the levels of these substances are low. During the flight the most harmful substances for the air are in the form of CO_2 and NO_x and partly also H_2O, although this substance survives at high altitudes for much less time than CO_2. In conclusion, we can say that any sophisticated calculator will not reflect the absolute conditions of the flight in terms of weather, traffic or emergencies.

4.4 Carbon footprint of all scheduled passenger flights of Prague airport's summer flight schedule 2021.

In this part I will summarize and compare scheduled passenger routes from Prague airport during the summer schedule (from 1.4. to 31.10.2021) on the basis of the amount of carbon footprint.

To calculate the CF of scheduled routes, it was necessary to obtain inventory of all routes that depart from Prague airport.[86] To accomplish this, I used the website of Prague airport where is possible to find all scheduled routes. There I clicked on each destination and then appeared the calendar with the number of flights for each individual day, including airline, the type of the aircraft and the flight distances for individual flights.

The first step was to make a list of all routes departing from Prague airport during the summer 2021. In this process, it was found that a total of 122 destinations will be flown from Prague in the summer.

Afterwards it was important to determine the distances between origins and destinations for each individual route. This was done by using the Great Circle Distance website.[87] Even if airlines usually don't fly directly, because of weather conditions and "traffic jam" in the air there wasn't made any correction to the distance flown. To calculate

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[86] *Letiště Praha: Letové trasy a řád*. Flight Connections, 2021
[87] *Great Circle Mapper*.2021.

the distance travelled per summer schedule, I took the length of flight and multiplied it by the number of flights of summer schedule.

The next step was to calculate the CO_2 emissions of all routes from Prague airport. For this purpose, I used the Master emission calculator which after entering data in the form of a distance in nautical miles and a specific aircraft estimates the emissions of CO_2.

After then it was possible to process all data. For better understanding the results I had to convert nautical miles to kilometres, I also calculated the number of flights, CO_2, distances for each individual route.

4.4.1 Carbon footprint of routes

When we summarize the number of destinations in Prague, we get the number 122, but the total number of routes includes even those. However, the actual number of routes is larger as it also includes destinations that serve 2 or more airlines. At first we check the individual routes that have the highest impact on environment based on the number of CO_2.

Based on data I sorted all the routes according to the percentage of impact on total carbon footprint. From table below we can see that the most impact has the route to Dubai with the percentage of 6,4% of total carbon footprint during summer schedule. This number represents 18 235t CO_2, that was emitted by aircraft engines on all routes from Prague to Dubai during the entire summer schedule. Interestingly, although the airline plans to operate only one flight a day on the B773 in the summer, it is still ranked first with its route. From table we can also see that the airline Smartwings occupies 5 places in the first 15 most polluting routes. The reason we have to search in airport data, and we get the result that it is the most common carrier at Prague airport. Also is possible to say that these routes with the largest number of produced carbon footprints reflect the demand for the given destinations or vice versa, the demand for Prague.

The route with the second highest CF is the Turkish airlines route to Istanbul. This destination is for me a little bit surprise in numbers of flights (512). Actually, I didn’t know that this route is so much used or better planned to be used in future. from my point of view, the number of frequencies on this route will certainly be reduced, due to the crisis caused by the current pandemic and the fact that people will not have the money to fly somewhere. The fourth destination by ranking represents 2,9% of total carbon footprint, I find it interesting also for number of flights. This is due to the fact that Amsterdam airport works as a huge hub from where people fly to many other destinations around the world.

From the table we can also read that the amount of CO_2 does not depend only on the number of flights but also on the size of the aircraft. In general, the larger the aircraft, the more carbon footprint it creates. Then we can also conclude that the greater the distance is, the higher is the CF.

Rank	Destination	Airline	Aircraft	Total flights	Total distance (km)	CO_2 (t)	Percent of CF
1	Dubai	Emirates	B773	150	669150	18235	6,4%
2	Istanbul	Turkish airlines	A321	512	761344	10443	3,7%
3	Tel Aviv	Smartwings	B738	302	795166	8213	2,9%
4	Amsterdam	KLM	B738	777	546231	8191	2,9%
5	Tel Aviv	EL AL	B738	268	705644	7288	2,5%
6	Marsa Alam	Smartwings	B738	217	702212	7086	2,5%
7	Hurghada	Smartwings	B738	224	681408	6815	2,4%
8	London Heathrow	British Airways	A320	530	551730	6769	2,4%
9	Dubai	Flydubai	B738	151	673611	6574	2,3%
10	Rhodes	Smartwings	B738	286	538538	5870	2,1%
11	Doha	Qatar airways	B738	141	594456	5836	2,0%
12	Barcelona	Vueling	A320	368	499744	5634	2,0%
13	Frankfurt	Lufthansa	A319	739	298556	4908	1,7%
14	Paris	Air France	A320	436	371036	4882	1,7%
15	Malaga	Smartwings	B738	211	445843	4762	1,7%

Table 15 - Carbon footprint by route

4.4.2 Carbon intensity of routes

In this part I decided to calculate the carbon intensity of routes. The procedure of calculation was done based on the following equation:

$$RCI = \frac{RCF}{Distance} * 100$$

Where:

RCI … route carbon intensity (t CO_2/ 100km/ route); Distance … total distance of all flights on route (km), RCF… total amount of CO_2 for a given route and airline.

