Aircraft Particulate Matter Emission Estimation through all Phases of Flight

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## Title
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### Abstract:
This document presents a complete and consistent approach to estimate aircraft particulate matter (PM) emission through all phases of flight. This is based on an extensive literature review on available methods, so far only addressing parts of the problem. These are presented and compared.

In addition it proposes the first time an approach to overcome the problem of missing Smoke number (SN) information in the ICAO Engine Exhaust Emission Data Bank. The SN information is required to estimate PM, but not available for all engines currently in use by aviation.
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Executive Summary

Besides the ‘traditional’ pollutants like CO₂, SO₂ or NOₓ as well Particulate Matter emissions play a more and more important role in the discussion on the environmental effects of aviation. Recent studies showed a negative effect of an increase in Particulate Matter emissions: they disturb the radiative balance in the atmosphere and contribute to the global warming, and, on the other hand, they have negative effects on the human health when inhaled. To estimate the impact of Particulate Matter, tools and methods for prediction and simulation are required.

Within the framework of this diploma thesis a method will be presented that allows to determine the amount of Particulate Matter emitted by aircraft engines through all phases of flight. This method is based on an approach derived from the German DLR (Deutsches Zentrum für Luft- und Raumfahrt) and relies on the ICAO Smoke Number. The Smoke Number gives information on the amount of soot in the exhaust gas of an aircraft engine and is determined during engine certification. It is listed for each engine and operation mode of the ICAO Landing- and Take off cycle in the ICAO Engine Exhaust Emission Data Bank. The main difficulty is that this data is missing in many cases. Only 28.8% of the engines listed in the database have a complete set of Smoke Numbers. For this an algorithm, the so called “fill-the-gaps-algorithm”, was developed to overcome this problem and to complete the database.

The derived Particulate Matter estimation method was implemented into EUROCONTROL’s Advanced Emissions Model III (AEMIII) as a MS-Access based standalone module. This module is open to be linked to other emission prediction and simulation tools as for example the Airport Emission Estimation Calculation Tool AECT of the Institute of Aeronautical Engineering (LLT) at the Technical University of Munich.
Kurzfassung


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Acronyms

AEM    Advanced Emissions Model
AEM_PT Advanced Emissions Model Particulate Matter Tool
AFR    Air-to-fuel-ratio
ANSI   American National Standards Institute
APEX   Aircraft Particulate Matter Experiment
APP    Approach
ATC    Air Traffic Control
ATM    Air Traffic Management
BPR    Bypass ratio
CCN    Cloud Condensation Nuclei
CMD    Count Meridian Diameter
CoE    Centre of Excellence
CPC    Condensation Particle Counter
C/O    Climb Out
DC     Diffusion Charger
DLR    Deutsches Zentrum für Luft- und Raumfahrt
DMA    Differential Mobility Analyser
DMPS   Differential Mobility Particle Sizer
EEC    Eurocontrol Experimental Centre
EPA    Environmental Protection Agency
FAA    Federal Aviation Administration
FID    Flame Ionization Detector
FOA    First Order Approximation
FSC    Fuel Sulphur Content
GSD    Geometric Standard Deviation
HES    High End Simulator
HGF    Helmholtz - Gemeinschaft Deutscher Forschungszentren
ICAO   International Civil Aviation Organization
INCA   Interhemispheric differences in cirrus properties from anthropogenic emissions
LII    Laser Induced Incandescence
LTO    Landing- and Take off
MIT    Massachusetts Institute of Technology
MTF    Mixed Turbo Fan
NAAQS  National Ambient Air Quality Standards
NASA   North American Space Agency
OPC    Optical Particle Counter
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PAH    Polycyclic Aromatic Hydrocarbons
PARTNER  Partnership for Air Transportation Noise and Emission Reduction
PAZI    Partikel und Zirren
PM      Particulate Matter
POLINAT  Pollution from Aircraft Emissions in the North Atlantic Flight Corridor
RWY    Runway
SEE      Society, Environment, Economics
SLS     Sea Level Static
SN      Smoke Number
SNIF    Subsonic Assessment Near-Field Interactions Field
TEOM    Tapered Element Oscillating Microbalance
TF      Turbo Fan
TSP     Totally Suspended Particles
T/O     Take off
UMR    University of Missouri Rolla
VOC    Volatile Organic Compound
WP      Working Package
## Symbols

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</tr>
<tr>
<td>$\dot{V}$</td>
<td>$[m^3/s]$</td>
<td>Volume flow</td>
</tr>
</tbody>
</table>

**Chemical symbols:**
- Ar: Argon
- C: Carbon
- CH$_4$: Methane
- CO: Carbon monoxide
- CO$_2$: Carbon dioxide
- H: Hydrogen
- HC: Hydrocarbon
- H$_2$O: Water
- H$_2$SO$_4$: Sulphuric acid
- N$_2$: Nitrogen
- NO$_x$: Nitrogen oxides
- O: Oxygen
- SO$_2$: Sulphur dioxide

**Greek symbols:**
- $\alpha$: [-] Fuel-to-air-ratio
- $\eta$: [-] Polytrope efficiency
- $\kappa$: [-] Isentropic exponent
- $\lambda$: [-] Oxidation ratio
- $\Pi$: [-] Pressure ratio
- $\rho$: [kg/m$^3$] Density
- $\psi$: [-] Constant
- $\Phi$: [-] Equivalence ratio
Aircraft Particulate Matter Emission Estimation through all Phases of Flight
1 Introduction

Aviation is an integral part of the infrastructure of today’s society. It plays an important role in the global economy as it supports both commerce and private travel. Not to forget the role of aviation in military activities. So, aviation affects the lives of people all over the world. Especially lower prices and the increasing demand lead to an augmentation of worldwide air traffic. Over the past ten years, passenger traffic on scheduled airlines has increased by 60% [1]. It is expected that the demand for air travel will grow by about 5% [1] per year over the next 10 to 15 years. Such increases are not predicted concerning military aircraft, as they are expected to remain static or even decrease. [1]

Aviation fuel currently corresponds to 2-3% [1] of the total fuel used worldwide, of which the majority is used by civil aviation. By comparison, the whole transportation sector currently represents 20-25% [1] of the total fuel consumption worldwide. Therefore aviation sector consumes 13% [1] of the fossil fuel consumed by transportation, which is the second largest fraction after road transportation, which consumes 80%. [1] This steady increase of air traffic leads to an increasing impact on the environment and human’s health. In the past, much focus has been on the “traditional” emissions like carbon dioxide (CO$_2$) and nitride oxides (NO$_x$), but in recent discussions on the environmental impact of aviation Particulate Matter (PM) emissions became more important. [1]

The term “Particulate Matter” describes all solid and fluid particles in the atmosphere that stay in the air for a while instead of dropping onto ground directly, like soot, smoke, dust or droplets of oil and fuel, with a diameter that ranges from a couple of nanometres up to 100µm. Particles can be both primary and secondary pollutants. Primary particles are sent directly into the atmosphere through combustion processes (e.g. cars, trucks, aircraft and power plants), mechanical abrasion (brakes, tyres) or erosion. Secondary particles, on the other side, are formed through chemical reactions involving oxides, sulphur dioxide, VOCs (volatile organic compound) and ammonia.

Recent studies have shown that Particulate Matter has negative effects especially on earth’s atmosphere and human health. Particles suspended into the atmosphere perturb radiation balance (direct radiation effect) and enhance cirrus cloud formation (indirect radiation effect), with a change in global climate as consequence. As particles can be inhaled by human beings, they can deposit in different regions of the lungs –depending of their dimensions– and cause adverse health effects. Some particles are so small that they are able to pass the alveolar regions of the lung and even get into the blood.
At higher altitudes aviation is the only mode of transport and thereby the only source of emission. On and in the vicinity of airports aviation related PM emissions contribute to pollution of lower air layers (*Local Air Quality*) and may have negative effects on human health.

For environmental and for health reasons it is necessary to know the amount and type of pollutant that is emitted by an aircraft engine. Direct measurements are rather expensive and often very extensive. Therefore, software-tools are needed to estimate these emissions through simulations. Concerning the ‘traditional’ pollutants different methods are already existent. This is not the case for Particulate Matter emissions. As the awareness of the risks and importance of Particulate Matter grew during the recent years, research is still in its infancy and there are not many methods available to estimate this kind of pollutant.

This Study on Particulate Matter mainly consists of three “work packages” (WP):

WP 1: *Literature review on Particulate Matter*

WP2: *Review and Development of a method to estimate Particulate Matter emissions from aircraft through all phases of flight*

WP3: *Implementation of the method into an MS-Access based module, linked to EUROCONTROL’s “Advanced Emission Model III” (AEM III).*

Chapter 2 gives a brief overview on EUROCONTROL, the European Organisation for the Safety of Air Navigation, and its main objectives, the agency I worked at for my diploma thesis. Chapter 3 deals with the different types of pollutant formed during the combustion of fossil fuels in aircraft engines. Chapter 4 shows the results of the performed literature review on Particulate Matter. Besides some general information like particle size distribution, chemical composition, particle formation and measurement techniques, the impact of Particulate Matter on the environment and human’s health and regulatory aspects are discussed. Chapter 5 gives an overview on the different methods and approaches to determine the amount of emitted Particulate Matter emission. The comparison and assessment of the available methods leads to a method based on the ICAO Smoke Number that is presented in chapter 6. The objective of this study is to implement this method into EUROCONTROL’s Advanced Emission Model III (AEMIII), which will be described in chapter 7.
2 EUROCONTROL

EUROCONTROL is the European Organisation for the Safety of Air Navigation that currently (10/2005) unifies 35 Member States. The primary objective is the development a seamless air traffic management system for the entire European continent, a system that actually processes almost 60% of the world’s international flights. Main objectives are to increase air traffic safety and airspace capacity, to reduce air traffic delay, to enhance the air traffic management system's cost-effectiveness and to minimise aviation’s effect on the environment. [2][3]

![Map of EUROCONTROL Member States](image)

**Figure 1:** The 34 Member States of EUROCONTROL (before 01.07.2005). New member since 01.07.2005: Serbia and Montenegro

EUROCONTROL was founded in 1960 as an international civil and military organisation dealing with air traffic control on a European level. Today it is a worldwide leader in pioneering advancement in ATM technology, operational procedures and system interoperability. [3]

The EUROCONTROL EXPERIMENTAL CENTRE (EEC), situated in Brétigny-sur-Orge near Paris, France, was established as the research and development arm of EUROCONTROL about 40 years ago. Its initial responsibilities were to carry out operational research and testing air traffic control (ATC) methods, to perform opera-
tional demonstrations of the validity of the ATC system proposed and to evaluate operationally and technically the equipment being developed for ATC systems. [2] The EEC was the first establishment in the world to perform a totally digital simulation for ATC. A real time simulation replicates the control room of an ATC centre and the ATC system behaviour as well as the behaviour of the aircraft in the designated airspace. The controller interacts with the system in the same way as with the operational environment and dialogs with “pseudo pilots” who receive the instructions of the controller and “fly” the simulated aircraft. The purpose of a real time simulation is to obtain air traffic controller validation of the new features being simulated and tested, such as new tools, new airspace design, new procedures and new air routes. It is important to fully validate such new features before they can be operationally implemented by the national air navigation service providers. [2]

Today, EEC’s mission is to carry out research and development in order to improve air traffic management in Europe. Real-time simulations are still an important activity but mainly used to serve research, as one of many tools to evaluate, analyse and validate new concepts. The environment is seen as an increasingly constraining factor on the aviation industry and its ability to grow because of the augmenting public awareness, its perceived effect on climate change and the introduction of more legislation and operational restrictions. The former general perception was that aviation environmental issues were basically concentrated around airports, such as engine noise and thus not an ATM issue. [2]

In consequence of the rise in air traffic, environmental effects are increasingly influencing all phases of flight. Particularly at high altitude, aviation is the only mode of transport. And therein becomes apparent the importance of air traffic management concerning environmental issues. ATM can reduce aviation environmental impact and its effect on climate change by allowing traffic to fly more direct and at more fuel efficient flight levels, which will reduce fuel consumption and thus aviation emissions. This is the one of the main core business activity of EEC’s business division SEE (Society, Economics and Environment), the group I could participate during my stay in France. The goal of SEE is to estimate the potential contribution of ATM to lower the environmental impact of aviation. Areas of research are e.g. noise, local air quality and global air quality.
3 Aircraft engine emissions

Aircraft emit gases and particles directly into the upper layers of the troposphere and the lower layers of the stratosphere, where they affect the chemical composition of the atmosphere. As consequence a change in concentration of the natural greenhouse gases like carbon dioxide ($CO_2$), ozone ($O_3$) and methane ($CH_4$) and an increased formation of condensation trails -the so called “contrails”- can be seen. Contrails are triggered by those particles which exist in the exhaust gas of an aircraft engine. At specific conditions these contrails can transform to cirrus clouds, which contribute to worldwide climate change as well. This underlines the importance of Particulate Matter. [1]

Besides the impact of aircraft emitted pollutants in the higher regions of the atmosphere as well emissions on ground like on and in the vicinity around airports are from major importance. Here, especially the impact of Particulate Matter on human health as discussed later has to be mentioned.

This chapter will give a basic overview on the combustion process in aircraft engines, the resulting combustion products, their effects on human health and the environment.

3.1 Introduction

Figure 2 shows qualitatively the trend of the temperature and the concentration of the reaction products during the combustion process for example in an aircraft engine. For reasons of simplicity humidity and sulphur in the fuel are neglected.

![Figure 2: Schematic trend of the combustion process [8]](image-url)
The combustion starts with the ignition and the subsequent degradation of kerosene. In the first phase of the combustion, mainly hydrocarbon-fractions and radicals like oxygen O, atomic hydrogen H and OH are formed, followed by a strong production of carbon monoxide CO. The temperature grows relatively slow while nitrogen oxide (NOₓ) concentration remains low. A strong increase in soot-concentration can be noticed because of the high fraction of fuel. [8]

The second phase of the combustion is dominated by the oxidation of carbon monoxide and the recombination of the hydrocarbon-fraction and radicals. Water and carbon monoxide are formed in a high degree. It can be seen, that the temperature increases strongly, which leads to an enhanced production of nitrogen oxides. Triggered by oxidation processes the soot concentration decreases at the same time. [8]

In the case of an ideal combustion, water, carbon dioxide and nitrogen oxides would be the only emissions. Soot concentration would drop to zero and carbon monoxide, hydrocarbons and the radicals would completely react to water and carbon dioxide. In reality (real combustion) flame extinguishing in combustor wall regions and the inflow and mixture of air (e.g. from combustor cooling), lead to a premature interruption of the combustion. As a consequence, some of those substances rest in the exhaust gas. [8]

The emitted combustion products can be divided into two groups, as there are the products of incomplete and complete combustion. The most important substances and their impact on human health and environment are discussed below. Figure 3 gives an overview of the different substances and their amount produced during the combustion of fossil fuels in aircraft engines.

![Combustion Products in the Engine Exhaust](image.png)

Figure 3: Combustion Products in the Engine Exhaust [8]
3.2 Products of complete combustion

Kerosene is a mixture of different hydrocarbons, thus carbon dioxide and water are formed during the “theoretical” complete combustion of air, when the process is assumed to be ideal. According to [8] the chemical process for the complete combustion of a fossil fuel – in this case kerosene – is defined as follows [8]:

\[
C_a H_b + \lambda \cdot n'_{(\text{air})} \cdot O_2 + n'_{N_2} \cdot N_2 + n'_{Ar} \cdot Ar + n'_{CO_2} \cdot CO_2 \Rightarrow n''_{CO_2} \cdot CO_2 + n''_{H_2O} \cdot H_2O + n''_{O_2} \cdot O_2 + n''_{C,H_6} \cdot C_a H_b + n''_{N_2} \cdot N_2 + n''_{Ar} \cdot Ar
\]

Where:
- a the number of carbon atoms per molecule of the considered fuel
- b the number of hydrogen atoms per molecule of the considered fuel
- n’ the amount of the considered substance before combustion [mol]
- n” the amount of the considered substance after combustion [mol]
- \( \lambda \) oxidation ratio
  \[
  \lambda = \frac{1}{\phi}
  \]
- \( \lambda = 1 \) if combustion is stoechiometric

\[
n'_{(\text{air})} = a + \frac{b}{4}, \quad n'_{N_2} = 3.727, \quad n'_{Ar} = 0.044, \quad n'_{CO_2} = 0.0014
\]

\[
n''_{CO_2} = \eta_{BK} \cdot \psi \cdot a + \lambda \cdot \left(a + \frac{b}{4}\right) \cdot 0.0014
\]

\[
n''_{H_2O} = \eta_{BK} \cdot \psi \cdot \frac{b}{2}, \quad n''_{C,H_6} = 1 - \eta_{BK} \cdot \psi
\]

\[
n''_{O_2} = (\lambda - \eta_{BK} \cdot \psi) \cdot \left(a + \frac{b}{4}\right), \quad n''_{N_2} = \lambda \cdot \left(a + \frac{b}{4}\right) \cdot 3.727
\]

\[
n''_{Ar} = \lambda \cdot \left(a + \frac{b}{4}\right) \cdot 0.044
\]

\[
\eta_{BK} \quad \text{the degree of burnout}
\]

\[
\eta_{BK} = 1 \quad \text{in the case of complete combustion}
\]

Most occurring hydrocarbon molecules in kerosene are those who have 12 C-atoms. As 1kg kerosene contains 0,14kg hydrogen and its mean molar mass is 167kg/kmol, the chemical formula can be simplified to \( C_{12}H_{23} \). [8]
Applying this simplification on equation (3.1) allows to estimate the amount of emitted water and carbon dioxide: the \textit{(ideal)} combustion of 1kg fuel results in 1,24kg water and 3,15kg carbon dioxide. In assumption of stoechiometric conditions ($\lambda = 1$), an amount of 14,665kg air is needed to burn 1kg fuel, which corresponds to an fuel-to-air-ratio of $\alpha = 0.0682$. [8]

\textbf{Water:}  
The natural cycle of water (H$_2$O) in the troposphere is relative simple, as there is a continual cycling between water, water vapour, clouds, precipitation and ground water. Water in the vaporous aggregate state is a natural greenhouse gas. It lets pass short-wave solar radiation almost unhindered through the atmosphere onto the earth’s surface and absorbs the long-wave thermal radiation reflected from the surface. Therefore it contributes to the warming of atmosphere. [1] 
The emissions of water through aviation and other modes of transports into the troposphere are rather small compared with those flows within the natural cycle. However, the effects of contrails and enhanced cirrus formation triggered by water emissions must be considered, because of the direct radiative effect and the consequent influence on climate. An increased emission of water into the stratosphere - often caused by supersonic aircraft – can lead to an increased occurrence stratospheric clouds and the perturbation of ozone concentration. [1]

\textbf{Carbon Dioxide:}  
Carbon dioxide (CO$_2$) is a natural greenhouse gas and is not a pollutant in the conventional sense, with toxic characteristics as it is a central product of any human, animal or plant metabolism. It is an essential substance that makes life on earth possible. An increase in atmospheric carbon dioxide concentration, however, has a negative effect on the global climate as it leads to global warming. [1]  
There are no important formation or destruction processes taking place in the atmosphere itself. Atmospheric sources and sinks occur in general on earth’s surface - except for the aviation sector. The effect of carbon dioxide on climate change is direct and basically depends on its persisting concentration in the atmosphere. CO$_2$ molecules absorb outgoing infrared radiation emitted by earth’s surface and the lower atmosphere. This is by the way the main function of a “greenhouse gas”. During the past 200 years an increase in atmospheric carbon dioxide concentration of 25-35\% was determined. This caused a global warming of the lower atmosphere – the troposphere - and, at the same time, a cooling of the stratosphere. [1]
Besides the described combustion products, there are also some smaller amounts of substances that are emitted even during the complete combustion of fossil fuels. The most important ones are nitrogen oxides and sulphur oxides.

**Nitrogen Oxides: [1][5]**
Nitrogen oxides (NO\textsubscript{x}) are formed through the combustion of nitrogen (N\textsubscript{2}) which naturally exists in the air. They are present throughout the atmosphere and influence the chemistry of the troposphere and stratosphere in a high degree, as they are responsible for the production and formation of ozone. Possible sources are the Oxidation of N\textsubscript{2}O\textsubscript{3}, lightning or fossil fuel combustion. In the upper troposphere and the lower stratosphere aircraft NO\textsubscript{x} emissions tend to cause an increasing amount of ozone with a strengthening of the greenhouse effect as consequence. This is the major issue of emitted NO\textsubscript{x} by subsonic aircraft. On the other hand, emissions of NO\textsubscript{x} at higher altitudes (ca. 18km) of supersonic aircraft show an opposite tendency, as ozone is deleted there.

Besides the above mentioned atmospheric effects, NO\textsubscript{x} damages the human respiratory system (bronchitis, susceptibility to respiratory diseases) as it causes the formation of ozone near ground.

**Sulfur Dioxides:**
Sulfur dioxide is a toxic gas mainly formed through the combustion of sulfurous fossil fuels. It is one reason for the “acid rain” as sulfur dioxide reacts with water to sulfuric acid. Inhaled by humans it can lead to headache and sickness, but also, depending on the concentration, to heavy damage to lungs and bronchia and even to the nucleic acid, the carrier of our genetic properties. [6]

**Other products:**
Other products, also emitted during the complete combustion of fuels are metals, ceramics and minerals, derived from abrasion of several components in the engine and matters persistent in the ambient air. As well as ions and radicals with very short lifetime, like atomic oxygen (O) and loaded molecules (“Chemi-ions\textsuperscript{1}”). [6]

\textsuperscript{1} Chemi-ions: Chemi-ions are charged molecule clusters formed during the combustion process [7]
### 3.3 Products of incomplete combustion

During the real combustion process the fuel is not burned completely, as aforementioned. As consequence also some further substances are emitted, like Carbon Monoxide, Hydrocarbons and soot. These products consist of carbon and hydrogen and weren't oxidized completely to carbon dioxide and water.

**Carbon Monoxides:**
Carbon monoxide (CO) is a colorless and odorless gas produced during the incomplete combustion of fossil fuels. In the atmosphere it is oxidized to carbon dioxide. This reaction is triggered by UV-radiation and heat. The most important aspect of CO is the fact that it is toxic, as it attaches on blood’s haemoglobin and disturbs the transport of oxygen, if inhaled, which can even lead to decease. [5]

**Hydrocarbons:**
Hydrocarbons (HC) describe any chemical compounds that consist only of Carbon (C) and Hydrogen (H), like e.g. Methane (CH₄). Major source of HC is the incomplete combustion of fossil fuel. Most HC in atmosphere are not dangerous, but some of them are critical because of their carcinogen properties. It is known that HC also contribute to the formation of tropospheric ozone. [5]

**Soot:**
Apart from these gaseous products, also solid substances are formed during the combustion process. These substances basically consist of non-oxidized black carbon in its solid phase, often referred to as “soot”. Soot represents the non-volatile fraction of Particulate Matter emitted by aircraft engines. This kind of pollutant will be treated in detail in the following chapters.
4 Particulate Matter (PM)

This chapter will give detailed information on Particulate Matter. Starting with some important definitions, the characteristics and properties like size distribution and chemical composition will be presented. Other aspects that will be treated among others are the particle formation processes, measurement techniques, effects of particles on health and the environment, the role of Particulate Matter in aircraft certification and national and international regulations.

4.1 Definitions

The term *Particulate Matter* (PM) describes all small particles of solid or liquid suspended in the air, that don’t sink to ground directly but stay in the atmosphere for a while. It is the international scientific description for all airborne particles. Their dimensions and their chemical composition define the physical and chemical characteristics of Particulate Matter. [10]

Particles can be divided in two categories: primary and secondary Particulate Matter. *Primary Particulate Matter* is broadly defined as particles that enter the atmosphere as a direct emission from a stack or an open source. It is not formed due to a chemical reaction that occurs once the matter has been emitted. In combustion these particles are formed at high temperatures in the combustion zone. They consist of inorganic or organic species or a combination of both. The finest particles are produced by gas-to-particle conversion that forms nuclei or nano-particles. These then grow by coagulation and surface growth. The process of particle formation is described in detail in chapter 4.4. [12][20]

*Secondary Particulate Matter* can be broadly defined as particles that form through chemical reactions in the ambient air well after dilution and condensation have occurred. This happens usually some distance downwind from the emission point and not directly in the combustion zone. [12]

In this study the main focus is on primary Particulate Matter formed in or directly after the combustion zone of aircraft engines.
4.2 Size distribution of particles

Particle size, often indexed by the aerodynamic diameter\(^2\) in \(\mu m\), is an important parameter to determine the properties and effects of particles suspended into the atmosphere. The atmospheric deposition rates of particles, and therefore, their residence times are strongly dependent on their size. Particle diameters also influence the deposition patterns of particles within the lung, when inhaled. As well light scattering is strongly dependent on the optical particles size, when suspended in the atmosphere. Therefore, the effects of atmospheric particles on visibility, radiative balance and climate are influenced by the size distribution. The diameters of atmospheric particles range from 1nm to 100\(\mu m\). Figure 4 shows a typical size distribution of particles in ambient air related to number, surface area and volume. [19]

\[N_h = 7.7 \times 10^4,\quad \text{DGN}_h = 0.013,\quad \sigma_{n_h} = 1.7\]

\[N_a = 1.3 \times 10^6,\quad \text{DGN}_a = 0.009,\quad \sigma_{n_a} = 2.03\]

\[N_c = 4.2,\quad \text{DGN}_c = 0.97,\quad \sigma_{n_c} = 2.15\]

\[S_n = 74,\quad \text{DGS}_n = 0.023\]

\[S_a = 535,\quad \text{DGS}_a = 0.19\]

\[S_c = 41,\quad \text{DGS}_c = 3.1\]

\[V_n = 0.33,\quad \text{DGV}_n = 0.031\]

\[V_a = 22,\quad \text{DGV}_a = 0.31\]

\[V_c = 29,\quad \text{DGV}_c = 5.7\]

---

\(^2\) Aerodynamic diameter: The aerodynamic diameter is defined as the diameter of a spherical particle with an equal gravitational settling velocity and a material density of \(1/g/cm^3\). [19]

---

Figure 4: Typical size distribution of particles in ambient air [19]
These distributions show that most of the particles are quite small, below 0.1\(\mu m\), whereas most of the particle volume, and therefore most of the mass is found in particles which are larger than 0.1\(\mu m\). As the surface area of particles with a size between 0.1 and 1\(\mu m\) is quite large in relation to the volume, these particles are of major interest as they can carry toxic substances.

Other averaged atmospheric size distributions are shown in Figure 5 and Figure 6. They show the number of particles and the volume as a function of particle diameter for typical rural, urban influenced rural, urban and freeway influenced urban aerosols. [19]
When looking at the volume based size distribution the typical three peaks can be seen, which are often referred to as “modes”. The entire size distribution can basically be characterized by a *trimodal model*. These modes are defined primarily in terms of their particle formation mechanism. [19]

Particles with a size greater than 1 to 3µm are called *coarse particle* or *coarse mode particles*. They are often caused by mechanical processes (abrasion, etc.). This kind of particles is not very hazardous for humans as they do not get so deep into the lungs when inhaled and hence they can be ejected e.g. by cough. 

Particles with a size from 0.1 to 1µm are called *accumulation mode particles*. These particles are mainly formed by condensation and coagulation (cp. chapter 4.3). 

Particles with diameters between 10 and 100nm are called *Aitken mode particles*. They result from the growth of smaller particles of nucleation from higher concentration of precursors (cp. chapter 4.3). Freshly formed particles with diameters below 10nm are called *nucleation mode particles*. They are produced during active nucleation events. These smaller particles are quite dangerous, as they can be deeply inhaled into the lungs and hence penetrate the human organism. [19]

Particles of nucleation and Aitken mode belong to ultra-fine particles. Together with the particles of accumulation mode they are part of the fine particles. The different modes are illustrated in Figure 7. [19]

---

**Figure 7:** Volume size distribution, measured in traffic, showing fine and coarse particles and the nuclei and accumulation modes of fine particles [19]
Another possibility to define particle size fraction arises from consideration of size-selective sampling. Size-selective sampling refers to the collection of particles below or within a specified aerodynamic size range. Size fractions are usually specified by the 50% cut point size. [19]

- **PM$_{10}$** refers to particles collected by a sampling device that collects 50% of 10µm particles. In other words, these are all those particles with a diameter less than 10µm.
- **PM$_{2.5}$** describes all particles collected by a sampling device that collects 50% of 2.5µm particles and rejects 50% of 2.5µm particles. Their diameter is less than 2.5µm.
- **PM$_{0.1}$** are those particles collected by a sampling device that collects 50% of 0.1µm particles. They are less than 0.1µm.

A mass-based size distribution of ambient particulate matter showing different modes of particles together with the fractions collected by size-selective samplers (PM$_x$) can be seen in Figure 8. This figure shows quite good, that PM$_{10}$ covers all particles with sizes less than 10µm, analogue for PM$_{2.5}$ and PM$_{0.1}$ (not shown).

![Figure 8: Ambient Particulate Matter showing fine-mode articles and coarse-mode particles and the fractions collected by size selective samplers [19]](image-url)
The dimension of PM affects in a high degree its retention period in the atmosphere as well as its way of transport. As consequence, very small particles are able to cover a distance of some thousand kilometres in a few days (e.g. Sahara-dust) [10]. In general, the smaller and lighter a particle is, the longer it will stay in the air. Larger particles (greater than 10µm in diameter) tend to settle to the ground by gravity in matter of hours whereas the smallest particles (less than 1µm) can stay in the atmosphere for weeks. They are removed by precipitation. [6]

As introductory mentioned particles influence the atmosphere in a negative way and therefore they are able to change the global climate. Particles suspended in higher regions of the atmosphere are known to forward cirrus cloud formation (catchword contrails). An increase in cirrus cloud coverage can disturb the natural equilibrium of the global climate because of a change in solar and terrestrial radiation. This underlines the importance of particles emitted by aviation.

The size of particles also determines where in the body the particle may come to rest if inhaled. Particles deposited in the airways and in the tracheobronchial region are removed rather efficiently by mechanical action, e.g. through cough or the mucous membrane escalator. There is evidence that the smallest particles are able to deposit in alveolar regions of the lung where they can pass into the blood and do damage on the human organism.

More detailed information concerning the impact of Particulate Matter on human health and the environment is given in chapters 4.8 and 4.9.

The aerosol\(^3\) emitted from the combustor of an aircraft engine mainly consists of primary particles forming inside the combustor and volatile condensation particles nucleating in the cooling exhaust gas from gaseous precursors (s. Figure 13). Typical aerosol size distributions in the diluted exhaust gas of two different aircraft engines are shown in Figure 9 and Figure 10. These values derive from in-flight measurements at cruise. The dashed, dotted and solid lines correspond to the lognormal size distributions for the modes of primary, agglomerated and total black carbon exhaust aerosol.

---

\(^3\) *Aerosol*: A collection of particles suspended in gas. The term refers to both the particles and the gas in which the particles are suspended. [6]
The soot exhaust aerosol of the older technology engine (Rolls-Royce / Snecma M45H Mk501) consists of a primary black carbon mode with a diameter of 0.035µm and a mode of coagulated BC particles with a peak near 0.15-0.16µm. The total
number density at the nozzle exit plane is $3 \cdot 10^7 \text{ cm}^{-3}$. In contrast, the more modern technology engine (CFM International CFM56-3B1) emits far smaller particles with a primary mode at $0.025 \mu \text{m}$ and a coagulated mode at $0.15 \mu \text{m}$, as well as fewer particles with a number-concentration of $9 \cdot 10^6 \text{ cm}^{-3}$. [23]

A number-based particle size distribution for idle and take-off thrust derived from measurements in the engine exhaust plume of the ATTAS experimental aircraft from DLR (Deutsches Zentrum für Luft- und Raumfahrt) is shown in Figure 11. The measurements were performed at a distance of about 200m behind the aircraft. [22] It can be seen, that the number-concentration of larger particles - the coagulated particles - grows with increasing thrust setting.

Figure 12: Volume-based particle size distribution of a CFM56 engine [33]
Figure 12 shows the measured volume based size-distribution of Particulate Matter emitted by a CFM56 engine at ground tests at 100% thrust, performed during a study (APEX) in the U.S. The figured diagram also corresponds to the mass-based size distribution of these particles. It can be seen that the volume or mass is dominated by the larger particles in the fine mode which are at the same time less numerous than those particles in the ultra-fine mode. It also becomes apparent that the non-volatile particles mainly contribute to the ultra-fine mode.

### 4.3 Volatile and non-volatile Particulate Matter

Particulate Matter consists of both non-volatile and volatile substances [13]. On one hand, aerosol emitted by a jet engine combustion chamber consists of carbonaceous, *non-volatile PM*. The most prevalent substance is soot, which is formed during the incomplete combustion process. But also dust, metal or ceramic particles belong to this group.

The other dominating particle species in the engine exhaust aerosol is *volatile PM*. It is formed by the nucleation from gaseous precursors, primarily sulphuric acid and organic compounds in the cooling exhaust gas downstream the combustor [4]. Also non-volatile combustion particles may be coated with volatile material [15].

![Schematic distribution of non-volatile (black) and volatile particles (red) [4]](image)

When precursor species condense, they first form a coating on the surface of the non-volatile particles. If the volatile particles are present in a high concentration, additional volatile particles are formed from the gas phase. This leads to an external mixture of coated non-volatile PM and volatile PM, which is schematically shown in Figure 13. [15]

The freshly emitted aerosol near the exit nozzle plane of the combustor consists only of non-volatile soot particles. The volatile particles are formed through nucleation and coagulation downstream. Therefore it is difficult to estimate the amount of produced
volatile PM within the exhaust gas, as this process depends on the concentration of sulphuric species in the exhaust gas and the distance to the combustor. [33]

But the formation of volatile Particulate Matter is not only limited on the exhaust gas. Anywhere, where there are sulphates or organic compounds in the atmosphere, these substances can cause the formation of non-volatile particles through nucleation and condensation effects (Chapter 4.3).

### 4.4 Formation of Particles

The description of the formation-process of Particulate Matter in this work is focused on those particles resulting from anthropogenic sources in particular in the aviation sector. Particles with natural origin are not treated in this study.

A schematic sketch of the particle generation process in a gas turbine is shown in Figure 14.

![Figure 14: Particle generation in a gas turbine](image)

The particle formation process can basically be divided into two phases: the formation of non-volatile (carbonaceous) particles inside the combustor during the combustion itself and the development of a volatile species and their partial attachment on the existing combustion particles, which basically happens in the cooling exhaust gas.

#### 4.4.1 Formation of non-volatile PM

Most combustion processes that involve hydrocarbons produce soot. This type of pollutant is the most important and most prevalent component of non-volatile Particulate Matter in the aviation sector, as it is in most other transport sectors [9]. As mentioned before, under ideal conditions, combustion of hydrocarbons only leads to carbon dioxide and water. But under practical conditions, because of flame extin-
guishing near the combustor walls and the inflow and mixture of air, the combustion is interrupted prematurely, so that a small amount of soot remains in the exhaust gas. In locally fuel-rich regions, the combustion, also referred to as pyrolysis of hydrocarbons, generates intermediate species and radicals that lead to the formation of soot particles. [16]

The soot formation process can be divided into five principal steps: soot particle inception or nucleation, surface growth, particle coagulation, particle oxidation and hygroscopic growth. In the following, a general description of the soot formation process is given. Figure 15 shows this process graphically.

1. Soot particle inception: [16]
Soot particle inception, or nucleation, stands for the formation of the smallest solid soot particles from the hydrocarbon molecules, which exist in the gas-phase. Soot particle inception can be understood as the link between the main gas-phase combustion zone chemistry and soot particle dynamics, as there happens the gas-to-particle conversion of the gaseous species.

There are different approaches regarding the process of inception. These basically differ in the key gaseous precursors that are assumed: polyacetylenes, ionic species, or polycyclic aromatic hydrocarbons (PAH). The PAH hypothesis is the most ac-
cepted pathway, which involves the formation and growth of aromatic species. The soot formation process starts with the development of the first aromatic ring (benzene) from small aliphatics. These small aliphatics are the “building blocks” of soot formation. Following the formation of first ring aromatics, they can grow to form large PAH. Some of these have stable structures at high temperature. These species allow more and more “building blocks” to be added. At a certain size, some PAH species begin to stick to each other when colliding, while individual PAHs increase in size at the same time. This combined growth by molecular chemical reactions and physical collisions leads to the appearance of solid particles. The mean diameter of the soot particles in this phase of formation lies between 1 and 2nm.

2. Soot surface growth: [16]
Surface growth is the addition of gas-phase materials to the already formed particles. Although still uncertain, it is generally accepted that the principal gas-phase species that reacts at the particle surface is acetylene.

3. Soot Particle Coagulation: [16]
After the first soot particles are formed, the physical process of collisions between these particles leads to the formation of larger soot particles. This is called soot particle coagulation, and occurs simultaneously with the surface growth process. Particle coagulation usually is classified into two distinct processes: coalescent collision and agglomeration. In coalescent collision, two particles come together and merge to form a single larger particle. In agglomeration, two particles stick to each other to form a chain-like structure but the identity of individual particles is maintained. During agglomeration, soot particles form large chain-like structures and are called soot aggregates, which consist of nearly spherical primary particles with relatively uniform diameter.

4. Soot Particle Oxidation: [16]
Soot particle oxidation counterbalances soot surfaces growth by changing the mass of solid soot particles back into gas-phase species. It is the only process that reduces the total amount of soot present in flames and hence the only mechanism that removes soot emission from the exhaust. Oxidation of soot primarily occurs as a result of surface reactions with oxygen molecules and OH to form CO and CO₂. During this phase of formation the soot particles have a size between 10 and 30nm.
5. Hygroscopic growth: [18]
After the soot particle coagulation and oxidation, a rise in particle size through hygroscopic growth is initialised. This basically happens outside the combustor in the engine exhaust jet plume. In this phase the soot particles can have a diameter between 1 and 10µm. If hygroscopic growth continues, this can lead to cloud drop formation. This can also be seen in Figure 16.

![Figure 16: Soot / particle formation process (2) [18]](image)

The formation of non-volatile Particulate Matter caused by mechanical processes, like the abrasion of tyres or brakes, is trivial and has no needs to be described in detail. Table 1 shows some amounts of suspended Particulate Matter caused by abrasion on aircraft as these values may play a role in the estimation of emitted PM especially in the vicinity around airports. There are also some particles produced through abrasion in the engine itself, but these can be neglected for now.

<table>
<thead>
<tr>
<th></th>
<th>suspended PM [(\frac{kg}{LTO})]</th>
<th>Fraction PM(_{10})</th>
<th>Fraction PM(_{2.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>tyre-abrasion</td>
<td>0.13</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td>break-abrasion</td>
<td>0.00003</td>
<td>0.86</td>
<td>0.63</td>
</tr>
<tr>
<td>runway-abrasion</td>
<td>0.73</td>
<td>0.19</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 1: Emission of non-volatile PM through abrasion in aviation [14]

---

*Hygroscopic growth:* The process of growth through the absorption of water. [6]
4.4.2 Formation of volatile PM

As described previously, the other important species in the jet engine combustion aerosol are volatile condensation particles which are formed by the nucleation from gaseous precursors, primarily sulphuric acid ($H_2SO_4$). The nucleation of volatile Particulate Matter in the cooling exhaust gas is triggered by the presence of condensable gases and by the aerosol surface density of the already existing combustion particles. The amount of produced volatile PM depends in a certain extend on the fuel sulphur content (FSC), as can be seen in Figure 17.

![Figure 17: Volatile PM concentration for different FSC [18]](image)

Volatile condensation particles can either condense on the surface of existing particles or can nucleate to form new particles, depending of the concentration of the gaseous precursors (see also Figure 13). Condensation leads to a change in particle size distribution because of particle growth caused by mass transfer from the gas phase to an existing particle, without changing the number of particles [20]. Nucleation is the formation of new particles directly from the gas phase, number and particle mass increase [20]. An important parameter in particle nucleation and in particle growth by condensation is the saturation ratio defined as the ratio of the partial pressure of a species to its equilibrium vapour pressure above a flat surface at a specified temperature. For either condensation or nucleation to occur, the species vapour pressure must exceed its equilibrium vapour pressure. If this happens, the species is considered condensable. [19]
4.5 Chemical composition of particles

According to a study performed by the U.S. Environment Protection Agency (EPA), fine particles basically consist of sulphate, ammonium, hydrogen ions, elemental carbon, metal and organic compounds. Crustal materials such as calcium, aluminium, silicon, magnesium and iron can often be found in the coarse particles. Some primary organic materials such as pollen, spores and plant and animal debris are in the coarse mode. Certain components such as potassium and nitrate may be found in both the fine and coarse particle modes, but they are emitted by different sources or mechanisms. Potassium in coarse particles comes from soil; Potassium in fine particles originates in emissions from burning. Nitrate in fine particles comes primarily from the reaction of gas-phase nitric acid with gas-phase ammonia forming particulate ammonium nitrate. Nitrate in coarse particles comes primarily from the reaction of gas-phase nitric acid with pre-existing coarse particles. [19]

An overview of the chemical composition of aviation-related Particulate Matter is shown in Figure 18.

![Figure 18: Chemical composition of PM](image)

4.6 Sources of PM

In general it is possible to distinguish between anthropogenic – caused by humans – and natural sources. Both natural and anthropogenic sources can be divided into primary and secondary sources.

Primary anthropogenic sources emit Particulate Matter directly into the atmosphere. These include static sources like combustion in power-plants for the production of energy, the burn of waste, coal and oil as well as other industrial processes. In terms of mobile sources, traffic is the dominating emittent of PM, caused by the combustion of fossil fuels. Especially Diesel-driven trucks and cars emit important amounts of...
soot-particles. Besides the traffic on rail and sea, aviation contributes to the world-
wide emissions of Particulate Matter in a not to neglecting degree, especially when
regarding the fact, that the aircraft is the only mode of transport at high altitudes.
Thereby I refer on the impact of Particulate Matter on the atmosphere in chapter
4.10.1. [12]
Apart from these combustion-caused fractions, also particles from the abrasion of
tyres, brakes and roads -referred to as diffuse emissions- play an important role. [12]

Secondary anthropogenic sources emit reactive gases like Sulphur Dioxides,
Nitrogen Oxides, Ammoniac and volatile Hydrocarbons, which convert through
complex chemical reactions to secondary particles in the atmosphere. The reaction-
products of these substances are ammonium sulphates and ammonium nitrates as
well as aldehydes and ketones as oxidation products of volatile Hydrocarbons. These
substances attach easily to already existing particles in the atmosphere and form
secondary aerosols. [12]
Main sources for secondary Particulate Matter are static combustion plants (energy,
industry: \( \text{SO}_2, \text{SO}_3, \text{NO}, \text{NO}_2 \)), agriculture (\( \text{NH}_3 \)), chemical industry and petro-
chemistry. [12]

Primary Particulate Matter with natural origin derive from volcanoes (without the
emissions of gases), sea-salt-spray in coastal regions, erosion of soil in dry regions,
wind-blown dust, forest-fires, pollen and even micro organisms. [12]

Secondary Particulate Matter with natural origin derive from methane in humid
regions and nitrous oxide \( (\text{N}_2\text{O}) \) caused by biological activities in the soil as well as
volcanic gases. [12]
### 4.7 Comparison of ambient Particulate Matter

A comparative summary of the most important properties of ambient Particulate Matter is given in Table 2.

<table>
<thead>
<tr>
<th>Fine</th>
<th>Ultrafine</th>
<th>Accumulation</th>
<th>Coarse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation Processes:</td>
<td>Combustion, high-temperature processes, and atmospheric reactions</td>
<td>Condensation</td>
<td>Break-up of large solids/droplets</td>
</tr>
<tr>
<td>Formed by:</td>
<td>Nucleation</td>
<td>Coagulation</td>
<td>Mechanical disruption (crushing, grinding, abrasion of surfaces)</td>
</tr>
<tr>
<td></td>
<td>Condensation</td>
<td></td>
<td>Evaporation of sprays</td>
</tr>
<tr>
<td></td>
<td>Coagulation</td>
<td></td>
<td>Suspension of dusts</td>
</tr>
<tr>
<td>Composed of:</td>
<td>Sulfate, elemental carbon, and hydrogen ions</td>
<td>Sulfate, nitrate, ammonium, and hydrogen ions</td>
<td>Suspended soil or street dust</td>
</tr>
<tr>
<td></td>
<td>Elemental carbon</td>
<td>Elemental carbon</td>
<td>Fly ash from uncontrolled combustion of coal, oil, and wood</td>
</tr>
<tr>
<td></td>
<td>Organic compounds</td>
<td>Large variety of organic compounds</td>
<td>Nitrites/chlorides/sulfates from HNO₃/HSO₃/SO₂ reactions with coarse particles</td>
</tr>
<tr>
<td></td>
<td>with very low saturation vapor pressure at ambient temperature</td>
<td>Metals, compounds of Pb, Cd, V, Ni, Cu, Zn, Mn, Fe, etc.</td>
<td>Oxides of crustal elements (Si, Al, Ti, Fe)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Particle-bound water</td>
<td>CaCO₃, CaSO₄, NaCl, sea salt</td>
</tr>
<tr>
<td>Solubility:</td>
<td>Probably less soluble than accumulation mode</td>
<td>Largely soluble, hygroscopic, and deliquescent</td>
<td>Largely insoluble and nonhygroscopic</td>
</tr>
<tr>
<td>Sources:</td>
<td>Combustion</td>
<td>Combustion of coal, oil, gasoline, diesel fuel, wood</td>
<td>Resuspension of industrial dust and soil tracked onto roads and streets</td>
</tr>
<tr>
<td></td>
<td>Atmospheric transformation of SO₂ and some organic compounds</td>
<td>Atmospheric transformation products of NOₓ, SOₓ, and organic compounds, including biogenic organic species (e.g., terpenes)</td>
<td>Suspension from disturbed soil (e.g., farming, mining, unpaved roads)</td>
</tr>
<tr>
<td></td>
<td>High-temperature processes</td>
<td>High-temperature processes, smelters, steel mills, etc.</td>
<td>Construction and demolition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Uncontrolled coal and oil combustion</td>
</tr>
<tr>
<td>Atmospheric half-life:</td>
<td>Minutes to hours</td>
<td>Days to weeks</td>
<td>Minutes to hours</td>
</tr>
<tr>
<td>Removal Processes:</td>
<td>Grows into accumulation mode</td>
<td>Forms cloud droplets and rains out</td>
<td>Dry deposition by fallout</td>
</tr>
<tr>
<td></td>
<td>Diffuses to raindrops</td>
<td></td>
<td>Scavenging by falling rain drops</td>
</tr>
<tr>
<td>Travel distance:</td>
<td>&lt; 1 to 10s of km</td>
<td>100s to 1000s of km</td>
<td>&lt; 1 to 10s of km (small size tail, 100s to 1000s in dust storms)</td>
</tr>
</tbody>
</table>

*Table 2: Comparison of ambient Particulate Matter [19]*
4.8 Particle Measurement Techniques

In the following an overview will be given on the existing techniques to determine the number, mass and size distribution of Particulate Matter.

4.8.1 Particle Counting Techniques

Condensation Particle Counter (CPC)

A method to determine the number of particles and the particle concentration in an aerosol is by using a Condensation Particle Counter (CPC), a condensation growth method, that is able to detect all particles with a diameter larger than 3nm [35]. The mode of operation can be described as followed (cp. Figure 19):

In a first step, the aerosol enters through an inlet and is saturated with butanol at a temperature of 35°C. The saturated particles enter into a condensator (10°C) where they act as a nucleation germ for the butanol that grows to droplets with a size of up to 10µm. These droplets pass through a ray of light which leads to a flashing light scattering. The number of flashes gives information on the number of droplets and thus the number of particles which formed the droplets. Using a flow meter it is as well possible to determine the particles’ number-concentration. The counting efficiency for particles larger than 100nm is higher than 95%. [34]

Figure 19: sketch of the functionality of a condensation particle counter (CPC) [34]
Optical Particle Counter (OPC)
This measurement instrument is similar to the condensation particle counter (CPC) as it uses an optical scattering method to determine the number of particles passing through a ray of light. The main difference is that the OPC does not feature a saturator and a condensing tube. That’s also the reason that OPC covers only particles with a size larger than 0.1 µm. [35]

Flame Ionization Detector (FID)
The flame ionization detector (FID) is commonly used to measure hydrocarbon in engine exhaust, but it can also be used to measure Particulate Matter. The presence of carbon particles results in spikes in the FID signal, giving the number density. The area under the spikes has been shown to correlate with mass concentration. [36]

4.8.2 Particle Size Measurement Techniques

Differential Mobility Analyser (DMA)
A method to determine particle size distribution via size selection is by using a differential mobility analyser (DMA) based on the electric mobility (electrical mobility method) of different-loaded particles. Particles are loaded electrically positive or negative. This means, that they accept or release none, one or more electron loads, depending on a balance distribution. The aerosol is lead into the boarder of a cylindrical laminar (particle-free) flow. Using a radial electric field, the loaded particles move towards the electrode depending on their electric mobility (cp. Figure 20). Those particles with the ‘whished’ mobility reach the inlet of an analysator; all other particles are deposited and filtered. Based on the electrical mobility a “mobility diameter” can be derived. This measurement method covers particles of a size range 10 to 200nm. [34][35]

Scanning Mobility Particle Sizer (SMPS)
It is possible to use DMA in combination with CPC, which is then called Scanning Mobility Particle Sizer (SMPS). A continuous variation of the electrical mobility via changing the voltage (DMA) and counting the growing particles with the CPC permits the determination of a number-based size distribution of the particles in the regarded aerosol. [34]

Differential Mobility Particle Sizer (DMPS)
The differential mobility particle sizer (DMPS) is as well a combination of DMA and CPC to measure the number concentration in the aerosol flow. [36]
4.8.3 Mass and Volume fraction measurement

Tapered element oscillating microbalance (TEOM)
The tapered element oscillating microbalance (TEOM) is a widely used device for measuring Particulate Matter mass in real time. The particles are collected on a filter that is attached to the vibrating element of a tapered element oscillating microbalance (Figure 21). The element vibrates at a precise frequency, which changes according to the mass of particles on the filter, allowing a direct determination of collected mass. This frequency can be monitored continuously to give a signal proportional to the total mass of the filter. Although the signal can be monitored with high temporal resolution, the sensitivity of the device is limited by the change in mass necessary to create a detectable change in oscillating frequency. [36][37]
But in practice, divergences occur because of the presence of semi volatile components of Particulate Matter. That’s why the TEOM pre-heats the air to 50°C prior to particle collection in order to drive off associated water and other components which might lead to inconsistent and variable mass measurements. The heating causes the loss of some semi volatile particle components. [37]
The sampling efficiency of TEOM is shown in Figure 22.

This measurement technique is commonly used to monitor Particulate Matter in urban areas [39].
Aethalometer
The Aethalometer is a device that uses a continuous filtration and optical transmission technique to measure the concentration of black carbon. It measures the light attenuation through a quartz filter matrix where the fibre filter is assumed to act as a perfect diffuse scattering matrix in which the light-absorbing particles are embedded. Two detectors measure the light transmission through the filter; one measures the light passing though the particle-blackened spot while the other measures the light passing through a particle-free reference part of the filter. The difference in measured light intensity allows the determination of attenuation and therefore the derivation of black carbon mass concentration. Using a filter tape that is automatically advanced to a clean section allows making continuous measurements (cp. Figure 23). [36][39]

![Figure 23: Magee Scientific Aethalometer](image)

Opacimeter
The opacity meter, also called opacimeter, measures the extinction of light as it traverses the exhaust plume. Because the amount of extinction is a function of both Particulate Matter volume fraction and the path length, the extinction coefficient defined by the Beer-Lambert law is typically used as the parameter to characterize smoke [36]. For demonstration, the schematic measuring setup of a diesel opacimeter is shown in Figure 24.
According to [41] the opacity is defined as the fraction of light transmitted from a source which is prevented from reaching the observer of instrument receiver, expressed in percent. The transmittance T is the fraction of light transmitted from a source, through a smoke-obscured path, which reaches the observer instrument receiver, expressed in percent.