From the equation of route carbon intensity is clear that the calculation procedure is as follows: to calculate the RCI, first we divide the total amount of CO_2 per airline route by total distance the aircraft flown on the route during the summer schedule. Then for better visualisation we multiply the result by 100. We'll get the route carbon intensity in units of tCO_2 per 100km distance flown. After calculations we got the table Route carbon intensity (RCI). The table includes top 15 routes according to the tonnes of CO_2 per 100km travelled.

Rank	Destination	Airline	Aircraft	CO_2 (t)	Flights	Total Distance	tCO_2 per 100 km
1	Dubai	Emirates	B773	18235	150	669150	2,73
2	Budapest	Ryanair	B738	1243	149	70030	1,78
3	Munich	Lufthansa	E195	1952	420	110880	1,76
4	Vienna	Austrian	E195	3766	792	220176	1,71
5	Warsaw	Ryanair	B738	307	35	18095	1,70
6	Venice Treviso	Ryanair	B738	527	60	31020	1,70
7	Košice	Ryanair	B738	623	70	37030	1,68
8	Venice	Ryanair	B738	80	9	4761	1,68
9	Frankfurt	Lufthansa	A319	4908	739	298556	1,64
10	Milan Bergamo	Ryanair	B738	1058	111	66267	1,60
11	Copenhagen	Ryanair	B738	1073	110	68310	1,57
12	Copenhagen	Norwegian	B738	898	92	57132	1,57
13	Eindhoven	Transavia	B738	1025	103	66023	1,55
14	Milan Malpensa	Ryanair	B738	719	72	46440	1,55
15	Bologna	Ryanair	B738	728	72	47376	1,54

Table 16 – Route carbon intensity (RCI)

Emirates took the first place in terms of emissions per unit distance flown with its route to Dubai. Among the companies that produce the most tons of CO_2 per 100 km of distance flown, we can certainly include the company Ryanair, which de facto controlled the entire statistics with a total of 9 routes out of 15. It's seenable that Ryanair reflect its position at Prague airport. Ryanair uses a Boeing 738 for all flights even if they take only about an hour. When we check the table again and we concentrate on Ryanair's destinations, we can see that all these destinations are distanced from the location of Prague airport by an air distance of about one hour. Therefore it results together with the aircraft choice in higher route carbon intensity than other routes.

The route with the highest amount of tCO_2 per 100 km distance flown is as I said above company Emirates with 2,73 tCO_2 per 100 km travelled. The high value is probably connected with the relatively short distance of route for B773 in comparison to other widebody journeys of this aircraft. The Boeing 777 version 300 is able to fly up to distance about 6000 nm.[88] Therefore the flight to Dubai produces more CO_2 per distance than other aircrafts that are more suitable for this route.

The third place right after a Ryanair occupies the company Lufthansa on the usual route to Munich. The emissions of CO_2 per 100 km is in this case 1,76 in comparison with Austrian airlines route to Vienna where the tCO_2 per chosen distance is 0,05 smaller. Both companies use the same jet aircraft Embraer for the small routes. The problem is that the flights are too short, so it results in inefficient take-off and landing phase. These parts of flight contribute to the high carbon footprint per unit distance travelled.

Finally, I would like to show the top routes with the lowest carbon intensity number:

Rank	Route	Airline	Aircraft	CO_2 (t)	Flights	Total distance	tCO_2 per 100 km
1	Belgrade	Air Serbia	ATR42	185	55	40810	0,45
2	Luxemburg	Luxair	DHD9	300	103	59534	0,50
3	Warsaw	LOT	DHD9	1286	476	247520	0,52
4	Hurghada	Egyptair	A223	1286	48	146016	0,88
5	Lisbon	TAP	A319	4022	197	438719	0,92
6	Novosibirsk	S7	A320	924	22	98538	0,94
7	Sofia	Bulgaria Air	E195	1089	105	113400	0,96

Table 17 - Route carbon intensity, ranking from the lowest level of carbon intensity

The table with the lowest level of emissions per unit distance travelled gives the entire view on carbon intensity. The most environmentaly friendly route per 100 km is the route to Belgrade with utilization of ATR42. This aircraft is a small turboprop plane that is often used for short distances. In our case the route on board of this aircraft generates only 0,45 t CO_2 per 100 km. The following aircrafts in order 2 and 3 are also turboprop aircraft with around of 0,50 t CO_2 per 100 km travelled.

[88] *Skybrary: BOEING 777-300*. 2021.

It is also worth mentioning that the relatively recently manufactured aircraft A220-300, that has a capacity between the aircraft A320 and A319, has better engines and therefore the flight took the 4th place.