![Figure 24: operation of a diesel opacimeter [41]](image)

"Beer-Lambert-Law" [41]:\[
T = \frac{\text{transmitted light}}{\text{incident light}} = e^{-KL}
\]

\[N = 100 \cdot (1 - e^{-KL})\]

where:
- \(K\) ... absorption coefficient (smoke density)
- \(L\) ... effective path length through the smoke [m]

The measurement of the transmission \(T\) allows determining the opacity \(N\). The resulting soot-concentration can be determined e.g. from tables given in [41]. An equation to calculate the soot concentration –also referred to as smoke density- in the exhaust gas is given in [66].:

\[
c_{\text{soot}} \left[ \frac{mg}{m^3} \right] = -K \cdot \frac{\rho}{L} \cdot \ln\left( \frac{l}{l_0} \right) \cdot 10^3
\]
where: \( \frac{I}{I_0} \) … transmission; the fraction of incident light transmitted

Laser-induced incandescence
Laser induced incandescence (LII) is based on the fact that soot particles absorb laser light and reach, during the laser pulse, a temperature well above the flame temperature. As a consequence they emit a black body radiation that can be easily detected with a CCD camera or a fast photo-detector. The signal intensity is then proportional to the soot volume fraction. It is also possible to get information on particles’ size distribution through the cooling behaviour after laser heat up, as smaller particles cool faster than larger ones. [42][43]

Photometer / Nephelometer
Both photometer and nephelometer are light scattering aerosol monitors that use the elastic scattering of light directly from the aerosol to estimate mass concentration. However, because absolute elastic scattering is sensitive to particle size, number and refractive index, many assumptions are needed to relate the measurements to a physical quantity. [36]

4.8.4 Surface area measurement

Epiphanimeter
The epiphanimeter is an instrument that measures the surface concentration of aerosol particles in both the nuclei and accumulation mode size ranges. It is most sensitive to particles in the accumulation mode, but measurements of particles between 20 and 90nm were performed successfully. In an epiphanimeter, aerosol is passed though a charging chamber where lead isotopes created from a decaying actinium source are attached to the particle surfaces. The particles are transported through a capillary to a collecting filter. It uses a surface barrier detector to measure the level of radioactivity of the particles collected on the filter. The amount of radioactivity is proportional to the particle’s Fuchs surface area and follows Fuchs theory of attachment of radioactive isotopes. [36][44]

Diffusion Charger (DC)
The diffusion charger (DC) uses a corona discharge to attach positive ions to the PM surface. The particles are collected on a filter, from which the measured current is proportional to the surface. [36]
Photoelectric aerosol sensor
The photoelectric aerosol sensor (PAS) uses ultraviolet light to photo electrically charge Particulate Matter by stripping of electrons. Because the propensity for a particle to become charged depends on its composition, this device has been used to selectively measure carbon-bound PAH. By the simultaneous use of a DC and a PAS it is also possible to distinguish between particles arising from different combustion processes. [36]

4.9 Aircraft engine certification and PM
To control aircraft pollution from aircraft around airports, the International Civil Aviation Organization (ICAO) established emission measurement procedures and standards for soot, unburned hydrocarbons, carbon monoxide and nitrogen oxides. The measurements of the exhaust emissions of a single engine are performed at the manufacturer’s test facilities as part of the certification process, in compliance with the requirements of ICAO international standards and recommended practices of Annex 16 to the convention on international aviation. [1][45]

To characterize the operational conditions of the aircraft engine within the environs of an airport, the so called landing and take off (LTO) cycle was defined (Figure 25).

![Figure 25: The ICAO landing and take off cycle][1]

The ICAO LTO-cycle basically consists of following operation modes:

- Taxi Out / Taxi In
- Take Off
- Climb Out (to 3000ft)
- Final Approach / Landing
Concerning the aircraft engine certification these operation modes are ‘simulated’ by typical thrust settings and durations corresponding to those modes [45].

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Thrust setting</th>
<th>time in mode [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-Off</td>
<td>100% $F_{00}$</td>
<td>0.7</td>
</tr>
<tr>
<td>Climb</td>
<td>85% $F_{00}$</td>
<td>2.2</td>
</tr>
<tr>
<td>Approach</td>
<td>30% $F_{00}$</td>
<td>4.0</td>
</tr>
<tr>
<td>Taxi / ground idle</td>
<td>7% $F_{00}$</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Soot emissions are measured with the Smoke Number (SN), the “dimensionless term quantifying smoke emission level based upon the staining of a filter by the reference mass of exhaust gas sample and rated on a scale of 0 to 100” [45]. The smoke measuring system as recommended by the ICAO is shown schematically in Figure 26.

![Figure 26: Smoke Analysis System [45]](image)

A defined volume flow, which shall be within the range of 12kg to 21kg of exhaust gas per square meter of filter, is taken from the exhaust gas by a sample probe and passed through a filter. The sample probe is positioned directly behind the engine’s nozzle inside the exhaust jet. The particles contained in the exhaust gas are collected by the filter which leads to a soiling and blackening of the filter material as
consequence. Particles with a diameter less than 300nm are mainly passed through while only the larger particles are collected. This fact reflects the relative weak accuracy of measurement as those particles with the highest number concentration are not considered well. The degree of attenuation of the filter before and after the test is analyzed with a reflectometer, an instrument conforming to the American National Standards Institute (ANSI) Standard No. PH2.17/1977 for diffuser reflection density. [45]

The Smoke Number can be calculated using the following formula according to [45]:

\[
SN = 100 \cdot \left(1 - \frac{R_s}{R_w}\right)
\]

Where \( R_w \) and \( R_s \) are the absolute reflectance of the clean filter material and the stained filter respectively.

Measured Smoke Numbers are listed in the *ICAO Engine Exhaust Emission Data Bank*\(^5\). There exist some different approaches to get from the ICAO Smoke Number to a concentration of soot in the exhaust jet. These will be treated in chapter 5.

### 4.10 Effects of Particulate Matter emissions

#### 4.10.1 Environmental effects of airborne particulate matter

##### 4.10.1.1 Effects of particles on the atmosphere and the global warming effect

Particulate Matter has a negative effect on the global atmosphere as it disturbs the equilibrium of terrestrial and solar radiation. There are two mechanisms by which aerosols may exert radiative forcing: the *direct effect*, whereby aerosol particles scatter and absorb solar and long wave radiation, and the *indirect effect*, whereby aerosol particles act as cloud condensation nuclei (CCN) and modify the physical and radiative properties of clouds. Additionally for aircraft, merely flying through certain meteorological environments can result in formation of contrails, which affect both solar and long wave radiation budgets. [1]

Aviation related particle emissions basically consist of soot (=black carbon), as already described before. Soot particles primarily absorb incident solar radiation

\(^5\) A digital version of the ICAO Engine Exhaust Emission Data Bank is available on the homepage of the UK Civil Aviation Authority (CAA): [http://www.caa.co.uk/](http://www.caa.co.uk/).
(sunlight) [1]. Particles suspended in lower layers of the atmosphere – the troposphere – lead to a positive radiative forcing (warming) through the absorption of solar radiation. Particles emitted in higher regions – the stratosphere – contribute a negative radiative forcing that is countered by induced positive long wave radiative forcing. Thus, radiative forcing from black carbon aerosols is sensitive to their location relative to the tropopause. As these particles are quite small in size, this effect can be neglected however [1][8].

On the other hand, indirect radiation effects can not be neglected. Particles emitted through aircraft engines into the atmosphere act as Cloud Condensation Nuclei around which cloud droplets are formed [8]. This was shown in Figure 16 (chapter 4.4.1). This effect can be seen in form of condensation trails, short “contrails”, or cirrus clouds. Contrails are visible line clouds that form from water emitted by aircraft flying in sufficiently cold air. Contrails form when the increase in relative humidity that occurs in the engine plume during mixing of the warm and moist exhaust gases with the colder ambient air reaches liquid saturation. The threshold temperature decreases with flight level and increases with ambient humidity. Modern aircraft with higher overall propulsion efficiency cause contrails at slightly lower altitude than older aircraft (Figure 27). Ice particles evaporate quickly and contrails remain short when forming in dry ambient air. The fractional global coverage by short contrails is less then 0.0001% and hence of no importance to the climate. Contrails persist, sometimes for hours, and grow when the ambient air is very humid with humidity above ice saturation. Ice particles in such persistent contrails grow by uptake of water from surrounding air. Contrails cause a mean radiative forcing at the top of the atmosphere, in particular during night and over warm and bright surfaces. They reduce both the solar radiation reaching the surface and the amount of long wave radiation leaving the earth to space. [7]

Particles cause contrails that trigger cirrus clouds in air masses which are sufficiently humid to let contrails spread but not humid enough to let cirrus form naturally. An increase in cirrus cloud coverage tends to warm the surface of the earth. Long-term observations of cloud frequencies and satellite data show an increase of the frequency or cover of cirrus clouds. The increases are large in particular in regions with high air traffic density. [7]

This indirect radiative effect caused by contrails and cirrus clouds is estimated with $0.02 \frac{W}{m^2}$ and respectively 0 to $0.04 \frac{W}{m^2}$. [8]

Figure 28 shows the direct (soot) and indirect (contrails, cirrus clouds) impact of aviation related Particulate Matter emissions on the radiative forcing compared to other emissions.
Figure 27: This figure shows how modern (more efficient) aircraft (left, A340) cause contrails while older ones (right, B707) don’t at the same altitude [7]

Figure 28: Radiative forcing through aviation (1992) [1]
4.10.1.2 Effects of ambient airborne particulate matter on vegetation and the natural ecosystem

As mentioned before, PM in ambient air is not a single pollutant but represents a heterogeneous mixture of particles differing in origin, size and chemical constituents. The effects of exposures to a given mass concentration of PM of particular size may lead to widely differing toxic responses.

The deposition of PM onto vegetation and soil, depending on its chemical composition, can produce direct or indirect responses within an ecosystem. The ecosystem response to pollutant deposition is a direct function of the level of sensitivity of the ecosystem and its ability to ameliorate resulting change. The stressors of greatest environmental significance among the particles are those containing nitrates and sulphates whose indirect effects occur primarily via their deposition onto the soil. Upon entering the soil environment, they can alter the ecological processes of energy flow and nutrient cycling, inhibit nutrient uptake, change ecosystem structure, and affect ecosystem biodiversity (catchword “food-chain”). The effects on the growth of plants resulting from the deposition of PM containing nitrates and sulphates and the acidifying effect are the most important environmentally. The deposition on surfaces of plants can have either physical or chemical effects. Particles transferred from the atmosphere to plant surface may cause direct effects if they reside on the leaf, twig or bark surface for an extended period. This can lead to a reduction of light transmission which causes a decrease in photosynthesis. Furthermore it increases the plants’ susceptibility to diseases. [19]

4.10.1.3 Effects of Particulate Matter on visibility

Visibility is defined as the degree to which the atmosphere is transparent to visible light and the clarity and colour fidelity of the atmosphere. Visual range is the farthest distance a black object can be distinguished against the horizontal sky. Visibility impairment is any humanly perceptible change in visibility. [19]

Airborne Particulate Matter degrades visibility by scattering and absorbing light. Theses optical properties can be well characterized in terms of a light extinction coefficient, which is the fractional attenuation of light per unit distance. The efficiency with which different particles attenuate light depends upon particle size. Fine particles (accumulation mode) are much more important causing visibility impairment than coarse mode particles. [19]
4.10.1.4 Effects of Particulate Matter on materials
The effects of Particulate Matter on materials are related to both aesthetic appeal and physical damage. Primarily carbonaceous compounds cause soiling of commonly used building materials and culturally important items, such as statutes and works of art. Physical damage from the dry deposition of air pollutants such as PM containing sulphates and nitrates, and the absorption or adsorption of corrosive agents on deposited particles also can result in the acceleration of naturally occurring weathering processes of man-made building and cultural materials. [19] A significant detrimental effect of particle pollution is the soiling of painted surfaces and other building materials. Soiling changes the reflectance of opaque materials and reduces the transmission of light through transparent materials. Soiling is a degradation process that requires remediation by cleaning or washing, and, depending on the soiled surface, repainting. On the other hand, sulphuric compounds of particles can enhance the process of metal corrosion and deteriorate stone and cements by converting calcium carbonate to calcium sulphate dihydrate (gypsum). [19]

4.10.2 Effect of Particulate Matter on human health
The effect of aviation related Particulate Matter emissions on human health is of importance especially in the vicinity of airports. PM can penetrate the human organism as they can be inhaled into the lungs where they are deposited and evolve their impact. The depth of particle intrusion into the respiratory system, and hence their impact on human health basically depend on their size. [25] Larger particles like PM<sub>10</sub> tend to be deposited in the upper parts of the respiratory system, in the tracheo-bronchial region, where they can be removed rather efficiently by mechanical action like cough or the so called mucous membrane escalator, the ‘cleaning system’ of our lungs. Therefore, these particles do not pose a too big threat to human health. But particles of smaller size, particularly those particles with an aerodynamic diameter of less then 2.5µm (PM<sub>2.5</sub>) are more dangerous because they can penetrate more deeply into the lung and may reach even the alveolar regions, where the interchange of oxygen takes place. [26] The different places of particle deposition are shown in Figure 29.
In general the impact of Particulate Matter on human health is not as important as e.g. the impact of smoking, but there is an impact. Short term effects are higher rates of decease and hospitalization mostly because of already existing diseases of the cardio-vascular system for older people. Other effects are an increase of symptoms like diseases of the respiratory system, like asthma or cough. Long-term effects are
known as a general increase of respiratory diseases, a higher mortality rate because of an increase of diseases in the cardio-vascular system. Another long-term effect is a higher risk of cancer, especially in lung-cancer, caused by a permanent exposition to diesel soot. [15]

Figure 29: Deposition of Particulate Matter in the human body [18]
As stated before, the primary “entry portal” for Particulate Matter into the human body is the lung. The interactions of these particles within the lining of the lung lead to immunologic responses that cause a wide range of pulmonary effects. These effects include lung injury, inflammation and changes in the resistance to infection or sensitivity to allergens. An exposure to Particulate Matter can cause an altering in respiratory rate and tidal volumes. Soluble components of PM may diffuse into the circulatory system and may be distributed systemically or may perhaps activate cells within the lung to secrete mediators that likewise can move throughout the body. [27] This can then lead to effects on the human cardio-vascular system, as shown in Figure 30.

There is a growing number of reports associating PM with cardiac death, morbidity or altered cardiac function. According to U.S. EPA one possible way how PM influences the cardio-vascular system is via neural mechanisms involving the autonomic nervous system. PM may act via direct pulmonary irritant reflexes in the airways or through reflexes activated during pulmonary inflammation. This effect could affect cardiac function via nervous system networks that operate to protect the lung. Inflammatory changes in the heart could impair normal function in an already diseased or stressed heart. Also altered blood viscosity and circulation of cells are reported, which both are reasons for an increased risk of cardiac events. [27]
In the following the most important short- and long-time effects of an increased exposition of humans to Particulate Matter are described.

**4.10.2.1 Short term effects**

**Effects of an increase in PM concentration on mortality:**
According to a study performed in the United Stated (National Mortality, Morbidity and Air Pollution Study) based upon the 20 largest American cities, an $10 \mu g/m^3$ increase of $PM_{10}$ in the ambient air leads to an increase of daily overall mortality of 0.51% on the following day. This value was corrected later to 0.21% after revising the applied calculation-method.

A European study (APHEA) says that such an increase in concentration may lead to an increase in mortality of 0.4 to 0.6%. An increase in $PM_{2.5}$ of $10 \mu g/m^3$ may cause a rise in daily overall mortality of 0.34 to 0.57% according to a study performed on the West Midlands, U.K. and Erfurt, Germany. [28]

An increase of the daily mortality caused by cardio-respiratory diseases can be found at 0.68% and respectively 0.31% if $PM_{10}$ concentration rises, according to NMMAPS before and after the revision of the applied calculation method. [28]

**Effects of an increase in PM concentration in hospitality:**
The European study APEA registered an increase in hospitalisation because of cardio-vascular diseases of about 0.5% when the $PM_{10}$ concentration raised by $10 \mu g/m^3$ the day before and the cut-off day, as well as an increase of hospitalisation because of respiratory diseases from older people, and because of asthma from younger people and children of about 1% [29]. Source [28] mentions an increase of hospitalisation rate of 0.7% because of respiratory problems from people older then 65 years.

Typical short-term disturbances caused by an increased exposure to Particulate matter are: cough, throat rasping, bronchitis, asthma, higher pulse rate, heart rate variability, higher plasma viscosity, dyspnoea or degradation of lung functionality. The occurrence of these symptoms depends on the age and the state of health of each person. As a consequence an increase in the use of medicaments of 3.4% for people suffering from asthma was registered [30].
4.10.2.2 Long term effects

Because long term exposure to PM results in a substantial reduction in life expectancy, the long-term effects clearly have greater significance to public health then the short-term effects. \( \text{PM}_{2.5} \) shows the strongest association with mortality indicating a 4% increase in the risk of deaths from all causes per \( 10 \mu g/m^3 \) increase in long-term \( \text{PM}_{2.5} \) concentration [31]. Separated on death caused from cardiovascular diseases and lung cancer, the long-term increase in fine particle concentration led to and increase in mortality of 6% respectively 8% [31].

A long-term increase in \( \text{PM}_{10} \) of \( 10 \mu g/m^3 \) concentration may lead to a 30% higher risk to bronchitis in children and a higher risk of overall mortality of 10% for adults [32].

The effects related to long-term exposure include: increases in lower respiratory symptoms and chronic obstructive pulmonary disease, reductions in lung function in children and adults, as well as a reduction in life expectancy, due mainly to cardio-pulmonary mortality and lung cancer. [26]

4.11 Aviation related projects and research activities on Particulate Matter

There have been several projects dealing with Particulate Matter in the recent year. The most important ones will be presented in the following.

Concorde encounter (8 Oct. 1994)
The Concorde wake encounter was quasi the first experiment providing particle emission indices (unit: number per kg) for volatile and non-volatile aerosol particles in flight. The measurements of the emissions of the Concorde – equipped with Olympus 593 engines - were performed with the stratospheric research aircraft ER-2. [46]

SULFUR I-VII (1994-1999) [47]
The series of SULFUR experiments, initiated and coordinated by DLR, was performed to learn about the aerosol particle and contrail formation properties of an aircraft exhaust plume for different fuel sulphur contents, flight conditions and aircraft. The most important questions were [47]:
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

- How many soot particles are formed per mass unit of burned fuel and how large are these particles?
- How many volatile particles are formed per mass of burned fuel?
- What is the impact of fuel sulphur on contrail formation?
- How important is the FSC for volatile aerosol formation, soot activation and contrail ice crystal formation?

The experiments consisted of 10 flights with measurements performed in the young exhaust plume of various aircraft at separation distances varying from 25m to about 5km. Also ground measurements were done during SULFUR III-VI. The measurements inside and outside the aircraft plumes were performed on board the Falcon Aircraft from DLR, the ground experiments were done to measure particles and particle precursors close to the jet engine exit. [47]

Main aim of SULFUR I experiment was the visual observation of contrails and contrail formation. To see the influences of sulfur emissions on the nucleation of gaseous precursors, the contrail formation from the ATTAS experimental aircraft (DLR) was investigated using fuels with different fuel sulfur contents (FSC) on the two engines during the same flight. Contrail formation was then observed visually from another aircraft following at close distance. It could be seen, that short contrails form about 30m behind the engines, but no significant difference in the formation of contrails from the two engines was noticed. However, important knowledge on the contrail formation, like on the presumed conditions were achieved. [47]

The SULFUR II experiment was performed to cover larger FSC values and to measure the properties of particles formed depending on the FSC. The measurements were made with the ATTAS aircraft - with the possibility to use two different FSC’s for both engines at the same time - and the Falcon aircraft for observation and measurement. Most important results and conclusions from SULFUR II can be described as followed [47]: The fuel sulfur content has a measurable influence on the particle properties and contrail formation. The exhaust plume – the contrail- was already visible at ambient temperatures 5K cooler than the natural threshold temperature for contrail formation. The contrail remained visible at slightly lower altitude (25-50m) and higher temperatures (0.2-0.4K) when descending through the level of contrail onset. The higher FSC caused a larger optical thickness of the contrail. Particle measurements at low FSC indicate that the number of particles larger than 7nm measured in the plume originated primarily from emitted soot particles. An increase of the FSC by a factor of 30% led to an increase of particle number-concentration above 7nm by 25% and for particles above 18nm by 50%. [47]
During SULFUR III ground based measurements were performed to insure that the differences measured between the left and right engine exhaust plume originates from different FSC and are not caused by engine differences. [47]

In order to generalize the results to other aircraft the SULFUR IV experiment was launched. The Falcon aircraft was used to perform measurements in the young exhaust plume of an Airbus A310 at cruise and behind the ATTAS, with refined instruments. Using new knowledge on the nature of wake vortex formation, very close approaches (up to 25m) of the Falcon to the ATTAS and the Airbus aircraft were possible, as there are some positions within the vortex where steady flight conditions are possible. [45]

Main target of SULFUR V and SULFUR VI was to detect ultra-fine aerosols, ions and sulfuric acid and the composition and size distribution of ultra-fine particles and ions. SULFUR VII concentrates on the influence of engine technology and hence the engines’ efficiency on contrails and particles. In this experiment, contrail formation was observed behind two four-engine jet (A340, B707) aircraft with different engines flying wing by wing. The result is that there is an altitude range, in which the aircraft with high engine efficiency causes contrails while the other one with lower engine efficiency causes none. This was already mentioned before (Figure 27). Old engines emit more aerosols by mass, but the modern engines contribute a larger number, especially ultra-fine particle. [47]

**SNIF I-III + SUCCESS**

During the project SNIF (Subsonic Assessment Near-Field Interactions Field) particle emissions have been characterized for engines on several aircraft: a Boeing 737 equipped with PW JT8D engines, a Boeing B757 equipped with RR RB-211 engines and a T-38. The measurements were made in conjunction with a near field interaction study employing a ground-based LIDAR\(^6\) to explore the flow fields of the individual exhaust plumes for the engines of the B737. The B757 sampled under the project SNIF was later used as an emission source that was sampled by an instrumented NASA DC-8 under the project SUCCESS (Subsonic Aircraft Contrail and Cloud Effects Special Study). [48]

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\(^6\) LIDAR (light detection and ranging; laser imaging detection and ranging) is a technology to determine the distance to an object of surface using laser impulses [6]
The primary objectives of the project SUCCES was to study the effects of jet emissions on the atmosphere. Other objectives were: [48]

- the search for particulate signatures of air traffic emissions
- the characterization of the extent to which the soot particulates become coated with volatile materials such as sulfates
- the determination of the effective emission indices for the particulate component of engine exhaust in both the near and far field of aircraft exhaust plumes
- the particulate component of aircraft emissions as a function of ambient conditions
- the examination of the role of soot or volatile particle emissions in contrail formation
- the characterization of background levels of particulate matter concentrations in the operational regions

The most important results of these studies can be summarized as followed: the increased fuel sulfur content caused an increase in both volatile and non-volatile particle species; the ground based and airborne size distributions were found to be roughly similar, with the airborne samples showing some increased concentrations at the small and large ends of the size spectrum; variations in particle concentration and size distribution were observed with changing engine operation conditions, e.g. thrust, and between different engines of the same type; a tendency was noticed, that cleaner and more efficient engines produce more smaller particles. [48]

The overall objectives of the projects POLINAT I+II *(Pollution from Aircraft Emissions in the North Atlantic Flight Corridor)* were to determine by measurements and analysis the relative contribution from air traffic exhaust emissions to the composition of the lower stratosphere and upper troposphere at altitudes between 9 and 13km within the flight corridor over the North Atlantic, and to assess the effects of air traffic emissions in that region in relation to clean background and pollutant concentrations from various sources and to analyze their importance for changes, oxidizing capacity, aerosols and clouds. [49]
The observations of the non-volatile, soot-based particles in the upper troposphere and lower stratosphere, through altitude profiling, showed the presence of particles in the commonly used flight altitudes. The particle concentration and size distribution data was used to investigate the southern extend of the north Atlantic flight corridor. Vertical and horizontal profiles of the corridor were taken, which showed a time dependent enhancement of particulates within the corridor, which also correlated with
the periodicity for the air traffic. An enhancement of nonvolatile aerosol at corridor altitudes by a factor of 3.6 was noticed. [50]

**PATZI I+II (7/2000-6/2003)**

PATZI (Particles and Cirrus Clouds, Ger.: “Partikel und Zirren”) is a national project funded by DLR (German Aerospace Center) and is supported by the Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF). The main goal of PAZI is to better understand the formation of the ice phase in cirrus clouds from natural and anthropogenic aerosols and to improve microphysical and optical parameterizations of cirrus clouds in global models. This will allow to determine the impact of aviation soot-induced cirrus and contrail cirrus relative to cirrus formed on particles from other anthropogenic and natural sources and to compare the climate impact from aviation with the climate impact caused by other atmospheric changes. Another point is to develop means to reduce the aviation impact through changes in engine technology or air traffic management. [51]

This project consisted of several work packages. An important one dealt with the soot emissions and the aerosol precursors. Main targets were to study and understand the soot formation process and the prediction of global and fleet-averaged aerosol emission indices. For this, measurements were carried out in laboratory flames, behind real jet engines and segment of combustors and in DLR’s high pressure combustor test facility in Stuttgart, Germany. These measurements allowed characterizing the exhaust gas and the aerosol’s chemical composition as well as its size distribution. Furthermore an empirical model to estimate mass and number emission indices, size distributions, and total surface area concentrations of soot particles emitted by aircraft engines in flight conditions has been developed. Other work packages dealt with the ice formation in the atmosphere, measurements and modeling aerosols and cirrus clouds. [52]

**INCA (01/2001-01/2004) [53][54]**

The project’s acronym stands for “Interhemispheric differences in cirrus properties from anthropogenic emissions” and combines the work of several European universities and research centres, like the Stockholm University, DLR, University Blaise Pascal, Centre National de la Recherche Scientifique, University of Helsinki and the Norsk institutt for luftforskning. Main objective is to determine the difference in cirrus cloud properties on both hemispheres, which are of importance for climate and ozone distribution in the upper troposphere and lower stratosphere, in air masses with low and high aerosol loading.

The results drawn from the INCA project can be summarised in two major topics: The levels of pollution in the tropopause region of the southern and northern hemisphere
mid-latitudes are distinctly different, as the northern hemisphere shows several times higher loading of trace gases and aerosols. The relative humidity associated with cirrus clouds and the fraction of non-volatile particles found in crystals is higher in the southern hemisphere, the ice crystals are fewer and larger in the southern hemisphere.

The European project PartEmis (Measurement and prediction of emissions of aerosols and gaseous precursors from gas turbine engines) is focussed on the characterization and quantification of exhaust emissions from a gas turbine engine, which was composed of a combustor and a unit to simulate a three-shaft turbine section (Hot End Simulator, HES). Among others, aerosol properties were measured like the mass and number concentration, size distribution, mixing state, thermal stability of internally mixed particles, hygroscopicity, cloud condensation nuclei (CCN) activation potential, and the chemical composition. [21]
Some of the results in PartEmis found their way into this thesis, like e.g. concerning the size distribution and formation of aviation related Particulate Matter.

U.S. Particulate Matter National Roadmap [57]
The United States Particulate Matter National Roadmap was launched to create a unified regulatory research and development roadmap to understand and quantify aircraft particulate emissions. It is driven by the fact that there are still gaps in the knowledge concerning the impact of PM on health and environment. The roadmap is divided into five product groups: Measurement methodologies development (NASA, Aerodyne Research), technology development (NASA, PW), database development (UMR, FAA), impact assessment (PARTNER), and policy analysis (FAA). Within this Roadmap, the Centre of Excellence PARTNER and the APEX project play an important role in the research on PM.

PARTNER CoE
“The Partnership for Air Transportation Noise and Emission Reduction” (PARTNER) is the Center of Excellence (COE) for Aircraft Noise and Aviation Emissions Mitigation. It was established in September 2003 to forward technical and operational capabilities enabling quieter and cleaner aircraft, and is a product group for the impact assessment in the Particulate Matter National Roadmap. The partnership is co-sponsored by the U.S. Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA) and Transport Canada. [55][57]
Among others, PARTNER deals with the measurement, metrics and health effects of aviation related emissions. Participants of this project are: Boise State, Florida
International University, Massachusetts Institute of Technology (MIT), Stanford University, University of Central Florida, University of Missouri-Rolla, Aerodyne Research, Boeing, General Electric, Pratt and Whitney and Rolls Royce. The main objective is to characterize the emissions, both particles and condensable gaseous species from aircraft and airports through measurements, to model the microphysical processes associated with particle formation and to determine the health effects of emissions. PARTNER performed measurements of emission indices for both volatile and non-volatile Particulate Matter for several aircraft types with the objective to replace the Smoke Number in the ICAO emission database by an emission index for both types of PM. Until now, the emission indices for following aircraft were established: B727, B737, B747, B757, B767, B777, A319/320/321, DC9, DC10, MD80, MD11, L1011, B717, and Embraer ERJ145. Detailed measurement results will be published soon, a general overview on the results is shown in Figure 39 in chapter 5.2.2. [55][56]

APEX

The project APEX (Aircraft Particle Emissions eXperiment) belongs to the U.S. Roadmap's product group “database development”. Main objective of APEX is to characterize particle and trace gas precursor species from the NASA aircraft DC-8 equipped with a CFM56-2C1 engine at the engine exit plane as well as at selected downstream locations to advance the understanding of particles emissions and their evolution in the atmosphere from a current in-service turbofan engine. The measurements took place on Edwards AFB, CA, USA between April 15 and April 30 2004. Participants of these projects are: NASA, EPA, FAA, DOD, GE, PW, PW, ARI, MIT, PM, UCR, UMR. The project is sponsored by NASA, EPA and DOD. [58]

4.12 National and International Regulations and Standards on Particulate Matter Emission

Standards and recommended practices given by the ICAO for the certification of aircraft engine emissions: [59]

The International Civil Aviation Organisation (ICAO) composed standards and recommended practices for the certification of aircraft engine emissions. These can be found in ANNEX16 “Environmental Protection" Volume II – Aircraft Engine Emissions”. Apart from unburned hydrocarbons, carbon monoxide and nitrogen oxides, smoke or soot is also controlled for the certification of aircraft engines.
The smoke emissions are measured and reported in terms of the Smoke Number (SN) for the operating modes Take-off, climb, approach and taxi / ground idle with the corresponding thrust-settings of 100%, 85% 30% and respectively 7% of rated thrust (cp. Chapter 4.9). These standards must be applied to all engines whose date of manufacture is on and after 1 January 1983. The value of the measured Smoke Number of any engine and any thrust-setting shall not exceed the level determined from the following formula:

\[ SN_{\text{regulatory}} = 83.6 \cdot (F_{00})^{-0.274} \]

\[ \text{...or a value of 50 whichever is lower. This is applied for both subsonic and supersonic aircraft.} \]

This is at the same time the only regulatory aspect concerning Particulate Matter emissions from aircraft. All other regulations rely on the pollution of the ambient air to control particle concentration in urban areas.

**EU-guideline 1999/30/EG of 22 April 1999:** [11]

On April 22nd 1999 the Council of the European Union passed a guideline (1999/30/EC) relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, Particulate Matter (PM\(_{10}\)) and lead in ambient air.

Main objectives of this directive is to determine limit values and thresholds for the concentration of Particulate Matter – especially in urban areas -, to judge those concentrations by means of uniform methods and criteria and to conserve air quality where it’s good and to ameliorate it where it’s not the case in regard to Particulate Matter and other pollutants. The directives become effective on January 1\(^{st}\) 2005 and are carried out in two steps. The limit values for PM\(_{10}\) concentration in ambient air are given in Table 3. The annual limit for Particulate Matter in ambient air is 40\(\mu g/m^3\) in the first stage and 20\(\mu g/m^3\) in the second stage. The 24h limit of 50\(\mu g/m^3\) (25\(\mu g/m^3\)) shall not be exceeded more than 35 (7) times a year in the first (second) stage. Until now many cities exceeded these limits in a high degree, what actually lead to discussions to probably increase the limits or to postpone the date of effectiveness.
### Table 3: Limit values for Particulate Matter $PM_{10}$ [11]

<table>
<thead>
<tr>
<th>Averaging period</th>
<th>Limit value</th>
<th>Mass of tolerance</th>
<th>Date by which limit value is to be met</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STAGE 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. 24-hour limit value for the protection of human health</td>
<td>24 hours</td>
<td>$59 , \mu g/m^3 , PM_{10}$ not to be exceeded more than 35 times a calendar year</td>
<td>30% on the entry into force of this Directive, reducing on 1 January 2005 and every 12 months thereafter by equal annual percentages to reach 6% by 1 January 2005</td>
</tr>
<tr>
<td>2. Annual limit value for the protection of human health</td>
<td>Calendar year</td>
<td>$40 , \mu g/m^3 , PM_{10}$</td>
<td>20% on the entry into force of this Directive, reducing on 1 January 2005 and every 12 months thereafter by equal annual percentages to reach 6% by 1 January 2005</td>
</tr>
<tr>
<td><strong>STAGE 2(*)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. 24-hour limit value for the protection of human health</td>
<td>24 hours</td>
<td>$59 , \mu g/m^3 , PM_{10}$ not to be exceeded more than 7 times a calendar year</td>
<td>To be derived from data and to be equivalent to the Stage 1 limit value</td>
</tr>
<tr>
<td>2. Annual limit value for the protection of human health</td>
<td>Calendar year</td>
<td>$20 , \mu g/m^3 , PM_{10}$</td>
<td>50% on 1 January 2005 reducing every 12 months thereafter by equal annual percentages to reach 0% by 1 January 2010</td>
</tr>
</tbody>
</table>

(*) Indicative limit values to be reviewed in the light of further information on health and environmental effects, technical feasibility and experience in the application of Stage 1 limit values in the Member States.

NAAQS (National Ambient Air Quality Standards) (USA)

The U.S. Environmental Protection Agency (EPA) has established the National Ambient Air Quality Standards (NAAQS) within the Clean Air Act (1990) for different air pollutants like ozone, lead, carbon monoxide, sulfur dioxide, nitrogen dioxide and Particulate Matter. Main objective of these standards are to protect people and the environment from an excessive exposure to pollution. The NAAQS are shown in Table 4. There are two types of national air quality standards. The primary standards are to set limits to protect public health, including the health of sensitive populations such as asthmatics, children and the elderly. The secondary standards set limits to protect public welfare, including protection against decreased visibility, damage to animals, vegetation and buildings. [60]
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide</td>
<td>9 ppm</td>
<td>8-hour</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>35 ppm</td>
<td>1-hour</td>
<td>None</td>
</tr>
<tr>
<td>Lead</td>
<td>1.5 µg/m³</td>
<td>Quarterly Average</td>
<td>Same as Primary</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>0.053 ppm</td>
<td>Annual (Arithmetic Mean)</td>
<td>Same as Primary</td>
</tr>
<tr>
<td>Particulate Matter (PM$_{10}$)</td>
<td>50 µg/m³</td>
<td>Annual$^7$ (Arith. Mean)</td>
<td>Same as Primary</td>
</tr>
<tr>
<td></td>
<td>150 µg/m³</td>
<td>24-hour$^8$</td>
<td></td>
</tr>
<tr>
<td>Particulate Matter (PM$_{2.5}$)</td>
<td>15.0 µg/m³</td>
<td>Annual$^9$ (Arith. Mean)</td>
<td>Same as Primary</td>
</tr>
<tr>
<td></td>
<td>65 µg/m³</td>
<td>24-hour$^{10}$</td>
<td></td>
</tr>
<tr>
<td>Ozone</td>
<td>0.08 ppm</td>
<td>8-hour</td>
<td>Same as Primary</td>
</tr>
<tr>
<td>Sulfur Oxides</td>
<td>0.03 ppm</td>
<td>Annual (Arithmetic Mean)</td>
<td>-----</td>
</tr>
<tr>
<td></td>
<td>0.14 ppm</td>
<td>24-hour</td>
<td>-----</td>
</tr>
<tr>
<td></td>
<td>-----</td>
<td>3-hour</td>
<td>0.5 ppm</td>
</tr>
</tbody>
</table>

**Table 4: NAAQS [60]**

$^7$ To attain this standard, the 3-year average of the weighted annual mean PM$_{10}$ concentration at each monitor within an area must not exceed 50 µg/m³.

$^8$ Not to be exceeded more than once per year

$^9$ To attain this standard, the 3-year average of the weighted annual mean PM$_{2.5}$ concentration at each monitor within an area must not exceed 15 µg/m³.

$^{10}$ To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 65 µg/m³.
Other international regulations:
The following tables (Table 5, Table 6, Table 7) show some further international
regulations on Particulate Matter.

<table>
<thead>
<tr>
<th>Country</th>
<th>Aerosol</th>
<th>Level (µg m⁻³)</th>
<th>Averaging period</th>
<th>Guideline type</th>
<th>Date of implementation</th>
<th>Relevant law</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>TPM</td>
<td>150</td>
<td>1 month</td>
<td>not to be exceeded more than once per year</td>
<td>16-Apr-73</td>
<td>Ley 20.284</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>TPM</td>
<td>260</td>
<td>24 hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TPM</td>
<td>75</td>
<td>Annual</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>150</td>
<td>24 hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>50</td>
<td>Annual</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolivia</td>
<td>TPM</td>
<td>240</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td></td>
<td></td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>TPM</td>
<td>80</td>
<td>Annual</td>
<td></td>
<td></td>
<td></td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>150</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td></td>
<td></td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>50</td>
<td>Annual</td>
<td></td>
<td></td>
<td></td>
<td>61</td>
</tr>
<tr>
<td>Brazil</td>
<td>TPM</td>
<td>260</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td>22-Jun-78</td>
<td>Resolución No. 1215</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>TPM</td>
<td>75</td>
<td>Annual</td>
<td></td>
<td>22-Jun-78</td>
<td>Resolución No. 1215</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>150</td>
<td>24 hours</td>
<td>24-hr standard not to be exceeded by the annual 98th percentile</td>
<td>25-May-98</td>
<td>Decreto Supremo No 59/98</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>50</td>
<td>Annual</td>
<td></td>
<td></td>
<td></td>
<td>61</td>
</tr>
<tr>
<td>China¹</td>
<td>TPM</td>
<td>120 (i), 300 (ii), 500 (iii)</td>
<td>24 hours</td>
<td>Jan-96</td>
<td>GB 3095-1996</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TPM</td>
<td>80 (i), 200 (ii), 300 (iii)</td>
<td>Annual</td>
<td>Jan-96</td>
<td>GB 3095-1996</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>50 (i), 150 (ii), 250 (iii)</td>
<td>24 hours</td>
<td>Jan-96</td>
<td>GB 3095-1996</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>40 (i), 100 (ii), 150 (iii)</td>
<td>Annual</td>
<td>Jan-96</td>
<td>GB 3095-1996</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Colombia</td>
<td>TPM</td>
<td>400</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td>11-Jan-82</td>
<td>Decreto No. 2</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>TPM</td>
<td>100</td>
<td>Annual</td>
<td></td>
<td>11-Jan-82</td>
<td>Decreto No. 2</td>
<td>61</td>
</tr>
</tbody>
</table>

(i) Sensitive areas of special protection; (ii) typical urban and rural areas and (iii) special industrial areas.

Table 5: International standards on PM (1)
## Aircraft Particulate Matter Emission Estimation through all Phases of Flight

<table>
<thead>
<tr>
<th>Country</th>
<th>Aerosol</th>
<th>Level (µg m⁻³)</th>
<th>Averaging period</th>
<th>Guideline type</th>
<th>Date of implementation</th>
<th>Relevant law</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costa Rica</td>
<td>TPM</td>
<td>240</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td>Reglamento sobre inmisión de contaminantes atmosféricos</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>Annual</td>
<td></td>
<td></td>
<td>Reglamento sobre inmisión de contaminantes atmosféricos</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>150</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td>Reglamento sobre inmisión de contaminantes atmosféricos</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Annual</td>
<td></td>
<td></td>
<td>Reglamento sobre inmisión de contaminantes atmosféricos</td>
<td>61</td>
</tr>
<tr>
<td>Ecuador</td>
<td>TPM</td>
<td>250</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td>Registro Oficial No. 726</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>Annual</td>
<td></td>
<td></td>
<td>Registro Oficial No. 726</td>
<td>61</td>
</tr>
<tr>
<td>EU</td>
<td>PM10</td>
<td>50</td>
<td>24 hours</td>
<td>not to be exceeded more than 35 times a calendar year</td>
<td>COUNCIL DIRECTIVE 1999/30/EC</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>Annual</td>
<td></td>
<td></td>
<td>COUNCIL DIRECTIVE 1999/30/EC</td>
<td>11</td>
</tr>
<tr>
<td>Mexico</td>
<td>TPM</td>
<td>260</td>
<td>24 hours</td>
<td>Not to be exceeded</td>
<td>NOM-024-SSA1-1993</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>75</td>
<td>Annual</td>
<td></td>
<td></td>
<td>NOM-024-SSA1-1993</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>150</td>
<td>24 hours</td>
<td>not to be exceeded more than once per year</td>
<td>NOM-025-SSA1-1993</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Annual</td>
<td></td>
<td></td>
<td>NOM-025-SSA1-1993</td>
<td>61</td>
</tr>
<tr>
<td>Australia</td>
<td>PM10</td>
<td>50</td>
<td>24 hours</td>
<td></td>
<td></td>
<td></td>
<td>63</td>
</tr>
</tbody>
</table>

*Table 6: International standards on PM (2)*
### Table 7: International standards for PM (3)

<table>
<thead>
<tr>
<th>Country</th>
<th>Aerosol</th>
<th>Level (µg m⁻³)</th>
<th>Averaging period</th>
<th>Guideline type</th>
<th>Date of implementation</th>
<th>Relevant law</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>PM10</td>
<td>50</td>
<td>24 hours</td>
<td>not to be exceeded more than 35 times a calendar year</td>
<td>31-Dec-04</td>
<td>The Air Quality (England) Regulations 2000</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>40</td>
<td>Annual</td>
<td></td>
<td>31-Dec-04</td>
<td>The Air Quality (England) Regulations 2000</td>
<td>62</td>
</tr>
<tr>
<td>USA</td>
<td>PM10</td>
<td>150</td>
<td>24 hours</td>
<td>Primary &amp; Secondary</td>
<td>1990</td>
<td>NAAQS</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>PM10</td>
<td>50</td>
<td>Annual</td>
<td>Primary &amp; Secondary</td>
<td>1990</td>
<td>NAAQS</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>PM2.5</td>
<td>65</td>
<td>24 hours</td>
<td>Primary &amp; Secondary</td>
<td>1990</td>
<td>NAAQS</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>PM2.5</td>
<td>15</td>
<td>Annual</td>
<td>Primary &amp; Secondary</td>
<td>1990</td>
<td>NAAQS</td>
<td>60</td>
</tr>
</tbody>
</table>
5 Particle Estimation Methodologies: what is available?

In the following an overview on the different approaches to determine the amount of Particulate Matter emitted by aircraft will be given. Beginning with the description of the initial situation, methods to determine non-volatile and volatile particle emissions split up into those based on the ICAO Smoke Number and those who are not based on these values will be described. Also Particulate Matter emitted by mechanical processes will be dealt with. A discussion and an assessment of the different methods will lead to a decision on which method is the most promising and most accurate method.

5.1 Initial Situation

Usually the emitted amount of pollutants of an aircraft engine is specified in the form of the so called emission index (EI). The emission index is the mass of a substance in grams per kilogram of burned fuel. The produced mass of each pollutant is linked to the EI by the following definition:

\[ E = EI \cdot FF \cdot t_{\text{mode}} \cdot N_E \]

where:
- \( E \) … Mass of emitted pollutant [kg]
- \( EI \) … Emission Index EI \([\frac{g}{kg}]\)
- \( t_{\text{mode}} \) … Time in mode [s]
- \( N_E \) … Number of engines [-]

As already mentioned introductorily, the amount of emitted \( \text{CO}_2, \text{H}_2\text{O} \) and \( \text{SO}_2 \) -and hence their emission indices- are directly linked to the fuel properties which are the ratio of hydrogen and carbon, and the fuel sulphur content. Concerning the pollutants \( \text{HC}, \text{CO} \) and \( \text{NO}_x \), the emitted amount is strongly dependant on the combustion process, the emission indices are basically determined through measurements e.g. in engine test facilities at sea level static (SLS) conditions. The emission indices for \( \text{HC}, \text{CO} \) and \( \text{NO}_x \) for several engines are based on measurements can be found in several publications, like the ICAO Engine Exhaust Emission Data Bank, which is at the same time the largest and most important database.
However, this is not the case for soot and Particulate Matter. There is neither an emission index nor a concentration but only the Smoke Number available. Additionally the ICAO databank is the only database containing the Smoke Number. As mentioned in chapter 4.11 there have been some projects dealing with the measurement of PM emission indices for different aircraft-engine combinations on ground as well as in flight. The main problem is that until now the emission indices are available for only a few engines. Additionally the Smoke Numbers in the ICAO database are not complete for 71.2% of the engines listed and even missing completely (i.e. for each operation mode) for 27.5%. Around 61.6% of all listed engines are actually used worldwide. This resulted from the examination of actual flight traffic data.

5.2 Particulate Matter estimation from aircraft engines

Particulate Matter caused by the combustion of fossil fuels in aircraft engines consist of both volatile and non-volatile particles. This was shown before in chapter 4. In the following a detailed description of different methods to estimate Particulate Matter emissions will be given.

5.2.1 Non-volatile Particulate Matter

Concerning the non-volatile fraction of Particulate Matter caused by the incomplete combustion of fossil fuels it can be assumed as a good approximation that soot is the most prevalent substance in the non-volatile fraction (cp. Chapter 4). The estimation methods can basically be divided into those based on the Smoke Number given in the ICAO Engine Exhaust Emission Data Bank and those methods that are independent of it. As the Smoke Number is the only information on soot emissions in a “database format” the Smoke Number based methods are dominating.

5.2.1.1 Methodologies based on the ICAO Smoke Number

There are several approaches that were published ([8], [66], [68], [70], [71]) during the last three decades to estimate the amount of emitted soot based on the ICAO Smoke Number, which will be presented in the following. They all use a correlation between the Smoke Number and the soot-concentration in the engine exhaust gas based on measurements. There are different formulations, but the main difficulty is, that there is no direct connection between both values. These functions depend on the soot properties of the engine looked at -especially the particle size distribution.

[24]
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

The mathematical relation between the soot concentration and the soot emission index is defined as followed according to [63]:

\[
\text{EI}_{\text{soot}} \left[ \frac{g}{\text{kg}} \right] = \frac{c_{\text{soot}} \cdot A \cdot v}{\text{FF}}
\]

where:
- \( c_{\text{soot}} \) … Soot concentration \([\text{mg m}^{-3}]\)
- \( A \) … Effective exit cross section of the engine \([\text{m}^2]\)
- \( v \) … Flow velocity at the engine exit \([\text{ms}^{-1}]\)
- \( \text{FF} \) … Fuel Flow \([\text{kgs}^{-1}]\)

With the ulterior motive to apply this formula for as many aircraft as possible and the fact that data for engine geometry as well as engine exhaust speeds are rare, it is necessary to make some minor conversions.

Applying \( \dot{V}_{\text{exhaust}} [\text{m}^3 \text{s}^{-1}] = A \cdot v \) and

\[
\dot{V}_{\text{exhaust}} [\text{m}^3 \text{kg}_{\text{fuel}}^{-1}] = \frac{\dot{V}}{\text{FF}}
\]

(Volume of exhaust gas per kg burnt fuel)

leads to the formula in the form given in [65]:

\[
\text{EI}_{\text{soot}} \left[ \frac{g}{\text{kg}} \right] = c_{\text{soot}} \left[ \frac{\text{mg}}{\text{m}^3} \right] \cdot \dot{V}_{\text{exhaust}} \left[ \frac{\text{m}^3}{\text{kg}_{\text{fuel}}} \right]
\]

where \( \dot{V}_{\text{exhaust}} \) is defined as followed according to [65]:

**Turbofan engines (TF):**

\[
\dot{V}_{\text{exhaust}} = \frac{\text{AFR} \cdot (1 + \text{BPR})}{\rho_{\text{air}}} - \frac{3.37}{\rho_{O_2}} + \frac{3.15}{\rho_{CO_2}} + \frac{1.24}{\rho_{H_2O}}
\]

**Mixed turbofan engines (MTF):**

\[
\dot{V}_{\text{exhaust}} = \frac{\text{AFR}}{\rho_{\text{air}}} - \frac{3.37}{\rho_{O_2}} + \frac{3.15}{\rho_{CO_2}} + \frac{1.24}{\rho_{H_2O}}
\]
where: \( AFR \) … Air-to-fuel-ratio
\( \rho_{\text{air}} \) … Ambient air density
\( \rho_{O_2} \) … Density of oxygen
\( \rho_{CO_2} \) … Density of carbon dioxide
\( \rho_{H_2O} \) … Density of water (vapor)

Smoke measurements are made at the “last bit of metal” of the engine. On some engines the mixing of the bypass-air happens before (MTF), and on others this happens after the exhaust nozzle (TF). The acronyms are also noted in the ICAO Engine Exhaust Emission Data Bank.

Air-to-fuel-ratios (AFR) are typically 45-50 for take-off and 100-120 for idle. According to [65] the following AFR can be assumed for the four thrust settings in the ICAO databank:

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>thrust setting</th>
<th>AFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off</td>
<td>100% (F_{oo})</td>
<td>50</td>
</tr>
<tr>
<td>Climb out</td>
<td>85% (F_{oo})</td>
<td>60</td>
</tr>
<tr>
<td>Approach</td>
<td>30% (F_{oo})</td>
<td>100</td>
</tr>
<tr>
<td>Idle</td>
<td>7% (F_{oo})</td>
<td>120</td>
</tr>
</tbody>
</table>

A more simplified form of the correlation to calculate the soot emission index is given in [64]:

\[
EI \left[ \frac{g}{kg} \right] = \frac{c_{\text{soot}}}{\rho_{\text{air}}} \cdot AFR
\]

Therein the influence of oxygen, carbon dioxide and water are neglected as well as the distinguishing between TF and MTF engines.

### 5.2.1.1.1 “Champagne-correlation” (1971)

In “Standard Measurement of Aircraft Gas Turbine Engine Exhaust Smoke” D.L. Champagne [66] examines the -at that time- new standard system to measure soot emissions by aircraft engines as described in chapter 4.9. In his report he refers to a measurement campaign performed by General Electric on a J79 turbojet engine. The experiments consisted of sampling the exhaust gas and dividing the sample flow into
two parts: one to determine the Smoke Number, the other one to measure soot concentration (smoke density) using an aluminum oxide filter crucible. [66]

The measurement results are shown in Figure 31. The solid line corresponds to particles with a diameter less than 1µm, the dotted line corresponds to the larger particles.

![Figure 31: Relationship between Smoke Number (SN) and smoke density (soot concentration) of the exhaust gas [66]](image)

To examine the significance of the relationship between the Smoke Number and the soot concentration in the engine exhaust gas given above, Champagne used the equation to estimate soot density in an exhaust plume as given in chapter 4.8.3 ("opacimeter"). Champagne came to the conclusion, that the relationship described in Figure 31 is credible and is applicable to estimate the smoke density for a given Smoke Number. There is no mathematical formulation of the relationship in Figure 31 given published by Champagne. The only mathematical expression accessible to me—mass based however—is given in [67]:

\[
\text{mass} = f(SN)
\]
As the above correlations for the soot concentration are mass based and hence not applicable to the equations for the soot emission indices given before. A conversion using the density of the engine’s exhaust gas would be necessary. Transferring the measurement values from diagram in Figure 31 into a MS-Excel worksheet allows to derive an ‘own’ volume based approximation of this relationship (Figure 32, Figure 33).

![Graph showing relationship between soot concentration and SN (SN<20)](image)

**Figure 32: Relationship (approximated) between soot concentration and SN (SN<20)**
Thus the approximated equation for the relationship between the Smoke Number and the volume-based soot-concentration can be written as:

\[
\begin{align*}
\text{SN}<20: \\
c_{\text{soot}} \left[ \frac{\text{mg}}{\text{m}^3} \right] &= 0.0015 \cdot \text{SN}^2 + 0.0898 \cdot \text{SN} + 0.0208 \\
\text{SN} \geq 20: \\
c_{\text{soot}} \left[ \frac{\text{mg}}{\text{m}^3} \right] &= 0.0014 \cdot \text{SN}^{2.4711}
\end{align*}
\]

It shall be emphasized once again that this is only a mathematical approximation of the relation described by Champagne, as no other formulation was accessible to me during my literature review.
Example:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>11.1</td>
<td>8.5</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- Smoke Number -

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>1.19</td>
<td>0.89</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- Soot Concentration \( [mg/m^3] \)

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>0.44</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

- Emission Index \( [g/kg] \)

Assumptions: Altitude: FL=0  
Air density: 1.23 g/m³

5.2.1.1.2 "Hurley-correlation" (1993)

C.D. Hurley from the Defence Research Agency at Fanborough, UK, describes in his report “Smoke measurements Inside a Gas Turbine Combustor” [68] the quantitative measurement of the carbon loading inside a gas turbine combustor of a Rolls Royce RB211 engine. For soot concentrations less than 10mgm⁻³ he relied on the standard filter stain technique. For higher carbon loadings –this is the case inside the combustor- the filter stain technique is not adequate enough. For the higher soot concentrations Hurley uses a nephelometer. The principal disadvantages of a nephelometer are that the response depends on the aerosol's particles size distribution and the shape of the particles and there is a lower detection limit of 10mgm⁻³. To overcome these disadvantages the nephelometer had to be calibrated and operated in parallel with the more sensitive filter stain technique. [68]

The calibration was performed as followed [68]: The smoke samples from the combustor were simultaneously measured gravimetrically and with the nephelometer over a wide range of smoke levels. This enabled the nephelometer to be calibrated in situ to negate the effects of particle size and shape. The calibration of the filter stain instrument was carried out by gravimetric methods using an other soot source as
sampling times were rather long (up to 6 hours). The calibration curves for the nephelometer and the filter stain instrument (Smoke Number) are shown in Figure 34 and Figure 35.