On the figure below I would like to show how the total amount of CF changes in month in absolute numbers. From the graph is quite clear that based on the coronavirus the demand for travel is low from April until May, so the airlines cut their summer schedule in order to save some money. While in July and August there is hope that the life and travelling will be back to normal so therefore the airlines increased dramatically their frequencies. From my point of view, the reduction of frequencies will surely continue, because people will be afraid to travel or they won't have money for that. The month with the highest number of CF is the August, more precisely 55 007 t CO_2. During this month the airlines plan to increase the utilization of their fleet. From this month we can see there is a decline in CF until October. From this graph we can conclude that our environment is mostly hit during the summer – between June till beginning of September.

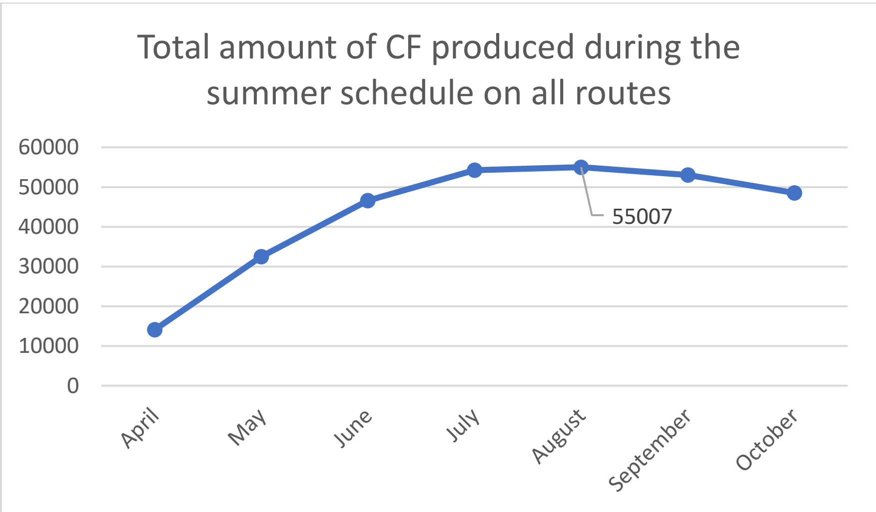

Figure 17 - Total amount of CF produced during the summer schedule on all routes (tCO_2)

5 Conclusion

The goal of this study for theoretical part was to provide information on what kind of emissions are emitted by the aircraft engine during the flight and movement of the aircraft on the ground, to outline and describe methods by which emissions can be calculated, and also provide information about aircraft fuel and possibilities of its calculation.

The benefit of the theoretical part is in particular, a complete description of the individual emissions that the aircraft produces with the number of emissions that are emitted by the engine from different thrust setting. A large part of work was dedicated to aircraft operations where the reader can easily understand certain phases of the aircraft and then he can use it for its own calculation. Also, I have described in detail terms LTO and CCD that are all together used later for calculations. Most of the theoretical part I spent with methods such as 3 methodological tiers, the method ICAO and the Master emission calculator. In the last part I dealt with fuel, what it consists of and in what ways it is possible to calculate fuel.

The main aim was to determine the amount of CF in the form of carbon dioxide produced by aircrafts during landing take-off phase at Prague airport in a certain period.

I calculated the total amount of CF for Prague airport from LTO cycles. I found out that there was an increase in CO_2 emissions each year practically until year 2019. From where due to corona crisis the level of CF massively declined. Also in my work is seenable the difference between 4 aircraft categories that were allocated to the total numbers based on proportions received from the airport source. During this phase I was working with concrete engines and aircrafts.

Based on the calculation of the previous aim, another goal, including a comparison of the carbon footprint from the LTO cycles of Prague Airport with competing airports, was calculated. In this part there were compared 3 airports with Prague airport. Concretely Budapest, Wien, and Munich airport. From the results was clear that the most impact from LTO cycles on the environment has Munich airport, followed by Wien, Prague and Budapest.

Then another goal was to go through calculating emissions of certain aircraft on for a specific chosen route. I chose the concrete route from Prague to Stockholm based on real data. I compared it with real flight from flightradar and then calculated the entire procedure. From theoretical knowledge the result for emissions wasn't surprising. The highest number of emissions is represented by carbon dioxide, followed by H_2O and NO_x. I also checked the difference between the other emissions. The highest impact has CO and HC during IDDLE phase that means when the aircraft is taxing and using thrust 7%. Even if on the graph is the highest amount CCD, we must take into consideration the time spent in each phase.

The last objective was to calculate the carbon footprint of Prague airport's regular airline routes within the summer flight schedule of 2021. In this part I obtained all data about routes from Prague airport, including aircraft type, route, kilometres. I summarized data and then compiled them in excel sheet. I compared them based on tCO_2 per 100 km and on the percentage of the total CF.

I see a future in reducing carbon footprint in the possibility of new aircraft engines and the use of electric wheel drive after each landing. As air transport continues to evolve, there is a need to focus more on the carbon footprint in the future.

To conclude I liked my topic and definitely I would like to continue studying it.

At the end of this work I will add the aerial quote: "You can take off, but you have to land."

6 References

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