For our purposes only the diagram in Figure 35 is from interest, showing the soot concentration as a function of the Smoke Number. According to [68] the soot concentration can be written as followed:

\[
\frac{c_{\text{soot}}}{\text{m}^3} = 6.32 \cdot 10^{-2} \cdot \text{SN} + 8.17 \cdot 10^{-3} \cdot \text{SN}^2 - 3.01 \cdot 10^{-4} \cdot \text{SN}^3 + 4.05 \cdot 10^{-6} \cdot \text{SN}^4
\]
Example:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>11.1</td>
<td>8.5</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- Soot Concentration \( [\text{mg/m}^3] \)-

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>1.34</td>
<td>0.96</td>
<td>0.07</td>
<td>0.08</td>
</tr>
</tbody>
</table>

- Emission Index \( [\text{g/kg}] \)-

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>0.06</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Assumptions: Altitude: FL=0
Air density: 1.23 g/m³

5.2.1.1.3 “DLR-correlation” (1997, 2001)

Two further correlations to calculate the soot concentration in the exhaust gas of an aircraft engine using the Smoke Number are published by the German DLR (Deutsches Zentrum für Luft- und Raumfahrt). They are based on the measurement campaigns performed by Champagne, Whyte (chapter 5.2.1.2.1) and Hurley (Figure 36). The relative deviation of this function is at around ± 7% [8]. This is not primarily caused by measurement errors, but by the size properties of the particles because the filter’s efficiency for larger particles is better than for the smaller ones. It can be expected that the deviations will become larger when adding data from coming modern engines with a different particle size distribution. [8]
This function can be mathematically described by the following equation [8]:

\[
\frac{c_{\text{soot}}}{m^3} = 2.6156 \cdot 10^{-6} \cdot SN^4 - 1.0998 \cdot 10^{-4} \cdot SN^3 + \\
+ 2.2367 \cdot 10^{-3} \cdot SN^2 + 0.10955 \cdot SN + 1.2842 \cdot 10^{-3}
\]

Validity: \(0 \leq SN \leq 56\)
Accuracy: \(R^2 = 0.997\)
Published in 2001

Another correlation published by DLR in [69] is the following:

\[
\frac{c_{\text{soot}}}{m^3} = 3.25 \cdot 10^{-6} \cdot SN^4 - 1.27 \cdot 10^{-4} \cdot SN^3 + \\
+ 3.22 \cdot 10^{-3} \cdot SN^2 + 8.76 \cdot 10^{-2} \cdot SN + 1.4 \cdot 10^{-1}
\]

Validity: \(0 \leq SN \leq 30\)
Published in 1997

The comparison of both correlations by DLR from 1997 and 2001 is given in Figure 37. Both functions show a nearly accordance for Smoke Numbers within \(0 \leq SN \leq 30\).
Figure 37: Comparison of both correlations published by DLR

Example:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>11.1</td>
<td>8.5</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- Soot Concentration \([mg/m^3]\) -

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>1.23</td>
<td>0.94</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- Emission Index \([g/kg]\) -

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>0.05</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Assumptions: Altitude: FL=0
Air density: 1.23 g/m³
5.2.1.1.4  “Compound factor” method

Another Smoke Number based method is the so called “compound factor method” mentioned in [70]. It is a basic methodology that allows to estimate a Particulate Matter emission index using a known PM emission index for a reference engine. The reference EI is then corrected by comparing the Smoke Numbers of the actual engine with the values of the reference engine. The mathematical correlation is:

\[ E_{I_i} = \frac{SNI}{SN_{ref}} \cdot EI_{ref} \]

Unlike the correlations mentioned before (Champagne, Hurley, DLR), the “compound factor method” allows to determine an emission index in a direct way. The underlying assumption in this approach is that the change in PM mass emissions is correlated to the change in SN. This is the largest source of uncertainty in this method. This method might be of bigger interest, if more Particulate Matter emission indices are available.

5.2.1.1.5  “First Order Approximation” (2003)

The “First Order Approximation” (FOA) is a method that allows the prediction of PM emissions in the vicinity of airports. Similar to the “DLR correlation” the FOA is based on the work of Champagne, Whyte and Hurley, using curve fitting techniques. This resulted in an equation to predict non-volatile PM emissions that permits a quantification of the Smoke Number to the mass of PM emitted per volume exhaust. The curves of Champagne and the new derived curve as well as the fit statistical parameters can be seen in Figure 38. [13][70]
The trend line provides an upper limit to the presented data and as such is considered conservative. It can be seen that when a power law equation is used, a good fit to the data is determined. [70]

Assuming stoechiometric burn conditions at standard atmospheric conditions the equation to predict the mass of emitted non-volatile Particulate Matter for commercial aircraft can be written as follows [70]:

\[
ER = 0.6 \cdot SN^{1.8} \cdot FF
\]

where:  \( ER \) … Emission rate of PM \([\text{mg/s}]\)

Converting the emission rate to an emission index \( (ER = EI \cdot FF) \) leads to:

\[
EI[\frac{g}{kg}] = 0.6 \cdot SN^{1.8}
\]

It must be emphasized that this method is not meant to be a static method, but it is continually updated and improved until it is no longer needed, e.g. when the measured Smoke Number is replaced by real emission indices. The most recent publication [13] gives a more extended version of the equation given before. This formula considers volatile Particulate Matter now as well:

\[
ER_{\text{total}} = 2.4 \cdot SN^{1.8} \cdot FF
\]
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

According to [13] it is assumed that the ratio of volatile PM and non-volatile PM is 4/1.

Example:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>11.1</td>
<td>8.5</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>0.05</td>
<td>0.03</td>
<td>0.0006</td>
<td>0.0007</td>
</tr>
</tbody>
</table>

Assumptions:  
Altitude: FL=0  
Air density: 1.23 g/m³

5.2.1.1.6 “FRAPORT-correlation”

In order of the Fraport AG (Airport Frankfurt / Main, Germany) a study was performed to estimate and to prognosticate emissions caused by traffic in the aviation sector around the German airport Frankfurt / Main. Besides the ‘traditional’ emissions as well soot and PM10 emissions were considered. According to [71] the emission index for soot can be calculated using following equation:

\[
EI_{\text{soot}} \left[ \frac{g}{kg} \right] = 0.025 + 0.00023 \cdot \exp \left( \frac{SN}{2.65} \right)
\]

For the operation modes idle and approach:

\[
EI_{\text{soot}} \left[ \frac{g}{kg} \right] = 0.3 \cdot \left( 0.025 + 0.00023 \cdot \exp \left( \frac{SN}{2.65} \right) \right)
\]

While:  
\( EI_{\max} = 0.1 \text{kgkg}^{-1} \)

Concerning the emissions of PM_{10} the Fraport study says:  
\( EI_{PM10} = 2 \cdot EI_{\text{soot}} \)
Example:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>11.1</td>
<td>8.5</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C2</td>
<td>0.012</td>
<td>0.009</td>
<td>0.008</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Assumptions: Altitude: FL=0
Air density: 1.23 g/m³

5.2.1.2 Methods not based on the ICAO Smoke Number

As the Smoke Number is the only information on soot emissions available in a database format for a lot of engines, Smoke Number based methods are more numerous. But there are also attempts to estimate particle emissions independent of the SN. These will be presented in the following.

5.2.1.2.1 “Whyte-correlation” (1982)

A correlation to calculate a soot emission index is given by R.B. Whyte in the AGARD advisory report [72], which can be written as follows:

\[
E_{I_{\text{sout}}} \left[ \frac{g}{kg} \right] = 1.08 \cdot 10^{-29} \left( \frac{P}{O/C} \right)^{2.7} \cdot \left( \frac{H/C}{O/C} \right)^{5.45} \cdot T_3^{-8.66}
\]

Where:
- \( P \) … pressure [Pa]; (the reference does not further explain which pressure exactly is meant)
- \( O/C \) … oxygen / carbon atomic ratio
- \( H/C \) … hydrogen / carbon atomic ratio (fuel)
- \( T_3 \) … Combustor inlet temperature [K]
This equation emphasizes the influence of factors like pressure, inlet temperature, hydrogen content and oxygen / carbon ratio on the soot emission index. Pressure as well as combustor inlet temperature can be determined via thermodynamics, the atomic ratio of hydrogen / carbon and oxygen / carbon depend on the fuel properties and the air-to-fuel-ratio respectively.

### 5.2.1.2.2 “Particle number correlation” (1998)

A further correlation is mentioned by the DLR in [63]. It describes the dependency of the soot concentration of the particle size distribution and number concentration and is defined as follows [63]:

\[
c_{\text{soot}} = N \cdot \frac{\rho \cdot \pi}{6} \cdot [\text{CMD} \cdot \exp(1.5 \cdot \ln^2 \text{GSD})]
\]

where:
- \( N \) … soot particle number concentration \([\text{kg}^{-1}]\)
- \( \rho \) … density for loosely packed BC agglomerates
  \( \rho = 1.5 \text{gcm}^{-3} \)
- \( \text{CMD} \) … count median diameter of soot particles
- \( \text{GSD} \) … geometric standard deviation

This method needs information on the number of particles emitted by the aircraft engine, which can be measured e.g. by using the techniques described in 4.8.1.

### 5.2.1.2.3 “Simple Factor Method”

The “Simple Factor Method” uses a common factor for all aircraft or for large groups of aircraft. This can be seen in Table 8. TSP is an acronym for total suspended particulates, which is the former term used for Particulate Matter.
The simple factor method is useful for a first rough estimation of Particulate Matter emissions produced by aircraft, but it is not very accurate. Different aircraft–engine combinations are not represented accurately enough.

### 5.2.1.3 Altitude correction (“P3-T3-correlation”)

It is the main objective to determine the soot and PM emissions through all phases of flight. As already mentioned the production rates of soot are strongly dependent on the combustion process, i.e. on the type of aircraft engine, on the actual operation condition and on the ambient conditions. This means that apart from the current thrust setting (mode) there is also a dependency of the altitude – hence ambient pressure and temperature - and the air speed. The ICAO Smoke Number is determined under static sea level conditions. Therefore these values are not appropriate to determine the emissions for in-flight situations and therefore an altitude correction must be applied. This is also the case for the emissions of nitrogen oxides, hydrocarbons and carbon monoxide. This correlation is developed by the German DLR and can be found in [24], [69] or [73]. It is applicable for those methodologies based on the ICAO Smoke Number. The “P3-T3-correlation” to calculate the soot emission

<table>
<thead>
<tr>
<th></th>
<th>Emission Factor (kg LTO^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO</td>
</tr>
<tr>
<td><strong>International</strong></td>
<td></td>
</tr>
<tr>
<td>Approach</td>
<td>0.989</td>
</tr>
<tr>
<td>Taxi / Idle</td>
<td>16.9</td>
</tr>
<tr>
<td>Takeoff</td>
<td>0.238</td>
</tr>
<tr>
<td>Climbout</td>
<td>0.260</td>
</tr>
<tr>
<td><strong>Domestic</strong></td>
<td></td>
</tr>
<tr>
<td>Approach</td>
<td>0.626</td>
</tr>
<tr>
<td>Taxi / Idle</td>
<td>7.66</td>
</tr>
<tr>
<td>Takeoff</td>
<td>0.0835</td>
</tr>
<tr>
<td>Climbout</td>
<td>0.107</td>
</tr>
<tr>
<td><strong>Regional</strong></td>
<td></td>
</tr>
<tr>
<td>Approach</td>
<td>0.961</td>
</tr>
<tr>
<td>Taxi / Idle</td>
<td>6.36</td>
</tr>
<tr>
<td>Takeoff</td>
<td>0.0790</td>
</tr>
<tr>
<td>Climbout</td>
<td>0.254</td>
</tr>
<tr>
<td><strong>General Aviation: Piston</strong></td>
<td></td>
</tr>
<tr>
<td>Approach</td>
<td>2.89</td>
</tr>
<tr>
<td>Taxi / Idle</td>
<td>1.29</td>
</tr>
<tr>
<td>Takeoff</td>
<td>0.261</td>
</tr>
<tr>
<td>Climbout</td>
<td>2.97</td>
</tr>
</tbody>
</table>

Table 8: Emission factors per LTO by mode [74]
index for any flight condition basically consists of three steps. A more detailed description of this process will be given in chapter 6:

1. Thrust, SN  \( \Rightarrow \)  \( T_3, c_{\text{soot}} \) (SLS)
2. \( T_3, c_{\text{soot}} \) (SLS)  \( \Rightarrow \)  \( T_3, c_{\text{soot}} \) (in flight)
3. \( T_3, c_{\text{soot}} \) (in flight)  \( \Rightarrow \)  EI_{\text{soot}} \) (in flight)

In the first step the reference soot concentration at SLS is determined from the Smoke Number using the correlations of soot concentration versus Smoke Number as shown in chapter 5.2.1.1. Concerning those SN based correlations that calculate a soot emission index directly the soot concentration can be derived using one of the formulas in chapter 5.2. The combustor inlet temperature \( T_3 \) can be determined via thermodynamics.

In the second step the concentration of soot for conditions other than SLS is calculated using the reference functions (at SLS) and the thermodynamic engine data in flight. Necessary data are the combustor inlet pressure \( p_3 \), the flame temperature \( T_{\text{Fl}} \) and the equivalence ratio \( \Phi \), which considers the actual ratio of atomic carbon to atomic oxygen \( \text{C/O} \). The soot concentration for in-flight-conditions can then be determined with the following correlation:

\[
c_{\text{soot}} \left( \frac{\text{mg}}{\text{m}^3} \right) = c_{\text{soot,ref}} \left( \frac{\Phi}{\Phi_{\text{ref}}} \right)^{2.5} \left( \frac{p_3}{p_{3,\text{ref}}} \right)^{1.35} e^{\frac{20000}{T_{\text{Fl}}}} \left( \frac{20000}{T_{\text{Fl,ref}}} \right)
\]

where:
- \( c_{\text{soot,ref}} \) ... reference soot concentration at SLS [\( \text{mg m}^{-3} \)]
- \( \Phi, \Phi_{\text{ref}} \) ... equivalence ratio [-]
- \( p_3, p_{3,\text{ref}} \) ... combustor inlet pressure [bar]
- \( T_{\text{Fl}}, T_{\text{Fl,ref}} \) ... combustor inlet temperature [K]

The stoechiometric flame temperature \( T_{\text{Fl}} \) is defined as follows according to [69]:

\[
T_{\text{Fl}} = 2281\text{K} \cdot \left( p_{3}^{0.009375} + 0.000178 \cdot p_{3}^{0.055} \cdot (T_3 - 298) \right)
\]

Alexander Kugele
The reference variables (subscripted with ref) are the SLS values at the same combustor inlet temperature $T_3$ as that of the flight operating condition being considered. In this manner the combustor inlet temperature is indirectly accounted for. In the third step the soot concentration in the combustor is converted into a soot emission index $E_{I_{\text{soot}}}$ according to the correlations given in 5.2.

### 5.2.2 Volatile Particulate Matter

Regarding the estimation of aviation caused volatile Particulate Matter emission, there are no ‘real’ calculation methodologies available, as research in this kind of pollutant is still in its infancy. Until now there are only a few measurement results available that allow to roughly estimate the amount of emitted volatile PM as a function of the amount of non-volatile or total PM in the form:

$$E_{I_{\text{PMvol}}} \approx x\% \cdot E_{I_{\text{PMnv}}}$$

or

$$E_{I_{\text{PMvol}}} \approx x\% \cdot E_{I_{\text{PMtot}}}$$

According to [21] the volume fraction and hence the mass fraction of volatile PM for particles with a diameter less than 30nm is $\leq 15\%$. The volume fraction of particles larger than 50nm is 2 to 5% depending on the fuel sulfur content. Assuming that volatile Particulate Matter basically consists of particles with a diameter less than 30nm (cp. Figure 12) the emission index for $PM_{\text{vol}}$ can be estimated to:

$$E_{I_{\text{PMvol}}} \approx 15\% \cdot E_{I_{\text{PMtot}}}$$

According to a diagram in [18] the fraction of volatile Particulate Matter contributes with 38% of total Particulate Matter, when assuming that the main components of the volatile species are sulfates:

$$E_{I_{\text{PMvol}}} \approx 38\% \cdot E_{I_{\text{PMtot}}}$$

The Center of Excellence PARTNER (cp. Chapter 4.11) dealt with the measurement of emission indices for volatile and non-volatile Particulate Matter. Emission indices at cruise conditions for different aircraft types are shown in Figure 39.
The mean emission index for non-volatile PM (black line) lies at around 0.05 g kg\(^{-1}\) while the mean emission index for volatile particles is 0.08 g kg\(^{-1}\). The comparison of these values results in:

\[
EI_{PM_{vol}} \approx 16\% \cdot EI_{PM_{nv}}
\]

However, when watching the particular values for each aircraft, this assumption appears to be not quite accurate. It seems that the emission index for volatile PM is not proportional to the non-volatile species. Hence it is doubtful if such a formulation is possible at all. But until now it’s the only way.

What makes matters worse is the fact that the amount of emitted volatile Particulate Matter also depends on the distance downstream to the aircraft engine. As mentioned before, volatile particles are formed in the cooling exhaust gas, what means that with increasing distance to the aircraft engine the volatile fraction increases as well. According to [33] the fraction of volatile Particulate Matter direct at the engine exit plane tends to zero. Hence it is as well a question of definition in which point of the exhaust plume the distribution of emitted PM is determined.
The “First Order Approximation” [13] (cp. 5.2.1.1.5) emanates from a 3 to 1 or 4 to 1 [13] ratio for volatile components compared to non-volatile components. Written in another form:

\[ EI_{PMvol} \approx 300\ldots400\% \cdot EI_{PMnv} \]

The reason for this strong difference to the estimations before might be found in the distance to the engine. This is not further addressed to in the literature.

5.3 Estimation of Particulate Matter emissions caused by non-combustive processes

The estimation of suspended Particulate Matter caused by abrasive processes on tyres, breaks and runways can be performed by using estimated values in Table 1 (chapter 4.4.2.), which are based on the U.S. Environmental Protection Agency. A detailed description on how to use these values is given in chapter 6.

5.4 Discussion and conclusion

The main aim of this study is to develop a complete, pragmatic, applicable and most accurate method as possible to estimate the amount of Particulate Matter caused by aircraft operation. There are several approaches that have already been shown before, which will be discussed in the following. This discussion will result in a first sketch of a method that will be presented in detail in chapter 6.

Before starting the discussion and the comparison of these different strategies, it shall be recalled what are the objectives, what is needed and what is available?

The main objectives –among others- are to develop a method that allows the estimation of Particulate Matter emissions caused by aircraft for as many aircraft-engine configurations as possible. The method must be applicable through all phases of flight. The considered species are total suspended Particulate Matter, non-volatile PM, volatile PM, PM$_{10}$, PM$_{2.5}$ and PM$_{0.1}$. Accuracy and simplicity should always stand in the foreground.

To meet these requirements a method is needed that is based on as few assumptions as possible. As it is the case for other pollutants, the estimation of Particulate Matter emissions requires an emission index in the form \( gkg^{-1} \), preferentially in a database-format to apply the calculation for as many aircraft configurations as possible. To consider changing conditions for different flight phases an altitude.
correction method must be applied, as it is the case for e.g. nitrogen oxides or hydrocarbons, which are also strongly dependent on the combustion properties.

Concerning the question on what is available to make an estimation of Particulate Matter possible, following can be said. The calculation requires an emission index for PM which is not available in the desired form at present. The only information on the amount of emitted non-volatile Particulate Matter is listed in the ICAO Engine Exhaust Emission Data Bank in terms of the Smoke Number. Main obstacle is that this database is not complete: more than 50% of the values are missing. When applying one of the presented methods, which are based on the Smoke Number, further thoughts must be made to overcome this problem when meeting the requirements of accuracy and the objective to consider as many aircraft-engine combinations as possible. The actual problem is that there are only a few measurement-based emission indices for PM available. In addition, these measurements are not standardized.

As explained in chapter 5.2.1.2 there are some methods available to determine an emission index for Particulate Matter – predominantly the non-volatile species. The requirement to perform the calculation for as many configurations as possible excludes the “simple factor method” because of already mentioned reasons.

The “particle number correlation” requires information on particle number and size distributions, both values which are not available at present, particularly not in a database-format.

The “Whyte-correlation” depends in a strong degree on the combustor inlet temperature. This value must be determined via thermodynamics by using a huge amount of assumptions. The therefore caused error would be strengthened in a high degree as the power of \(T^3\) is 8.

It was already indicated before, that the only more or less useful source of information on the amount of emitted non-volatile PM is given in terms of the Smoke Number. Thus, the most promising approaches to estimate non-volatile PM emissions while meeting the requirements given above are those methods which are based on the Smoke Number. These methods should be considered as an interim approach, until measured data in the form of an emission index for both volatile and non-volatile PM are available. [13][56]

A comparison of the discussed methods based on the Smoke Number is shown in Figure 40 for the CFM56-5C2 engine at SLS. As the “compound factor” method requires a known emission index for non-volatile Particulate Matter, this method is not treated here.
The Compound factor method seems to be very useful when a PM emission index for a specific engine is already known and the emission index for a similar engine shall be determined by using the corresponding Smoke Numbers. But this method is primarily not useful in this case as no reference emission index is available. Additionally, this method assumes that the change in Particulate Matter emissions is correlated to the change in the Smoke Number. This is a further source of inaccuracy that should be avoided.

The FRAPORT-correlation as presented in chapter 5.2.1.1.6 is not accurate enough because of its limitations concerning the maximum soot emission index (0.1 g/kg). This value is already exceeded with Smoke Numbers higher than 15. Higher Smoke Numbers are not modeled at all. As shown in Figure 40, the characteristic of this method is similar to the other approaches. In lower thrust regimes the soot emission index corresponds to those determined with other methods. At higher thrust settings the deviation in comparison to the other methods is rather high.

The Champagne-correlation is the oldest approach to determine a soot concentration by using the Smoke Number. Its age and the fact that no useful mathematical equation was accessible to me during my literature research exclude this correlation. Because of their actuality, the most promising methods seem to be the “Hurley-correlation” (1993), the “DLR-correlation” (1997-2001) and the “First Order Approximation” (2003). Hurley’s correlation is based on the results of Champagne, while the DLR-correlation as well the First Order Approximation is based on the results from...
Hurley and Champagne [13]. This relationship can be seen as well in the characteristics of the soot emission indices from Figure 40. However, the emission indices determined with the First Order Approximation are generally lower than those from “Hurley-” or the “DLR-correlation”.

A decision on which correlation is the best one is still not possible at this moment. Therefore all three correlations will be considered for the time being. The implementation in the intended estimation tool and the results should allow a conclusion, which method is the most appropriate one.

These thoughts allow now to elaborate a first sketch of a method to estimate Particulate Matter emissions through all phases of flight. A detailed description of this draft will be presented in chapter 6.
6 PM Emission Estimation Methodology

This chapter will show step by step a procedure to estimate the amount of emitted Particulate Matter for any flight phase. As discussed before the presented method is based on the Smoke Number which is listed in the ICAO Engine Exhaust Emission Data Bank. As mentioned before, three correlations will be considered. Closing, a validation will follow by comparing the results with data from other studies to come to a conclusion concerning two items: the accuracy of the results and the question which correlation is the most appropriate one.

The basic steps to estimate the amount of emitted Particulate Matter produced by aircraft in all flight phases based on the ICAO Smoke Number can be summarized as followed:

1. Determine the missing Smoke Numbers in the ICAO Engine Exhaust Emission Data Bank.
2. Calculate the concentration of non-volatile Particulate Matter ($PM_{nv}$) in the aircraft engine exhaust gas for ground conditions.
3. Calculate the concentration of non-volatile Particulate Matter in the engine’s exhaust gas for in flight conditions.
4. Determine the emission index for non-volatile Particulate Matter for all conditions.
5. Estimate the emission indices for volatile PM ($PM_v$), $PM_{10}$, $PM_{2.5}$ and $PM_{0.1}$.
6. Estimate the emitted mass [kg] for each species and flight phase.

A detailed description of each step will be given in the following chapters.

6.1 Determination of the missing Smoke Numbers

6.1.1 Preliminary considerations

As a first step a strategy must be found to overcome the problem of the missing Smoke Numbers. The actual (electronic) version of the ICAO database offers data based on measurements during engine certification for 243 different engine types. A basic structure of the database is shown in Figure 41.
Typical Smoke Numbers are:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT9D-20</td>
<td>12.3</td>
<td>9.5</td>
<td>2.5</td>
<td>0.7</td>
</tr>
<tr>
<td>RB211-22B</td>
<td>14.7</td>
<td>12.9</td>
<td>8.0</td>
<td>3.1</td>
</tr>
<tr>
<td>CFM56-5C2</td>
<td>11.1</td>
<td>8.5</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The overview shown below gives a first impression on the amount and the relations of available and missing data in the emission database concerning the Smoke Number:

<table>
<thead>
<tr>
<th>Percentage of availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of engine types listed:</td>
</tr>
<tr>
<td>Number of necessary SNs (T/O, C/O, App, Idle):</td>
</tr>
<tr>
<td>Number of engine types with a complete set of SN (T/O, C/O, App, Idle):</td>
</tr>
<tr>
<td>Number of available SN for T/O mode:</td>
</tr>
<tr>
<td>Number of available SN for C/O mode:</td>
</tr>
<tr>
<td>Number of available SN for App mode:</td>
</tr>
<tr>
<td>Number of available SN for Idle mode:</td>
</tr>
<tr>
<td>Number of available maximum SN:</td>
</tr>
<tr>
<td>Total number of SN available (except max SN):</td>
</tr>
</tbody>
</table>
As discussed before, a major requirement is to apply this methodology on as many aircraft as possible. Only 28.8% of the engines listed in the database obtain a complete set of Smoke Numbers, which is not enough to meet this requirement. Therefore, a strategy or algorithm must be developed to derive the missing values by relying on the available data. As a first step the main objective is to “get rid of” the gaps.

The first idea was to look for a relationship between the Smoke Number of engine of similar thrust and their date of production. The objective was to derive a kind of function in the form. This consideration relies on the fact that the Smoke Number decreases with advancing year of production:

\[ iSN_i = f(\text{year of production}) \]

where: \( i \) ... corresponding mode of the ICAO LTO-cycle

The expected trend line was thought to look like shown in Figure 42.

But the result of this attempt showed that there was no ‘real’ trend to recognize as the values scatter in a high degree as can be seen in Figure 43 for engines with a thrust between 50 and 100kN at take off thrust.
Figure 43: Take off Smoke Number versus test year / year of production for the CFM56-engines

Because of the relative high error this approach is not suited enough for our purposes.
The U.S. Federal Aviation Agency (FAA) recently published a new version of their emission estimation tool EDMS V4.3, which now offers the possibility to consider Particulate Matter emissions from aircraft. The implemented method is the “First Order Approximation” which is also based on the Smoke Number. Their strategy to overcome the missing values of the Smoke Number is to use the maximum SN for these “gaps”. In other words: for engines where all Smoke Numbers -except the maximum SN- are missing, the maximum Smoke Number is used for each mode, which means that the Smoke Number and hence the amount of emitted soot is the same for both idle mode and full thrust at take off. For those engines missing one, two or three Smoke Numbers, these gaps are as well set to the maximum Smoke Number. This method is rather uncomplicated, but physical properties of soot production are not well represented.
Apart from determining all missing values to close the gaps, the physical properties concerning soot emissions should be considered. A promising approach to do this is to rely on the data that already exist. Using known Smoke Numbers and their dependency on different thrust settings should allow to determine the unknown values for similar engines, with e.g. similar rated thrust, pressure ratio or manufacturer.
These thoughts were carried on and an algorithm was developed being able to derive the missing Smoke Numbers for all engines in the ICAO Engine Exhaust Emission Data Bank. According to its function it is called “Fill-the-gaps-algorithm”, which will be presented in the following.

### 6.1.2 “Fill-the-gaps-algorithm”

**Basic steps:**

1. Preliminary preparations
2. Assign engines to engine groups
3. Determine a typical “Smoke Number trend” for each engine group and operation mode
4. Calculate the missing values in relation to the Smoke Number trend of the engines within a group

**1. Preliminary preparations:**

As a first step some minor preliminary preparations are required. Some engines are listed more than once because of variation in fuel injection systems, combustor types or date of measurement (prototype, certification, afterward). The differences in the Smoke Numbers can be assumed to be negligible and these entries can be combined to one. The corresponding Smoke Numbers are merged by averaging the Smoke Numbers of the respective engines if available. If a Smoke Number is missing, only the existing values are considered for averaging. At the same time the amount of missing values can be reduced by this. An example illustrates this procedure:

**Example 1:**

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR700-715B1-30 (1)</td>
<td>3.55</td>
<td>2.90</td>
<td>1.03</td>
<td>0.89</td>
</tr>
<tr>
<td>BR700-715B1-30 (2)</td>
<td>4.56</td>
<td>4.13</td>
<td>0.96</td>
<td>0.07</td>
</tr>
<tr>
<td>BR700-715B1-30</td>
<td>4.055</td>
<td>3.515</td>
<td>0.995</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Example 2:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF6-80C2B4F (1)</td>
<td>7.30</td>
<td>4.70</td>
<td>2.30</td>
<td>2.30</td>
</tr>
<tr>
<td>CF6-80C2B4F (2)</td>
<td>6.90</td>
<td>4.50</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>CF6-80C2B4F</td>
<td>7.10</td>
<td>9.20</td>
<td>2.30</td>
<td>2.30</td>
</tr>
</tbody>
</table>

Example 3:

<table>
<thead>
<tr>
<th>EngineID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF6-80C2A2 (1)</td>
<td>6.50</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>CF6-80C2A2 (2)</td>
<td>6.50</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>CF6-80C2A2 (3)</td>
<td>5.80</td>
<td>3.20</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>CF6-80C2A2</td>
<td>6.27</td>
<td>3.20</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

2. Engine grouping:

A possibility to determine the missing values of the Smoke Number is to compare the respective engine to those engines with complete data. In other words: the idea is to use the given values to determine a ‘typical’ Smoke Number trend as a function of the operation mode or thrust setting and to derive therewith the missing values.

To determine this ‘typical’ trend, a first idea was to merge all Smoke Numbers of those engines owning all four values for the four modes take off, climb out, approach and idle to one single trend line. This step would assume that all engines behave the same characteristics. The comparison illustrated in Figure 44 shows however, that there are big variations in the Smoke Number trend depending on the operation mode which are mainly caused by differences in the combustor design and fuel injection systems.

To consider these differences as well as other engine characteristics it is more useful to assign each engine to a representative group of engines e.g. from the same manufacturer and the same series. Engines of one series are often related to each other e.g. in terms of core engine design, pressure ratio, by pass ratio.

11 The ICAO Engine Exhaust Emission Databank lists a Smoke Number of ‘0’. In this case the Smoke Number is assumed as not existing.
The more detailed the grouping is the more precise the engines’ characteristics can be considered. A possible grouping could look like follows:

Figure 44: Comparison of the Smoke Number for different aircraft engines
<table>
<thead>
<tr>
<th>Group ID</th>
<th>Engine series</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CF34</td>
<td>GE</td>
</tr>
<tr>
<td>2</td>
<td>CF6</td>
<td>GE</td>
</tr>
<tr>
<td>3</td>
<td>GE90</td>
<td>GE</td>
</tr>
<tr>
<td>4</td>
<td>CFM56-2</td>
<td>CFM</td>
</tr>
<tr>
<td>5</td>
<td>CFM56-3</td>
<td>CFM</td>
</tr>
<tr>
<td>6</td>
<td>CFM56-5</td>
<td>CFM</td>
</tr>
<tr>
<td>7</td>
<td>CFM56-7</td>
<td>CFM</td>
</tr>
<tr>
<td>8</td>
<td>BR700-710</td>
<td>BMW / RR</td>
</tr>
<tr>
<td>9</td>
<td>BR700-715</td>
<td>BMW / RR</td>
</tr>
<tr>
<td>10</td>
<td>D-30</td>
<td>Aviadgatel</td>
</tr>
<tr>
<td>11</td>
<td>PS-90</td>
<td>Aviadgatel</td>
</tr>
<tr>
<td>12</td>
<td>AE3007</td>
<td>Allison</td>
</tr>
<tr>
<td>12</td>
<td>FE73</td>
<td>Allied signal</td>
</tr>
<tr>
<td>13</td>
<td>V2500</td>
<td>IAE</td>
</tr>
<tr>
<td>14</td>
<td>NK-8</td>
<td>KKBM</td>
</tr>
<tr>
<td>15</td>
<td>PW</td>
<td>PW</td>
</tr>
<tr>
<td>16</td>
<td>RB211</td>
<td>RR</td>
</tr>
<tr>
<td>17</td>
<td>SPEY</td>
<td>RR</td>
</tr>
<tr>
<td>18</td>
<td>TAY</td>
<td>RR</td>
</tr>
<tr>
<td>19</td>
<td>TRENT</td>
<td>RR</td>
</tr>
<tr>
<td>20</td>
<td>ALF 502 / LF507</td>
<td>TL</td>
</tr>
<tr>
<td>21</td>
<td>D-36</td>
<td>ZMKB</td>
</tr>
</tbody>
</table>

The comparison of the Smoke Numbers as a function of the operation mode for the engines of the BR700-715 series (1 = take off, 2 = climb out, etc.) show a good agreement to these thoughts (Figure 45).
3. Smoke Number trend determination:
As a next step the representative Smoke Number trend for each engine group is determined. For this the Smoke Number values for each engine and for each operation mode are merged to one single averaged value. This procedure is illustrated in the following example for the “BMW Roll-Royce” engines which are assigned to the group ID 17:

<table>
<thead>
<tr>
<th>Engine ID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR700-715A1-30</td>
<td>3.24</td>
<td>2.73</td>
<td>0.97</td>
<td>0.91</td>
</tr>
<tr>
<td>BR700-715A1-30</td>
<td>4.33</td>
<td>3.96</td>
<td>0.77</td>
<td>0.11</td>
</tr>
<tr>
<td>BR700-715B1-30</td>
<td>3.55</td>
<td>2.90</td>
<td>1.03</td>
<td>0.89</td>
</tr>
<tr>
<td>BR700-715B1-30</td>
<td>4.56</td>
<td>4.13</td>
<td>0.96</td>
<td>0.07</td>
</tr>
<tr>
<td>BR700-715C1-30</td>
<td>3.89</td>
<td>3.09</td>
<td>1.09</td>
<td>0.87</td>
</tr>
<tr>
<td>BR700-715C1-30</td>
<td>4.86</td>
<td>4.26</td>
<td>1.12</td>
<td>0.04</td>
</tr>
<tr>
<td>Group ID 17</td>
<td>4.09</td>
<td>3.51</td>
<td>0.99</td>
<td>0.48</td>
</tr>
</tbody>
</table>

There are some engine groups without any engine having a complete set of Smoke Numbers. As a consequence at least one of the averaged Smoke Numbers would be missing. In this case, the missing values are derived by comparison to another group.
with complete Smoke Numbers and similar thrust. The calculation of the missing values happens by simple interpolation. The procedure is shown by following example:

<table>
<thead>
<tr>
<th>Group ID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>j</td>
<td>e</td>
<td>f</td>
<td>x</td>
<td>y</td>
</tr>
</tbody>
</table>

The variables a to f represent the known average Smoke Numbers for the engine groups i and j. The variables x and y are the unknown Smoke Numbers. It is assumed that the soot emission and hence the Smoke Number behave similar for engines groups with similar thrust. Therefore the relations between the Smoke Numbers for the respective operation modes behave similar.

\[
\frac{b}{a} \approx \frac{f}{e}; \quad \frac{c}{b} \approx \frac{x}{f}; \quad \frac{d}{c} \approx \frac{y}{x};
\]

This leads to the following:

\[
x = f \cdot \frac{c}{b}; \quad y = x \cdot \frac{c}{b};
\]

A more general formulation:

\[
\left[ SN_{k+1}\right]_{\text{group}, j} = \left[ SN_k\right]_{\text{group}, j} \cdot \left[ SN_{k+1}\right]_{\text{group}, j}
\]

where:

- i … engine group with complete Smoke Numbers
- j … engine group with missing Smoke Numbers
- k … engine operation mode (k=1, 2, 3)

This procedure does only work if at least one of the four Smoke Numbers is available. If no Smoke Numbers are known at all for the engines within an engine group - this is e.g. the case for the "International Aero Engines" V2500 series- the corresponding values must be determined using the Smoke Numbers of an engine group with similar rated thrust. This step assumes that soot emission properties for engines
of similar thrust class are basically the same. Concerning the averaged Smoke Numbers for the different engine groups it must be added, that absolute values are not from primary interest. The most important information needed is the relation between the Smoke Numbers for the different engine modes. The following example illustrates this more clearly:

<table>
<thead>
<tr>
<th>Group ID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>j</td>
<td>w</td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
</tbody>
</table>

\[ w = a; \quad x = b; \quad y = c; \quad z = d; \]

4. Calculation of the missing Smoke Numbers
This step calculates the missing values of the ICAO Smoke Number for each engine listed in the database. Apart from a few exceptions the value of the Smoke Number is maximal at take off mode, as fuel concentration in the combustor chamber is very high at this thrust setting. Hence, if the Smoke Number for the take off mode is missing, the maximum Smoke Number must be used, which is available for 97.5% of the engines. As a result almost all engines offer at least a Smoke Number for the take off mode. Concerning those engines that do have neither a Smoke Number nor a maximum Smoke Number, the values must be set to ‘0’ as no information at all is given. An example shall illustrate this:

<table>
<thead>
<tr>
<th>Engine ID</th>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>x</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
</tr>
</tbody>
</table>

The variable x represents the unknown Smoke Number for an engine with the Engine ID i. The other variables b, c and d stand for the Smoke Numbers for the other modes and can be known or unknown. Assuming that the maximum Smoke Number (e) is situated at the take off mode (T/O) it can be stated:

\[ a = e \]
Or more general:

\[
\text{SN}_{T/O} = \text{SN}_{\text{max}}
\]

This procedure leads to the situation that at least the Smoke Number for take off is known for (almost) all engines. The missing Smoke Number values for the other operation modes are determined by comparing with the average Smoke Number trend of the group to which the respective engine is assigned to. Once again an example for the CFM56-5C3/P engine shall explain the procedure.

The information given in the ICAO Engine Exhaust Emission Data Bank for this engine is like the following. Only the Smoke Number for the take off mode is known all other values are missing:

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Engine ID} & \textbf{T/O} & \textbf{C/O} & \textbf{App} & \textbf{Idle} \\
\hline
CFM56-5C3/P & 11.6 & x & y & z \\
\hline
\end{tabular}
\end{table}

The variables x, y and z are the unknown Smoke Numbers. In this example the engine with the engine ID CFM56-5C3/P is assigned to the group with the group ID 6. The Smoke Number trend for this group was determined to according step 3:

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Group ID} & \textbf{T/O} & \textbf{C/O} & \textbf{App} & \textbf{Idle} \\
\hline
6 & 8.33 & 5.75 & 3.093 & 1.87 \\
\hline
\end{tabular}
\end{table}

The unknown Smoke Numbers are calculated by assuming that the relation between the values for two different operation modes for one specific engine behave like the relation between those values for the entire engine group. In this example this means:

\[
\frac{x}{11.6} = \frac{5.75}{8.33} \quad \Rightarrow \quad x = \frac{11.6 \cdot 5.75}{8.33} \\
\text{(analog for y and z)}
\]
A more general formulation of this procedure:

\[
\frac{\text{SN}_{i+1}}{\text{SN}_i}^{\text{engine}} = \frac{\text{SN}_{i+1}}{\text{SN}_i}^{\text{group}} \Rightarrow \frac{\text{SN}_{i+1}}{\text{SN}_i}^{\text{engine}} = \left(\frac{\text{SN}_{i+1}}{\text{SN}_i}^{\text{group}}\right)_{\text{engine}} \cdot \left(\frac{\text{SN}_{i+1}}{\text{SN}_i}^{\text{group}}\right)_{\text{engine}}
\]

Where: \( i \) … operation mode (i=1, 2, 3)

Thus it is possible to determine all missing Smoke Numbers for almost each engine listed in the ICAO Engine Exhaust Emission Data Bank. The Smoke Number for at least one of the operation modes or the maximum Smoke Number must be available.

### 6.1.3 Validation

There are two possible ways to validate the “fill-the-gaps-algorithm” described before. A first approach is to simply compare the Smoke Numbers graphically for the engines of one group before and after applying the algorithm. A further possibility is to take an engine with a complete set of Smoke Numbers and to delete systematically one or more Smoke Numbers before applying the algorithm. The comparison of the values before and after the derivation allows a conclusion on the quality of the algorithm.

Figure 46 and Figure 47 show the Smoke Numbers for the General Electric (GE) engines of the CF34-series before and after applying the “fill-the-gaps-algorithm”. The complete Smoke Number set is only listed for the engine ID’s CF34-31 and CF34-3B, while the SNs for all other engines of this series are given only for the operation modes take off and climb out. The derived values are highlighted in Figure 47. It can be seen that the Smoke Number trend for all engines is basically the same.

The results for the CFM56-5 series engines are shown in Figure 48 and Figure 49. For this engine group only a few engines have a complete Smoke Number set. Most engines just list the Smoke Number for the take off mode. The comparison of both figures show that the determined values correspond well to the given ones.

A more or less extreme example is given in Figure 50 and Figure 51. In most cases the smoke numbers for the engines of the JT-series (Pratt and Whitney) are limited to the take off mode. Only one engine (JT15D-5C) offers a value as well for the climb out mode. The missing values are determined in relation to the Smoke Number trend given from the engines of the CFM-5 series as their average rated thrust is similar.
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Figure 46: Smoke Numbers for the GE CF34–series before applying the algorithm

Figure 47: Smoke Numbers for the GE CF34–series after applying the algorithm
Figure 48: Smoke Numbers for the CFM56-3-series before applying the algorithm

Figure 49: Smoke Numbers for the CFM56-3-series after applying the algorithm
Figure 50: Smoke Numbers for the JT-series before applying the algorithm

Figure 51: Smoke Numbers for the JT-series after applying the algorithm
It is simply not possible to guarantee that the determined Smoke Numbers, especially those in “extreme” cases like for the JT-series or those engines where no information is available at all. The objective of this algorithm is to simulate physical properties as far as possible. Main obstacle is that there is no other measurement data available.

A further possibility to validate the algorithm in a more appropriate way is to do as if there were measurement results available, simply by taking an arbitrary engine that has a complete set of Smoke Numbers in the original database and deleting systematically the Smoke Numbers step by step. The before deleted Smoke Numbers are derived by applying the algorithm. The comparison of the determined values with the original data gives information on the quality of the algorithm. The results are shown in Figure 52, Figure 53 and Figure 54 for several engines. This has been done for all combinations of missing Smoke Numbers. It can be seen clearly that the deviances are not so big and all trend lines behave similarly. The thicker black line is the original line.

![Comparison of original and derived values of GE90-85 B engine](image)

**Figure 52: Systematic deletion of known Smoke Numbers; results for the GE90-85**
Comparison of original and derived values of CF6-80C2B4F engine

The "original" line shows the complete set of Smoke Numbers given in the ICAO Aircraft Engine Emission Database. In studies 1 to 14 different SNs were deleted to see difference between derived SN and original SN.

Figure 53: Systematic deletion of known Smoke Numbers; results for the CF6-80C2B4F

Comparison of original and derived values of BR715-C1-30 engine

The "original" line shows the complete set of Smoke Numbers given in the ICAO Aircraft Engine Emission Database. In studies 1 to 14 different SNs were deleted to see difference between derived SN and original SN.

Figure 54: Systematic deletion of known Smoke Numbers; results for BR700 715-C1-80
A comparison between the determined Smoke Numbers and the original values is shown in Figure 55. It can be seen that the maximum deviation of this algorithm lies at around 25-30%.

Figure 55: Comparison of determined Smoke Numbers with the original values

Concluding it can be stated that the “fill-the-gap-algorithm” described in this chapter is an accurate method to determine the missing Smoke Numbers in the ICAO Engine Exhaust Emission Data Bank that tries to consider the physical properties and characteristics of the aircraft engine and its combustion process. There are some assumptions that had to be done, especially when dealing with those engines that do not offer any information on the Smoke Number. This is the major source of uncertainty.

Knowing the Smoke Numbers for almost all engines listed in the ICAO Engine Exhaust Emission Data Bank permits to determine the soot concentration within the engine exhaust plume and the emission index for non-volatile Particulate Matter according to the methods described in chapter 5.2.1, which will be presented in the following.
6.2 Estimating the concentration of non-volatile Particulate Matter in the engine exhaust gas

The algorithm described before allows us to determine the missing Smoke Number for all engines listed in the ICAO Engine Exhaust Emission Data Bank. This allows us to apply one of the before mentioned correlation to determine the concentration of non-volatile Particulate Matter within the engine exhaust gas. According to the conclusion in chapter 5.4 the correlations that come into question are:

- DLR-correlation
- Hurley-correlation
- First Order Approximation

The oldest one is the Hurley-correlation, which has been developed in 1993. The newer DLR-correlation (1997-2001) is based on the Hurley correlations which is also the case for the First Order Approximation. The main difference between DLR and FOA is that the FOA assumes an exponential function for the relation between Smoke Number and soot concentration, while the DLR describes this correlation using a polynomial of fourth degree. At this moment it is not possible to come to a conclusion on which correlation is the most accurate one. The methodology described in the following will concentrate on the DLR-correlation. Required changes or important information concerning on of the other two methods are addressed at the respective moment.

The basic approach is aligned with EUROCONTROL’s Advanced Emission Model III, as it is planed to include the here described method to estimate Particulate Matter emissions.

A flight mission can be divided into flight phases being part of the ICAO landing- and take off cycle (cp. Chapter 4.9) and phases not being part of it like climb, cruise and descent. According to this the estimation of the concentration of non-volatile Particulate Matter in the exhaust gas of an aircraft engine can be divided as well into the phases of the LTO cycle and the other phases.

Concentration estimation of non-volatile Particulate Matter for the phases of the LTO-cycle:

As shown in chapter 4.9 the ICAO landing and take off cycle consists of the phases taxi in / out, take off, climb out (to 3000ft) and approach with the corresponding thrust settings of 7%, 30%, 85% and 100%. It can be assumed that atmospheric changes up to the altitude of 3000ft are negligible. The concentration of non-volatile Particu-
late matter for the different phases of the LTO-cycle with the corresponding thrust settings and Smoke Numbers can be estimated using the correlation given in 5.2.1.1.3:

\[
c_{\text{soot},i} \left[ \frac{\text{mg}}{\text{m}^3} \right] = 2.6156 \cdot 10^{-6} \cdot \text{SN}_i^4 - 1.0998 \cdot 10^{-4} \cdot \text{SN}_i^3 + \\
+ 2.2367 \cdot 10^{-3} \cdot \text{SN}_i^2 + 0.10955 \cdot \text{SN}_i + 1.2842 \cdot 10^{-3}
\]

Where: \( i \) … LTO-cycle operation mode (i=1, 2, 3, 4)

To illustrate this procedure a simple example:

*Engine ID:* CF6-50A

*Smoke Numbers:*  
<table>
<thead>
<tr>
<th>T/O</th>
<th>C/O</th>
<th>App</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.52</td>
<td>12.03</td>
<td>1.49</td>
<td>2.14</td>
</tr>
</tbody>
</table>

*Expanded to all LTO-phases:*

<table>
<thead>
<tr>
<th>LTO-phase</th>
<th>SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi out</td>
<td>2.14</td>
</tr>
<tr>
<td>Take off</td>
<td>12.52</td>
</tr>
<tr>
<td>Climb out</td>
<td>12.03</td>
</tr>
<tr>
<td>Approach</td>
<td>1.49</td>
</tr>
<tr>
<td>Landing</td>
<td>1.49</td>
</tr>
<tr>
<td>Taxi in</td>
<td>2.14</td>
</tr>
</tbody>
</table>

*Applying the “DLR-correlation” gives following results for the soot concentration:*

<table>
<thead>
<tr>
<th>LTO-phase</th>
<th>( c_{\text{soot}} \left[ \frac{\text{mg}}{\text{m}^3} \right] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi out</td>
<td>0.3956</td>
</tr>
<tr>
<td>Take off</td>
<td>0.9171</td>
</tr>
<tr>
<td>Climb out</td>
<td>0.6367</td>
</tr>
<tr>
<td>Approach</td>
<td>0.2638</td>
</tr>
<tr>
<td>Landing</td>
<td>0.2638</td>
</tr>
<tr>
<td>Taxi in</td>
<td>0.3956</td>
</tr>
</tbody>
</table>
When using the “Hurley-correlation” the relationship for the concentration of non-volatile Particulate Matter given in chapter 5.2.1.1.2 has to be used.

Applying the First Order Approximation requires some minor changes, as this method gives a direct relation between the Smoke Number and an emission index for Particulate Matter. For reasons of uniformity this emission index has to be converted to a concentration primarily using a relationship given in chapter 5.2.1.1:

\[
EI \left[ \frac{g}{kg} \right] = \frac{c_{\text{soot}}}{\rho_{\text{air}}} \cdot AFR
\]

The values for the air-to-fuel ratio (AFR) are given in chapter 5.2.1.1, \( \rho_{\text{air}} \) is the density of the ambient air.

**Concentration estimation of non-volatile Particulate Matter in flight:**
Soot formation depends in a high degree from the operation condition of the aircraft engine. Changing altitudes lead to changes in atmospheric conditions (air density, air pressure, Temperature) that influence the combustion process. Also varying air speed has to be mentioned. Similar to the emissions of nitrogen oxides, sulfur dioxides or hydrocarbons, these effects must be considered. As mentioned before the data listed in the ICAO Engine Exhaust Emission Data Bank is based on measurements performed at Sea Level Static. To consider atmospheric changes an altitude correction must be applied using the correlation described in chapter 5.2.1.3 developed by the German DLR. For the sake of completeness and clarity the correlations are shown again.

\[
c_{\text{soot}} \left[ \frac{mg}{m^3} \right] = c_{\text{soot,ref}} \cdot \left( \frac{\Phi}{\Phi_{\text{ref}}} \right)^{2.5} \cdot \left( \frac{p_3}{p_{3,\text{ref}}} \right)^{1.35} \cdot \frac{e^{\frac{T_{\text{Fl}}}{20000}}}{e^{\frac{T_{\text{Fl,ref}}}{20000}}}
\]

where:
- \( c_{\text{soot,ref}} \) … reference soot concentration at SLS [mg m\(^{-3}\)]
- \( \Phi, \Phi_{\text{ref}} \) … equivalence ratio [-]
- \( p_3, p_{3,\text{ref}} \) … combustor inlet pressure [bar]
- \( T_{\text{Fl}}, T_{\text{Fl,ref}} \) … combustor inlet temperature [K]

The reference soot concentration at SLS \( c_{\text{soot,ref}} \) is the soot concentration for ground level. In the step before the concentration was determined just for the operation
modes and thrust settings from the ICAO LTO-cycle. The reference soot concentration for ground level for the other thrust settings than those defined by the ICAO can be determined by linear interpolation, which is illustrated in Figure 56.

![Reference soot concentration interpolation](image)

**Figure 56: Reference soot concentration interpolation**

AEMIII is an emission estimation model that is based on the actual fuel and not on the actual thrust setting of an aircraft. For reasons of uniformity the operation modes and the respective thrust settings are expressed in terms of the corresponding fuel flow. Apart from the Smoke Number and the other pollutants as well as fuel flow data for the different operation modes is listed for each engine.

The interpolation of soot concentration for any fuel flow happens as follows. The actual fuel flow and the corresponding soot concentration are indexed with an ‘x’:

\[
FF_x < FF_{idle}:
\]

\[
c_{soot,ref,x} = c_{soot,ref,idle} \cdot \frac{FF_x}{FF_{idle}}
\]

\[
FF_{idle} \leq FF_x < FF_{App}:
\]

\[
c_{soot,ref,x} = c_{soot,ref,idle} + \frac{(c_{soot,ref,App} - c_{soot,ref,idle}) \cdot (FF_x - FF_{idle})}{(FF_{App} - FF_{idle})}
\]
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Therefore it is possible to determine the soot concentration within the exhaust gas at ground level when knowing the actual fuel flow or the corresponding thrust setting.

The equivalence ratio \( \Phi \) is the ratio between carbon and hydrogen of the used fuel. The variation for different flight levels and atmospheric conditions can be assumed to be marginal. Therewith it can be said:

\[
\frac{\Phi}{\Phi_{\text{ref}}} \approx 1
\]

Hence the correlation can be simplified to:

\[
c_{\text{soot}} \left[ \frac{mg}{m^3} \right] = c_{\text{soot,ref}} \cdot \left( \frac{p_3}{p_{3,\text{ref}}} \right)^{1.35} \cdot e^{\frac{20000}{T_{\text{r},p}}} \cdot \left( \frac{20000}{T_{\text{r},p,\text{ref}}} \right)\]

\( p_3 \) and \( p_{3,\text{ref}} \) are the combustor inlet pressures for any flight phase and for sea level static conditions respectively. These parameters can be determined using thermodynamic estimation.

The total pressure \( p_t \) for an ideal gas is defined as follows [75]:

\[
p_t = p \left[ \frac{c^2}{2 \cdot c_p \cdot T} + 1 \right]^{\frac{\kappa}{\kappa - 1}}
\]
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Where:  
\( c \) … streaming velocity [m/s]  
\( C_p \) … specific heat capacity [J/kgK]  
\( T \) … static temperature [K]  
\( \kappa \) … isentropic exponent  
\( p \) … static pressure

The Mach number of the considered air flow is:

\[
Ma = \frac{c}{a} = \frac{c}{\sqrt{\kappa \cdot R \cdot T}}
\]

Where:  
a … speed of sound [m/s]

The gas constant can be written as:

\[
R = C_p \cdot \frac{\kappa - 1}{\kappa}
\]

Hence the relation between static and total pressure can be converted to:

\[
\frac{p_t}{p} = \left[ \frac{\kappa - 1}{2 \cdot Ma^2 + 1} \right]^{\frac{\kappa}{\kappa - 1}}
\]

In turbo machinery the combustor inlet plane in an aircraft engine is indexed with ‘3’. Therefore the static pressure \( p_3 \) is determined by:

\[
p_3 = p_{t3} \cdot \left[ \frac{\kappa - 1}{2 \cdot Ma_3^2 + 1} \right]^{\frac{\kappa}{\kappa - 1}}
\]

Hence, the static combustor inlet pressure depends on the total combustor inlet pressure and the local Mach number.

To determine the Mach number of an air flow inside an aircraft engine, information on the air mass flow as well as geometric data is required. This data is not available or at least accessible for the variety of engines listed in the ICAO database. According to [76] the Mach number at the compressor exit plane \( Ma_2 \) typically lies between 0.3 and 0.4. The variation of the Mach number caused by the transition from compressor
to combustor can be assumed to be minimal. Hence the Mach number at the combustor inlet $Ma_3$ should be as well within the same region. The isentropic exponent is 1.4 when assuming an ideal gas.

The total combustor inlet pressure $p_{t3}$ corresponds to the total pressure at the compressor exit plane (‘2’), which can be expressed by the compressor’s pressure ratio:

$$\Pi_{\text{compressor}} = \Pi_{1-2} = \frac{p_{t2}}{p_{t1}} = \frac{p_{t3}}{p_{t1}}$$

Where: $p_{t1}$ … total pressure at combustor inlet [N/m²]

Losses of total pressure caused by the engine inlet (‘0’) can be neglected. Hence it the combustor pressure ratio can be written as:

$$\Pi_{1-2} = \frac{p_{t3}}{p_{t0}}$$

Where: $p_{t0}$ … total pressure at engine inlet

The total engine inlet pressure is caused by the deceleration of the airflow and can be determined by following correlation:

$$p_{t0} = p_0 + \frac{1}{2} \cdot \rho_{\text{air}} \cdot c_0^2$$

Where: $p_0$ … ambient static pressure [N/m²]

$\rho_{\text{air}}$ … ambient air density [kg/m³]

$c_0$ … air speed [m/s]

Hence the static combustor inlet pressure for any thrust setting can be written as:

$$p_3 = \left( \frac{F}{F_{00}} \cdot (\Pi_{1-2} - 1) + 1 \right) \cdot p_{t0} \cdot \left( \frac{k - 1}{2} \cdot Ma_3^2 + 1 \right)^{-\frac{k}{k-1}}$$

Where: $\frac{F}{F_{00}}$ … thrust setting [%]
The combustor pressure ratio is an engine parameter that primarily depends on the engine’s revolution and compressor design. This data is basically unknown or at least not easily accessible. But there is an overall engine pressure ratio listed in the ICAO Engine Exhaust Emission Data Bank for each engine. Assuming that the compressor is ‘responsible’ for ca. 66% [77] of the total pressure ratio of the engine, the static combustor inlet pressure follows to:

\[
p_3 = \frac{F}{F_00} \cdot \left(0.66 \cdot \Pi_{\text{engine}} - 1\right) + 1 \left(p_0 + \frac{1}{2} \cdot \rho_{\text{air}} \cdot c_0^2 \right) \left(\frac{k-1}{2} \cdot \frac{\Pi_{\text{engine}}}{\Pi_{\text{engine}} - 1} \cdot \text{Ma}_3^2 + 1\right)^{-\frac{k}{k-1}}
\]

Where: \(\Pi_{\text{engine}}\) … overall engine pressure ratio [-]

The reference static combustor inlet pressure is determined by using the corresponding air density on ground.

The stoechiometric flame temperature \(T_{\text{Fi}}\) is defined as [69]:

\[
T_{\text{Fi}} = 2281 \cdot \left[p_3^{0.009375} + 0.000178 \cdot p_3^{0.055} \cdot (T_3 - 298)\right] \text{[K]}
\]

Where: \(T_3\) … combustor inlet temperature [K]

pressures are written in bar

The combustor inlet pressure has been determined in a step before. The unknown parameter is the combustor inlet temperature \(T_3\), which is not given as well and has to be determined by applying thermodynamic relationships.

The total temperature is defined as:

\[
T_t = T + \frac{c^2}{2 \cdot c_p}
\]
Using the definition for the Mach number the combustor inlet temperature $T_3$ can be written as [78]:

$$T_3 = T_{i3} \cdot \left(1 + \frac{\kappa - 1}{2} \cdot \text{Ma}_3^2\right)^{-1}$$

The total combustor inlet temperature $T_{i3}$ is unknown and must be determined using assumptions and thermodynamic relationships. As no work or energy is neither added nor extracted between the compressor exit and the combustor inlet plane the corresponding total temperatures can be assumed as constant.

$$T_{i3} = T_{i2}$$

The process in an aircraft engine combustor can be characterized by a polytrope change of state, the relationship between the total temperatures at the compressor exit and inlet planes can be written as [78]:

$$\frac{T_{i3}}{T_{i1}} = \left(\frac{p_{i3}}{p_{i1}}\right)^{\frac{n-1}{n}} = \left(\Pi_{1-2}\right)^{\frac{n-1}{n}}$$

Where: $n$ … polytrope exponent

The polytrope exponent can be expressed by the polytrope efficiency $\eta$ [78]:

$$\frac{n-1}{n} = \frac{1}{\eta} \cdot \frac{\kappa}{\kappa - 1}$$

Therewith it follows:

$$\frac{T_{i3}}{T_{i1}} = \left(\frac{p_{i3}}{p_{i1}}\right)^{\frac{\kappa-1}{\kappa \eta}} = \left(\Pi_{1-2}\right)^{\frac{\kappa-1}{\kappa \eta}}$$

Hence, the static combustor inlet temperature for any thrust setting results in:

$$T_3 = T_{i1} \cdot \left(\frac{F}{F_{00}} \cdot (\Pi_{1-2} - 1) + 1\right)^{\frac{\kappa-1}{\kappa \eta}} \cdot \left(1 + \frac{\kappa - 1}{2} \cdot \text{Ma}_3^2\right)^{-1}$$
No work or energy is added or extracted between engine inlet and compressor inlet plane, hence it can be said:

\[ T_{10} = T_{1f} \]

With:

\[ T_{10} = T_0 + \frac{c_0^2}{2 \cdot c_p} \]

According to [77] and [78] the polytrope efficiency of the combustor can be assumed to:

\[ \eta \approx 0.95 \]

This leads to the relationship for the combustor inlet temperature for any thrust setting:

\[ T_3 = T_{10} \cdot \left( \frac{F}{F_{00}} \cdot \left(0.66 \cdot \Pi_{\text{engine}} - 1\right) + 1\right)^{\frac{\kappa - 1}{\kappa \cdot \eta}} \cdot \left(1 + \frac{\kappa - 1}{2} \cdot M_{\text{a}}^2\right)^{-1} \]

The changes of the combustor inlet temperature for the different flight conditions can be assumed to be marginal [69], hence it can be written:

\[ T_3 = T_{3,\text{ref}} \]

All parameters are now known and hence it is possible to determine the soot concentration within the engine’s exhaust gas for any flight condition.
6.3 Emission index for non-volatile Particulate Matter caused by the combustion in aircraft engines

To determine the emission index of non-volatile Particulate Matter (indexed with ‘PMnv’) the correlation in the following form as shown in chapter 5.2.1.1 is used:

\[
EI_{PMnv} \left( \frac{g}{kg} \right) = \frac{c_{soot}}{\rho_{air}} \cdot AFR
\]

Therein is \(c_{soot}\) the concentration of non-volatile Particulate Matter that has been derived in the previous step and \(\rho_{air}\) the density of the ambient air. The only missing parameter is the air-to-fuel-ratio (AFR). As mentioned in chapter 5.2.1.1 the AFR for the different thrust settings and the corresponding fuel flows can be assumed as:

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>thrust setting</th>
<th>AFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off</td>
<td>100% (F_{00})</td>
<td>50</td>
</tr>
<tr>
<td>Climb out</td>
<td>85% (F_{00})</td>
<td>60</td>
</tr>
<tr>
<td>Approach</td>
<td>30% (F_{00})</td>
<td>100</td>
</tr>
<tr>
<td>Idle</td>
<td>7% (F_{00})</td>
<td>120</td>
</tr>
</tbody>
</table>

To determine the air-to-fuel-ratios for other thrust settings / fuel flows than those given by the ICAO, a linear interpolation similar to that shown in 6.3 must be performed. The schematic trend of the AFR as a function of the fuel flow is shown in Figure 57.
Figure 57: Trend of the air-to-fuel-ratio (AFR)

The interpolation of the air-to-fuel-ratio to determine the AFR for any thrust setting or fuel flow is shown in the following:

\[ FF_x < FF_{idle} : \]

\[ AFR_x = AFR_{idle} \]

\[ FF_{idle} \leq FF_x < FF_{App} : \]

\[ AFR_x = AFR_{App} + \frac{(AFR_{idle} - AFR_{app}) \cdot (FF - FF_{idle})}{(FF_{app} - FF_{idle})} \]

\[ FF_{App} \leq FF_x < FF_{C/O} : \]

\[ AFR_x = AFR_{C/O} + \frac{(AFR_{app} - AFR_{C/O}) \cdot (FF - FF_{app})}{(FF_{C/O} - FF_{app})} \]

\[ FF_{C/O} \leq FF_x \leq FF_{T/O} : \]

\[ AFR_x = AFR_{T/O} + \frac{(AFR_{C/O} - AFR_{T/O}) \cdot (FF - FF_{C/O})}{(FF_{T/O} - FF_{C/O})} \]

\[ FF_x > FF_{T/O} : \]

\[ AFR_x = AFR_{T/O} \]
Thus it is possible to determine the total amount of non-volatile Particulate Matter produced during the combustion of kerosene for any flight phase and any thrust setting / fuel flow.

6.4 Emission index for volatile Particulate Matter caused by the combustion in aircraft engines

As discussed before in chapter 5.2.2 there is no consistent method or equation available to determine the amount or at least an emission index of volatile Particulate Matter. Until now the only way to determine the emitted amount of volatile PM is to estimate the emitted amount per kg non-volatile Particulate Matter. Or in other words:

\[ EI_{PM_{vol}} \approx x \% \cdot EI_{PM_{nv}} \]

The comparison of the information given by references [18], [21] and [56] scatters in a high degree and does not allow a precise conclusion on the amount of volatile Particulate Matter compared to the non-volatile fraction. According to this the ratio between volatile and non-volatile Particulate Matter can be estimated to:

\[ EI_{PM_{vol}} = 16 \ldots 61\% EI_{PM_{nv}} \]

The volatile fraction is dominated by the ultra fine particles, which are very light and at the same time rather numerous. Hence the mass concentration and the mass based emission index for volatile Particulate Matter must tendentially lie around the lower values.

Another important aspect when dealing with volatile Particulate Matter is the distance to the point of emission. According to [33] there is no volatile Particulate Matter formed up to a downstream distance of less than 1m.
6.5 Determination of the mass of emitted Particulate Matter caused by the combustion in aircraft engines

To determine the mass of Particulate Matter in kg the following equation is used. It can be found in several references, e.g. in [74]:

\[ E[\text{kg}] = E \left[ \frac{g}{\text{kg}} \right] \cdot FF \left[ \frac{\text{kg}}{\text{s}} \right] \cdot N_E \cdot t_{\text{mode}} \cdot \frac{1}{1000} \]

According to this, the emitted mass is a function of the emission index \( E \) determined a step before, the actual fuel flow \( FF \), the number of engines \( N_E \) and the duration of the corresponding operation condition \( t_{\text{mode}} \).

6.6 Emission rates for Particulate Matter caused by mechanical processes

Particulate Matter emissions caused by mechanical processes are of interest during the LTO-cycle while the aircraft has contact to ground. As shown in chapter 4.4.1 and 5.3 these mechanical processes are basically the abrasion of tyres, brakes and runways. An overview was given in chapter 4.4.1 in Table 1 [14]. According to this the average amount of emitted Particulate Matter by abrasive mechanisms for each LTO-cycle is assumed as following [14]:

<table>
<thead>
<tr>
<th>Type</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyres</td>
<td>0.13  kg/LTO</td>
</tr>
<tr>
<td>Brakes</td>
<td>0.0003 kg/LTO</td>
</tr>
<tr>
<td>Rwy</td>
<td>0.73   kg/LTO</td>
</tr>
</tbody>
</table>

Reference [14] does not distinguish at all between different aircraft weights, number of gears, numbers and size of tyres. Hence these values should be treated carefully. But until now there is practically no other information available. The following example reveals this.
Example:

Airport: EDDM / MUC  
Nr. of Rwys: 2  
Nr. of LTO’s per year: ~190000

⇒ annual abrasion: 130700kg/a  
69350kg/a/rwy

This would mean that around 70t of each runway is “converted” into Particulate Matter per year, which is definitely too much.

6.7 Estimating the Particulate Matter Size distribution (PM\(_{10}\), PM\(_{2.5}\) and PM\(_{0.1}\))

When estimating the amount of emitted particles it is from major interest to get information on the size distribution of these particles to estimate for example their impact on the environment or health. In chapter 4.2 it was shown that the size distribution of suspended Particulate Matter depends in a high degree of their formation process. As introductory mentioned, Particle size is commonly written as PM\(_{10}\), PM\(_{2.5}\) and PM\(_{0.1}\). In the following some information is given on how to estimate the amount of emitted Particulate Matter related or separated on their particle size. The estimation of PM\(_{10}\), PM\(_{2.5}\) and PM\(_{0.1}\) happens in accordance to their definition which was shown in chapter 4.2.

PM\(_{10}\) includes all particles with an aerodynamic diameter of less than 10µm. These are all those particles which are formed through combustion in the aircraft engine, which are smaller than ~3µm, and partially those particles caused by abrasive processes. This can be written as:

\[
E_{PM10}[kg] = E_{PM,combustion}[kg] + E_{PM,abrasion,d<10\mu m}[kg]
\]
The fraction of abrasive Particulate Matter with a diameter less than 10µm can be estimated according to Table 1 in chapter 4.4.2.

<table>
<thead>
<tr>
<th>Abrasive process</th>
<th>fraction of ( PM_{10} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyre</td>
<td>30%</td>
</tr>
<tr>
<td>Brakes</td>
<td>86%</td>
</tr>
<tr>
<td>Runway / taxiway</td>
<td>19%</td>
</tr>
</tbody>
</table>

PM\(_{2.5}\) covers all particles with an aerodynamic diameter of less than 2.5µm. These contain all those particles which are formed during the combustion process (cp. Chapter 4.2) and partially some particles caused by abrasion. This can be written as:

\[
E_{PM_{2.5}}[kg] = E_{PM,\text{combustion}}[kg] + E_{PM,\text{abrasion},d<2.5\mu m}[kg]
\]

The fraction or ratio of Particulate Matter with a diameter less than 2.5µm caused by mechanical processes can be also estimated according to Table 1 in chapter 4.4.2.

<table>
<thead>
<tr>
<th>Abrasive process</th>
<th>fraction of PM(_{2.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyre</td>
<td>2%</td>
</tr>
<tr>
<td>Brakes</td>
<td>63%</td>
</tr>
<tr>
<td>Runway / taxiway</td>
<td>5%</td>
</tr>
</tbody>
</table>

The smallest mode is PM\(_{0.1}\). These are particles with an aerodynamic diameter less than 0.1µm. As described in chapters 4.2 and 4.4.2, these particles are dominated by the volatile species and hence have no big influence on the mass of Particulate Matter. According to [18] and [25] the fraction of PM\(_{0.1}\) is between 3.5 to 5% of the total emitted mass of Particulate Matter. Expressed mathematically:

\[
E_{PM_{0.1}}[kg] = 3.5...5\% \ E_{PM_{\text{tot}}}[kg]
\]

Where:

\[
E_{PM_{\text{tot}}}[kg] = E_{PM,\text{combustion}}[kg] + E_{PM,\text{abrasion}}[kg]
\]
6.8 Validation and conclusion

The presented method was implemented into the EUROCONTROL's Advanced Emissions Model III (AEMIII) as a stand alone module (“AEM_PT”) based on MS-Access. As mentioned before three types of correlations – “DLR-correlation”, “Hurley-correlation”, and “FOA”- were used to determine the soot concentration within the exhaust gas of the aircraft engine based on the Smoke Number. A detailed description of the implemented module will be given in chapter 7. In the following the results determined by that module will be compared with results from other studies or research projects based which are based on measurements and calculations. As indicated several times before, the main problem when dealing with Particulate Matter emissions is the lack of information and measurement data as there have been only a few studies working with this kind of pollutant.

The objective of the validation of the module developed within the framework of this study is to come to a conclusion on the accuracy of the implemented method and to exclude errors. The main function of this Particulate Matter estimation module is to determine the mass of emitted Particulate Matter and its fractions for each flight phase and the complete mission of any aircraft. These are in detail: total PM, volatile PM, non-volatile PM, PM_{10}, PM_{2.5} and PM_{0.1}. Because of the dependency of emitted mass of any pollutant on the actual fuel flow and the respective duration of the flight phase, a comparison based on the corresponding emission indices is more practical. Most information concerning Particulate Matter emissions is given by the German DLR, however limited to the non-volatile species. There are data available based on calculations performed by the DLR’s Institute of Propulsion Technology for several aircraft-engine combinations and data based on measurements behind aircraft performed by the DLR’s Institute of Atmospheric Physics (cp. Chapter 4.11). Within the framework of the Center of Excellence PARTNER a project called “APEX” was launched to determine mass and number based emission indices for Particulate Matter of a NASA experimental DC-8 aircraft equipped with CFM56-2C1 engines (cp. Chapter 4.11). This data covers the non-volatile as well as the volatile fraction of Particulate Matter measured on different distances downstream the engine exit. The measurement results will be published in the form of a publicly accessible database in the internet, which however was not available during my work unfortunately. These data would be rather useful to validate the results of emitted volatile Particulate Matter and would as well allow making the assumptions more accurate. There are basically no other mass based emission indices available from other sources. That’s the case as well for the different particle modes like PM_{10}, PM_{2.5} and PM_{0.1}. Until now, the only way to check the accuracy and correctness of the module...
and the implemented method is to compare the results of emitted non-volatile Particulate Matter with those values given by the DLR. Whether the validation is limited on the non-volatile species it is at least possible to check the accordance of the presented method as it is mainly based on the method developed by the DLR.

A further objective of this validation is to compare the three different correlations for the soot concentration and to come to a conclusion on which one is the most accurate correlation compared to the results based on calculations and measurements.

The calculations are based on flight missions recorded from Simulations at EEC which are logged in AEMIII in form of a traffic and a flight file. The traffic file contains information on e.g. the departure airport, the destination or the aircraft type for each mission. An example is given below [79].

The flight file basically contains information on each flight leg of each mission, e.g. the operation condition (climb, cruise, descent, etc.), the speed or altitude. An example is given below [79]:

(KEY;AZA465;05:49:18;Cruise;HEIDL;Navaid;FALSE;FALSE;445.00;0.00;49.350318;8.483338;350.00;350.00;350.00;FlightPhaseEnroute;350.00;60.00;
KEY;FFR3501;05:49:19;Cruise;DINKE;Navaid;FALSE;FALSE;430.00;0.00;49.016983;9.950007;350.00;350.00;350.00;FlightPhaseEnroute;350.00;60.00;
KEY;RMC617;05:49:20;Climb;SPEZL;Navaid;FALSE;FALSE;370.00;1000.00;50.066985;9.516674;369.52;370.00;370.00;FlightPhaseEnroute;370.00;70.00;
KEY;DLH4173;05:49:20;Descent;HOFEN;Navaid;FALSE;FALSE;420.00;0.00;49.650318;10.116675;372.23;100.00;100.00;FlightPhaseDescent;100.00;50.00;
KEY;CPA057X;05:49:21;Cruise;TULSI;Navaid;FALSE;FALSE;480.00;0.00;47.916981;11.916677;380.00;380.00;380.00;FlightPhaseEnroute;380.00;60.00;
KEY;TYR411X;05:49:21;Climb;#FB;FALSE;FALSE;480.00;0.00;47.916981;11.916677;380.00;380.00;380.00;FlightPhaseClimb;380.00;175.00;

For a more detailed description on AEMIII I refer on the AEMIII User Guide [79]. For the validation of the implemented method, those missions were analyzed that correspond to the information given in the respective reference. In other words: if a reference lists data for a flight with an Airbus A320-200 for a cruising altitude at FL300 only the corresponding fitting flights are considered.

Alexander Kugele
Emission index of non-volatile PM at 100% SLS thrust:
Reference [69] gives emission indices for soot 100% SLS thrust for different aircraft engines based on calculations. These can be seen in Table 9.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Year of production</th>
<th>EI of soot [g/kg] at 100% SLS thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT3D-3B</td>
<td>ca. 1962</td>
<td>0.829</td>
</tr>
<tr>
<td>JT8D-15</td>
<td>ca. 1970</td>
<td>0.101</td>
</tr>
<tr>
<td>RB211-22B</td>
<td>ca. 1971</td>
<td>0.089</td>
</tr>
<tr>
<td>RB211-524B</td>
<td>ca. 1975</td>
<td>0.100</td>
</tr>
<tr>
<td>CF6-50C2 / E2</td>
<td>ca. 1977</td>
<td>0.010</td>
</tr>
<tr>
<td>ALF 502R-5</td>
<td>ca. 1980</td>
<td>0.063</td>
</tr>
<tr>
<td>CF6-80 C2B1F</td>
<td>ca. 1980</td>
<td>0.037</td>
</tr>
<tr>
<td>CFM56-3B2</td>
<td>ca. 1983</td>
<td>0.025</td>
</tr>
<tr>
<td>PW 4460</td>
<td>ca. 1986</td>
<td>0.043</td>
</tr>
<tr>
<td>CFM56 5C2</td>
<td>ca. 1990</td>
<td>0.052</td>
</tr>
</tbody>
</table>

Table 9: (calculated) Emission indices of soot at 100% SLS thrust [69]

A comparison between the calculated values given by DLR [69] and those determined in AEMIII using the “DLR-correlation”, the “Hurley-correlation” and the “FOA” are shown in Table 10, Table 11 and Table 12.

<table>
<thead>
<tr>
<th>Engine</th>
<th>Soot-EI [g/kg] at 100% SLS thrust from reference [69]</th>
<th>Soot-EI [g/kg] at 100% SLS thrust (“DLR correlation”)</th>
<th>relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT3D-3B*</td>
<td>0.829</td>
<td>0.730</td>
<td>-11.90%</td>
</tr>
<tr>
<td>JT8D-15*</td>
<td>0.101</td>
<td>0.082</td>
<td>-18.54%</td>
</tr>
<tr>
<td>RB211-22B</td>
<td>0.089</td>
<td>0.076</td>
<td>-14.13%</td>
</tr>
<tr>
<td>RB211-524B</td>
<td>0.100</td>
<td>0.096</td>
<td>-4.25%</td>
</tr>
<tr>
<td>CF6-50C2</td>
<td>0.020</td>
<td>0.022</td>
<td>11.35%</td>
</tr>
<tr>
<td>CF6-50E2**</td>
<td>0.063</td>
<td>0.038</td>
<td>-39.22%</td>
</tr>
<tr>
<td>ALF 502R-5</td>
<td>0.037</td>
<td>0.070</td>
<td>88.14%</td>
</tr>
<tr>
<td>CFM56 3B2</td>
<td>0.025</td>
<td>0.031</td>
<td>23.85%</td>
</tr>
<tr>
<td>PW 4460</td>
<td>0.043</td>
<td>0.042</td>
<td>-2.03%</td>
</tr>
<tr>
<td>CF6-80C2B1F</td>
<td>0.037</td>
<td>0.036</td>
<td>-2.98%</td>
</tr>
<tr>
<td>CFM56 5C2</td>
<td>0.052</td>
<td>0.057</td>
<td>8.73%</td>
</tr>
</tbody>
</table>

Table 10: Comparison of the results determined with AEMIII and the DLR-correlation
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

<table>
<thead>
<tr>
<th>Engine</th>
<th>Soot-EI [g/kg] at 100% SLS thrust from reference [69]</th>
<th>Soot-EI [g/kg] at 100% SLS thrust (&quot;Hurley-correlation&quot;)</th>
<th>relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT3D-3B*</td>
<td>0.829</td>
<td>0.601</td>
<td>-27.52%</td>
</tr>
<tr>
<td>JT8D-15*</td>
<td>0.101</td>
<td>0.085</td>
<td>-15.62%</td>
</tr>
<tr>
<td>RB211-22B</td>
<td>0.089</td>
<td>0.079</td>
<td>-11.57%</td>
</tr>
<tr>
<td>RB211-524B</td>
<td>0.100</td>
<td>0.100</td>
<td>-0.44%</td>
</tr>
<tr>
<td>CF6-50C2</td>
<td>0.020</td>
<td>0.015</td>
<td>-23.06%</td>
</tr>
<tr>
<td>CF6-50E2**</td>
<td>0.063</td>
<td>0.034</td>
<td>-46.67%</td>
</tr>
<tr>
<td>ALF 502R-5</td>
<td>0.037</td>
<td>0.071</td>
<td>91.59%</td>
</tr>
<tr>
<td>CFM56 3B2</td>
<td>0.025</td>
<td>0.025</td>
<td>0.21%</td>
</tr>
<tr>
<td>PW 4460</td>
<td>0.043</td>
<td>0.038</td>
<td>-11.27%</td>
</tr>
<tr>
<td>CF6-80C2B1F</td>
<td>0.037</td>
<td>0.031</td>
<td>-16.81%</td>
</tr>
<tr>
<td>CFM56 5C2</td>
<td>0.052</td>
<td>0.055</td>
<td>6.63%</td>
</tr>
</tbody>
</table>

Table 11: Comparison of the results determined with AEMIII and the Hurley-correlation

<table>
<thead>
<tr>
<th>Engine</th>
<th>Soot-EI [g/kg] at 100% SLS thrust from reference [69]</th>
<th>Soot-EI [g/kg] at 100% SLS thrust (&quot;FOA&quot;)</th>
<th>relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT3D-3B*</td>
<td>0.829</td>
<td>0.801</td>
<td>-3.37%</td>
</tr>
<tr>
<td>JT8D-15*</td>
<td>0.101</td>
<td>0.085</td>
<td>-15.58%</td>
</tr>
<tr>
<td>RB211-22B</td>
<td>0.089</td>
<td>0.076</td>
<td>-14.90%</td>
</tr>
<tr>
<td>RB211-524B</td>
<td>0.100</td>
<td>0.108</td>
<td>7.97%</td>
</tr>
<tr>
<td>CF6-50C2</td>
<td>0.020</td>
<td>0.045</td>
<td>122.88%</td>
</tr>
<tr>
<td>CF6-50E2**</td>
<td>0.063</td>
<td>0.023</td>
<td>-63.98%</td>
</tr>
<tr>
<td>ALF 502R-5</td>
<td>0.037</td>
<td>0.065</td>
<td>75.61%</td>
</tr>
<tr>
<td>CFM56 3B2</td>
<td>0.025</td>
<td>0.015</td>
<td>-39.62%</td>
</tr>
<tr>
<td>PW 4460</td>
<td>0.043</td>
<td>0.027</td>
<td>-37.05%</td>
</tr>
<tr>
<td>CF6-80C2B1F</td>
<td>0.037</td>
<td>0.020</td>
<td>-45.70%</td>
</tr>
<tr>
<td>CFM56 5C2</td>
<td>0.052</td>
<td>0.046</td>
<td>-12.15%</td>
</tr>
</tbody>
</table>

Table 12: Comparison of the results determined with AEMIII and the FOA-correlation

Engines marked with * do not list a Smoke Number for the “take off mode” which corresponds to 100% thrust. The missing value was set to the maximum Smoke Number. The engines marked with ** are listed more than once, the Smoke Number is an average value.

The mean deviation of the results compared to the values given by reference [69] is 20.46% for the “DLR-correlation”, 22.85% for the “Hurley-correlation” and 39.89% for the “FOA”. One reason for these differences is the fact that the emission index is quite small and minor differences lead to huge percentile deviations. Other reasons may be different assumed Smoke Numbers for those engines marked with * or ** and an error caused by the assumption of the air-to-fuel-ratio (AFR), which seems to be more important. But in general it can be said, that the calculated values agree...
relatively good to those given by reference [69], especially for the “DLR-correlation” and the “Hurley-correlation”. The “FOA” results in relatively high deviations.

Figure 58: Comparison of the soot emission indices at 100% SLS thrust determined by AEMIII (using all three correlations) with the calculated values from DLR [69]

Concerning the question of the impact of the assumed values of the Smoke Number it can be seen, that the ‘biggest’ error is made when averaging the Smoke Numbers when more engines are merged together if they are listed more than once (**). Engines marked with (*) had a missing Smoke Number for the take off mode. It can be seen, that the assumption of setting the maximum value for this mode is not too bad, as the deviation of the respective emission indices is quite small.

Mean emission index of non-volatile Particulate Matter for different aircraft-engine combinations:

An overview on the mean emission index for non-volatile Particulate Matter for different aircraft-engine combinations is given by reference [69] and shown in Table 13.
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Engine</th>
<th>Mean soot EI [g/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B707</td>
<td>JT3D-3B*</td>
<td>0.294</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-22B</td>
<td>0.038</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-524B</td>
<td>0.027</td>
</tr>
<tr>
<td>A300</td>
<td>CF6-50C2</td>
<td>0.012</td>
</tr>
<tr>
<td>DC10</td>
<td>CF6-50C2</td>
<td>0.010</td>
</tr>
<tr>
<td>B747</td>
<td>CF6-50E2**</td>
<td>0.009</td>
</tr>
<tr>
<td>BAE 146</td>
<td>ALF 502R-5</td>
<td>0.038</td>
</tr>
<tr>
<td>B737</td>
<td>CFM56-3B2</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Table 13: Mean soot emission indices for different aircraft-engine combinations [69]

As can be seen there are relative big differences between the emission indices given in Table 13. Not only the characteristic of the respective engine, but as well mission data like the ratio of thrust to weight, distances, air speed and cruising altitudes influence the mean soot emission index in a high degree. This can be seen when comparing the A300, the B747 and the DC10, aircraft that use basically the same engines. The longer range and the higher cruising altitude lead to a lower mean soot emission index. [69]

A comparison of the results determined with AEMIII using the three different correlations are shown in the following tables (Table 14, Table 15, Table 16). As no exact information on the mission profile is given by reference [69], only those missions were considered and then averaged, where the cruising altitude is higher than FL250.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Engine</th>
<th>Mean soot EI [g/kg] from ref [69]</th>
<th>Mean soot EI [g/kg] (“DLR”)</th>
<th>Relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B707</td>
<td>JT3D-3B*</td>
<td>0.294</td>
<td>0.195</td>
<td>-33.59</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-22B</td>
<td>0.038</td>
<td>0.017</td>
<td>-54.60</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-524B</td>
<td>0.027</td>
<td>0.011</td>
<td>-59.36</td>
</tr>
<tr>
<td>A300</td>
<td>CF6-50C2</td>
<td>0.012</td>
<td>0.011</td>
<td>-6.88</td>
</tr>
<tr>
<td>DC10</td>
<td>CF6-50C2</td>
<td>0.010</td>
<td>0.013</td>
<td>26.11</td>
</tr>
<tr>
<td>B747</td>
<td>CF6-50E2**</td>
<td>0.009</td>
<td>0.009</td>
<td>-3.07</td>
</tr>
<tr>
<td>BAE 146</td>
<td>ALF 502R-5</td>
<td>0.038</td>
<td>0.016</td>
<td>-57.41</td>
</tr>
<tr>
<td>B737</td>
<td>CFM56-3B2</td>
<td>0.013</td>
<td>0.006</td>
<td>-51.46</td>
</tr>
</tbody>
</table>

Table 14: Comparison of the mean emission indices from AEMIII (“DLR-correlation”)
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Engine</th>
<th>Mean soot EI [g/kg] from ref [69]</th>
<th>Mean soot EI [g/kg] (“Hurley”)</th>
<th>Relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B707</td>
<td>JT3D-3B*</td>
<td>0.294</td>
<td>0.133</td>
<td>-54.91</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-22B</td>
<td>0.038</td>
<td>0.016</td>
<td>-58.21</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-524B</td>
<td>0.027</td>
<td>0.008</td>
<td>-69.60</td>
</tr>
<tr>
<td>A300</td>
<td>CF6-50C2</td>
<td>0.012</td>
<td>0.010</td>
<td>-20.36</td>
</tr>
<tr>
<td>DC10</td>
<td>CF6-50C2</td>
<td>0.010</td>
<td>0.010</td>
<td>2.96</td>
</tr>
<tr>
<td>B747</td>
<td>CF6-50E2**</td>
<td>0.009</td>
<td>0.006</td>
<td>-27.87</td>
</tr>
<tr>
<td>BAE 146</td>
<td>ALF 502R-5</td>
<td>0.038</td>
<td>0.015</td>
<td>-60.49</td>
</tr>
<tr>
<td>B737</td>
<td>CFM56-3B2</td>
<td>0.013</td>
<td>0.004</td>
<td>-71.37</td>
</tr>
</tbody>
</table>

Table 15: Comparison of the mean emission indices from AEMIII (“Hurley-correlation”)

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Engine</th>
<th>Mean soot EI [g/kg] from ref [69]</th>
<th>Mean soot EI [g/kg] (“FOA”)</th>
<th>Relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B707</td>
<td>JT3D-3B*</td>
<td>0.294</td>
<td>0.146</td>
<td>-50.18</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-22B</td>
<td>0.038</td>
<td>0.008</td>
<td>-79.58</td>
</tr>
<tr>
<td>L1011 Tristar</td>
<td>RB211-524B</td>
<td>0.027</td>
<td>0.005</td>
<td>-82.81</td>
</tr>
<tr>
<td>A300</td>
<td>CF6-50C2</td>
<td>0.012</td>
<td>0.006</td>
<td>-49.09</td>
</tr>
<tr>
<td>DC10</td>
<td>CF6-50C2</td>
<td>0.010</td>
<td>0.006</td>
<td>-36.84</td>
</tr>
<tr>
<td>B747</td>
<td>CF6-50E2**</td>
<td>0.009</td>
<td>0.003</td>
<td>-66.69</td>
</tr>
<tr>
<td>BAE 146</td>
<td>ALF 502R-5</td>
<td>0.038</td>
<td>0.009</td>
<td>-76.95</td>
</tr>
<tr>
<td>B737</td>
<td>CFM56-3B2</td>
<td>0.013</td>
<td>0.001</td>
<td>-91.41</td>
</tr>
</tbody>
</table>

Table 16: Comparison of the mean emission indices from AEMIII (“FOA”)

The average deviation between the values given in reference [69] and those determined by AEMIII using the three different correlations are 36.56%, 45.72% and 66.69% for the “DLR-correlation”, the “Hurley-correlation” and the “FOA” respectively. These values seem rather high, but it has to be emphasized once again, that the values of the emission indices are quite small, and hence, slight differences result in high percentile deviations. A more useful way to analyze the agreement of the calculated values is graphically, which is shown in Figure 59. The values for the Boeing 707 with the JT3D-3B engines are not included because of the high values for reasons of clearness. It can be seen that there are relatively strong deviations for the aircraft / engines L1011 / RB211-22B, L1011 / RB211-524B and the BAE146 / ALF 502R-5. For all three engines the Smoke Numbers are complete, hence assumptions made are as minimal as possible. Main reason for these variations might be different flight profiles, which were not available.
Figure 59: Comparison of the mean soot emission indices

Example mission calculation for an Airbus A340-300 with CFM56-5C2 engines:
Reference [80] describes a flight mission calculation performed by DLR with an Airbus A340-300 equipped with CFM56-5C2 engines. This is shown in Figure 60.

Figure 60: Flight mission calculation A340-300 with CFM56-5C2 by DLR [80]
The given flight mission includes taxi in and out and a step climb from 10060m to 11280m (FL330 and FL370) the flight range is 4000km with a cruise Mach number of 0.82. According to this the emission index of soot is below 0.01g/kg during taxi out and increases to its maximum of well above 0.05 during take off and decreases continuously during the climb phase. The main parameter to cause this behaviour is the decreasing combustor inlet pressure. The reduction in thrust at 10060m results in a decreasing combustor inlet pressure and thereby the emission index drops from about 0.02 to a cruise value of about 0.012g/kg. During cruise this value decreases further on when the aircraft is getting lighter. The emission index increases during the step climb and drops in the second cruise phase due to lower pressure values in the combustor inlet. During descent the emission index decreases due to the lower power settings of flight idle and finally increases due to higher power settings in the approach phases and the changing ambient conditions. For taxi out as well for taxi in the soot emission index is below 0.01g/kg [80].

The emission indices for non-volatile Particulate Matter for the same flight mission determined with AEMIII using the different correlations are shown in Table 17, Table 18 and Table 19.

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Soot EI [g/kg] from ref. [80]</th>
<th>Soot EI [g/kg] with AEMIII (“DLR”)</th>
<th>Relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take off</td>
<td>0.05</td>
<td>0.057</td>
<td>13.08</td>
</tr>
<tr>
<td>Climb out</td>
<td>0.05</td>
<td>0.052</td>
<td>3.50</td>
</tr>
<tr>
<td>Climb</td>
<td>0.035</td>
<td>0.030</td>
<td>-15.25</td>
</tr>
<tr>
<td>Cruise FL330</td>
<td>0.012</td>
<td>0.008</td>
<td>-36.34</td>
</tr>
<tr>
<td>Cruise FL370</td>
<td>0.011</td>
<td>0.006</td>
<td>-46.16</td>
</tr>
<tr>
<td>Descent</td>
<td>0.06</td>
<td>0.011</td>
<td>82.70</td>
</tr>
<tr>
<td>Approach</td>
<td>0.012</td>
<td>0.019</td>
<td>56.99</td>
</tr>
<tr>
<td>Taxi in</td>
<td>0.01</td>
<td>0.024</td>
<td>135.27</td>
</tr>
<tr>
<td>Taxi out</td>
<td>0.01</td>
<td>0.024</td>
<td>135.27</td>
</tr>
</tbody>
</table>

Table 17: Emission indices for non-volatile PM by AEMIII with “DLR-correlation” for the flight mission given in ref [80]
### Table 18: Emission indices for non-volatile PM by AEMIII with “Hurley-correlation” for the flight mission given in ref [80]

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Soot E1 [g/kg] from ref. [80]</th>
<th>Soot E1 [g/kg] with AEMIII (“Hurley”)</th>
<th>Relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take off</td>
<td>0.05</td>
<td>0.055</td>
<td>10.89</td>
</tr>
<tr>
<td>Climb out</td>
<td>0.05</td>
<td>0.047</td>
<td>-5.56</td>
</tr>
<tr>
<td>Climb</td>
<td>0.035</td>
<td>0.026</td>
<td>-26.50</td>
</tr>
<tr>
<td>Cruise FL330</td>
<td>0.012</td>
<td>0.003</td>
<td>-75.75</td>
</tr>
<tr>
<td>Cruise FL370</td>
<td>0.011</td>
<td>0.003</td>
<td>-73.54</td>
</tr>
<tr>
<td>Descent</td>
<td>0.06</td>
<td>0.004</td>
<td>-39.88</td>
</tr>
<tr>
<td>Approach</td>
<td>0.012</td>
<td>0.006</td>
<td>-51.63</td>
</tr>
<tr>
<td>Taxi in</td>
<td>0.01</td>
<td>0.008</td>
<td>-22.58</td>
</tr>
<tr>
<td>Taxi out</td>
<td>0.01</td>
<td>0.008</td>
<td>-22.58</td>
</tr>
</tbody>
</table>

### Table 19: Emission indices for non-volatile PM by AEMIII with “FOA” for the flight mission from reference [80]

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Soot E1 [g/kg] from ref. [80]</th>
<th>Soot E1 [g/kg] with AEMIII (“FOA”)</th>
<th>Relative error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take off</td>
<td>0.05</td>
<td>0.046</td>
<td>-8.64</td>
</tr>
<tr>
<td>Climb out</td>
<td>0.05</td>
<td>0.028</td>
<td>-43.49</td>
</tr>
<tr>
<td>Climb</td>
<td>0.035</td>
<td>0.015</td>
<td>-56.57</td>
</tr>
<tr>
<td>Cruise FL330</td>
<td>0.012</td>
<td>0.001</td>
<td>-90.73</td>
</tr>
<tr>
<td>Cruise FL370</td>
<td>0.011</td>
<td>0.001</td>
<td>-89.89</td>
</tr>
<tr>
<td>Descent</td>
<td>0.06</td>
<td>0.000</td>
<td>-94.47</td>
</tr>
<tr>
<td>Approach</td>
<td>0.012</td>
<td>0.001</td>
<td>-95.00</td>
</tr>
<tr>
<td>Taxi in</td>
<td>0.01</td>
<td>0.001</td>
<td>-92.88</td>
</tr>
<tr>
<td>Taxi out</td>
<td>0.01</td>
<td>0.001</td>
<td>-92.88</td>
</tr>
</tbody>
</table>

The average deviations for the "DLR-correlation", the “Hurley-correlation” and the “FOA” are 58.28%, 36.55% and 73.84%. It can be seen, that the emission indices especially for the flight phases with higher thrust settings show a higher accordance to the given values in reference [80]. Because of their duration, the most important flight phases are climb, cruise and descend. This depends on the total flight duration. The average deviations of the emission index during these phases are 45.11%, 53.92% and 82.92% for the “DLR-correlation”, the “Hurley-correlation” and the “FOA”. The graphical comparison of the results is shown in Figure 61.
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

The graphical comparison shows that the values determined with the “DLR-correlation” agree relatively well to those values determined by DLR. There are some differences, but these are basically not avoidable as there might be some differences between the models and the assumptions used by DLR and AEMIII. Again, the biggest differences can be seen when using the “FOA”.

In-flight measurements of non-volatile Particulate Matter:
Reference [73] describes the results of in-flight measurements of soot emissions behind an Airbus A310-300 equipped with CF6-80C2A2 engines and a Boeing B737-300 equipped with CFM56-3B1 engines. These measurements resulted in a soot emission index of 0.019±0.01 g/kg for the A310 (FL350) and 0.011±0.005 for the B737 (FL260). These values were predicted by calculations to 0.023 g/kg and 0.011 g/kg respectively (Table 20).

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Soot EI [g/kg] from ref. [73] (measured)</th>
<th>Soot EI [g/kg] from ref. [73] (calculated)</th>
<th>Soot EI [g/kg] with AEMIII (“DLR”)</th>
<th>Soot EI [g/kg] with AEMIII (“Hurley”)</th>
<th>Soot EI [g/kg] with AEMIII (“FOA”)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A310 / CF6-80C2A2</td>
<td>0.019</td>
<td>0.023</td>
<td>0.015</td>
<td>0.008</td>
<td>0.001</td>
</tr>
<tr>
<td>B737 / CFM56-3B1</td>
<td>0.011</td>
<td>0.011</td>
<td>0.010</td>
<td>0.006</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 20: Comparison with in-flight measurements [73]
These results show the best accordance when applying the “DLR-correlation”. The deviation between the measured and the calculated values (AEM) is between 21 and 9.1% when using the “DLR-correlation”. On the other hand, the deviation with “FOA” is 47.4 to 90.9%.

A comparison of all data found during the literature review with those determined with AEMIII and the different correlations are shown in the following pictures. Figure 62 shows all results using the “DLR-correlation”. It can be seen that the tendency of the results is rather good and an accordance to the values from other references can be noticed. Figure 63 the results of both other correlation from “Hurley” and “FOA”. As could be seen before, the “Hurley-results” agree relatively well to those from the “DLR-correlation”. The deviation when using the “FOA” is relatively strong, as already discussed before, especially in the region of low soot emission indices.

The comparison of all three correlations leads to the decision that the best agreement of emission indices for non-volatile Particulate Matter can be achieved when using the “DLR-correlation” in comparison with the measured and predicted (calculated) results from DLR.

![Validation of non-volatile PM emission indices](image)

**Figure 62: Results with „DLR-correlation“**
As mentioned before it is actually not possible to validate or verify the results concerning the volatile species of Particulate Matter and the size distributions as there is no data and no standardized measurement method available at present. The assumptions and procedures made in the previous chapters are all based only on information given in the literature. It remains to be awaited that such data will be published as soon as possible.

The comparison and discussion before showed that the here described methodology combined with the “DLR-correlation” is appropriate and accurate enough to determine the amount of emitted Particulate Matter - at least the non-volatile fraction – based on the ICAO Smoke Number. It was shown, that there is a relative good accordance to measured and calculated values from other studies. It might not be the “best” method as some assumptions were not able to be avoided, but until now it’s the only and -by the way- a quite simple method that allows determining the amount of emitted Particulate Matter for a huge amount of engines, even for those engines with sparse information on the Smoke Number. This method should be regarded as temporary, and should be advanced and further developed until the ICAO Smoke Number is replaced by an ordinary emission index for non-volatile and volatile Particulate Matter.
7 The Advanced Emission Model (AEMIII) and the Particulate Matter Module AEM_PT

The described methodology to estimate Particulate Matter emissions from aircraft was implemented into EUROCONTROL’s Advanced Emission Model. After a brief overview on AEMIII, the structure and the integration of the Particulate Matter module EM_PT will be presented.

7.1 Overview on AEMIII V1.5

The Advanced Emission Model (AEMIII) is a stand-alone system used to estimate aviation emissions ($CO_2$, $H_2O$, $SO_2$, $NO_x$, HC, CO, Benzene, VOC, TOC) and fuel burn. It is able to analyse flight profile data, on a flight-by-flight base, for air traffic scenarios of almost any scope and for global emissions from air traffic. [79] AEMIII uses several underlying databases (aircraft, aircraft engines, fuel burn rates and emission indices) provided by external data agencies in order to assure the quality of the information provided. This system information is combined with dynamic input data, represented by the air traffic profiles. [79] Below 3000ft, the fuel burn calculation is based on the Landing and Take off Cycle (LTO) defined by the ICAO Engine Certification specifications. ICAO LTO covers four engine operation modes, which are used in AEMIII to model the six following phases of operation: Taxi-out, Taxi-in (Idle), Take-Off, Climb-Out, Approach and Landing (Approach). The ICAO Engine Exhaust Emissions Data Bank includes emission indices and fuel flow for a very large number of aircraft engines. AEMIII links each aircraft appearing in the input traffic sample to one of the engines in the ICAO Engine Exhaust Emissions Data Bank. [79] Above 3000ft, fuel burn calculation is based on the “Base of Aircraft Data” (BADA). This database provides altitude and altitude dependent performance and fuel burn data for more than 150 aircraft types. Emission calculations are based on the ICAO Engine Exhaust Emissions Data Bank, but emission factors and fuel flow are adapted to the atmospheric conditions at altitude by using a method initially developed by The Boeing Company (The Boeing Method 2 – BM2) and modified by the EUROCONTROL Experimental Centre Business Unit (EEC-BM2). EEC-BM2 allows estimation of emissions for the pollutants $NO_x$, HC and CO. The emissions for the pollutants $H_2O$ and $CO_2$ are directly issued of the oxidation process of carbon and the hydrogen contained in the fuel with the oxygen contained in the atmosphere. The $SO_2$ emissions depend directly on the sulphur content of the used fuel. All three are
directly proportionally to the fuel burn. Benzene emissions, as well as VOG, TOG and all pollutants derived from VOC-TOG, are proportional to the HC emissions. [79]

For a more detailed description and further information on AEMIII I refer to the “AEMIII User Guide” [79].

Main objective of this diploma thesis is to extend the actual version of AEMIII (V1.5) by a stand-alone module AEM_PT AEM (Particulate Matter Tool) to allow the estimation of the Particulate Matter emissions treated in this study. The following will show in detail the functionality and the integration of this new module within AEMIII.

7.1.1 Performing a new study

This chapter describes the main steps and procedures to perform a new study using AEMIII with its module for Particulate Matter calculation AEM_PT. The description is performed in accordance to the “AEMIII User Guide” [79].

1. Opening New Study Dialogue:
To perform a new study select “New Study” from the opening menu (Figure 64).

![Figure 64: Select a new study](image)

2. Define Study Name:
A new window appears where the user can define a study name (Figure 65).
3. Define Study Output:
The following dialogue asks the user to specify the location for the data output (Figure 66).
4. **Load Traffic File:**
Specify the location of the traffic file that contains the traffic records, e.g. call signs (Figure 67).

![Figure 67: Load traffic file](image)

5. **Review the Traffic File:**
This window shows all traffic data listed in the traffic file. This allows examining the input data (Figure 68).
6. Load Flight File:
The user is asked to specify the location of the flight file that contains the records describing the individual flight phases of each flight (Figure 69).
7. Review Flight File:
In the following window shows all flight legs listed in the flight file. This allows examining the input data (Figure 70).

8. Settings:
Prior beginning the study the user is asked to make some settings that are necessary for the calculation. Here, the user has the possibility to decide if the Particulate Matter calculation is wished or not (Figure 71).
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Figure 71: Settings

**Traffic Sample Entry Time:**

**Off Block**
Select this option when the entry time in the traffic sample is the time that the aircraft begins to taxi.

**First Leg Start**
This option sets the entry time in the traffic sample to the time that the aircraft first becomes visible in the first leg of the flight file.

**Take Off**
Select this when the entry time in the traffic sample is the time that the aircraft begins its take off run.

**Take Off and Landing Times:**

**ICAO**
This option is selected when AEMIII builds virtual take off and landing legs. It will use times as specified in the application constants.

**Aircraft Specific**
Using this option allows AEMIII to build virtual take off and landing legs. It will use times as specified in Aircraft Mode times.
**Atmospheric Data Source:**

*International Standard Atmosphere*

If this option is checked AEMIII will use atmospheric data based on the International Standard Atmosphere (ISA) and the US Standard Atmosphere Supplements (for humidity) at 500m height intervals. The data values are then granulated to the actual study flight levels.

**Meteorological Data**

Using this option allows to import meteorological data from a file. This option is not available in the current version.

**Taxi Timings:**

*Airport Specific*

Select this option when it is desired that AEMIII builds virtual taxi legs using taxi in and out times from airport specific data. If data are not available, CFMU data are used. If CFMU data are not available, default data is used.

*CFMU*

Use this option when it is desired that AEMIII builds taxi legs using taxi in and out times from CFMU. If CFMU data are not available, default data is used.

*Default*

Select this when it is desired that AEMIII builds virtual taxi legs. It will use taxi in and out times as specified in the application constants.

**Complete Flight Profiles:**

Check the box if you wish AEMIII to partially or wholly complete the flight by adding missing legs.

*All Operations*

Completes the whole flight profile by adding LTO legs from departure and to arrival airport as well as joining these legs with the first and last known position of the aircraft according to the flight file.

*LTO Operations Only*

Add legs from departure and to arrival airport only.

**Copy Raw Data to Output:**

Check this box if it is desired to have the input flight and traffic data included in the output.
Consider Airport Elevation:
Checked
When AEMIII builds virtual legs it will use the airport elevation value specified in table “tblAirport” and all taxi and take off legs will begin at that flight level, if the data is unavailable for the airport then 0 will be assumed.

Unchecked
When AEMIII builds virtual legs it will assume airport is at 0 and all taxi and take off legs will begin at a flight level of 0.

Calculate Particulate Matter
Check this box if it is desired to perform Particulate Matter calculations.

DLR / Döpelheuer
If this option is selected, the “DLR-correlation” is used as shown in chapter 5.2.1.1.4.

First Order Approximation (FOA)
Select this option to use the correlation as shown in chapter 5.2.1.1.5.

Consider Abrasion (tyres, brakes, rwy)
Check this box to consider Particulate Matter emissions caused by mechanical processes (cp. Chapter 5.3).

9. Review study geographical and time limits:
Using the traffic and legs files AEMIII will by default specify the 3 dimensional and time limits of the study. It is possible to modify these limits if required by e.g. reducing the time span of the study or reducing the geographical area by modifying the maximum or minimum longitude or latitude. (Figure 72)
10. Application Constants:
Application constants are a series of pre-defined fields whose values effect the calculation of output from AEMIII (Figure 73).
11. Running the Study:
Pressing the “Start” button starts the calculation process (Figure 74).

![Figure 74: Running the study](image)

7.1.2 Reviewing a study
It is possible to review and analyze a study that has been performed previously. To start the review, select “Review Previous Study” from the opening menu (Figure 75).

![Figure 75: Review a previous study](image)

A new window will pop up, where the respective study can be selected from the list of all existing studies. The right side of the dialogue shows the details of all the options and variables that were used for the corresponding study (Figure 76).
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Figure 76: Review a previous study (2)

Route Emission Graphical Analysis
To perform a graphical analysis, select the study wished to analyse and click on the button “Route Emission Analysis” for the “traditional” pollutants $\text{CO}_2$, $\text{NO}_x$, HC etc. and “Route PM Emission Summary” to analyze the results for Particulate Matter ($\text{PM}_{\text{tot}}, \text{PM}_{\text{nv}}, \text{PM}_v, \text{PM}_{10}, \text{PM}_{2.5}, \text{PM}_{0.1}$). The graphical analysis module is previewed below. This module allows organising data into different views by selecting multiple aircraft on a specific rout and then viewing multiple pollutant emissions by single or all flight attitudes or viewing multiple attitudes by a single pollutant emission. (Figure 77)
Figure 77: Graphical analysis

View Flight Leg Emission Data
To view the actual Access database select the desired study and click the button “Flight Leg Emissions” for the “traditional” pollutants or “Flight Leg PM” for Particulate Matter Emissions. This allows to review the emissions for each flight leg. (Figure 78)
### View Flight Leg Emission Summary Data

To view the actual access database and the emissions for each flight, select the desired study and click on the button marked “Flight Emission Summary” for the “traditional” pollutants and “Flight PM Emission Summary” for Particulate Matter emissions (Figure 79).
View Flight Phase Emission Summary Data

To view the actual access database and the emissions for each flight phase for each flight, select the desired study and click on the button marked “Flight Phase Summary” for the “traditional” pollutants, and “Flight Phase PM Summary” for Particulate Matter emissions. (Figure 80)

![Flight Phase PM Emission Summary Data](image)

**Figure 80: View flight phase emission summary**

A more detailed description and further functions are treated more detailed in “AEMIII User Guide” [79].

### 7.2 The Particulate Matter estimation module AEM_PT

AEM_PT is a MS-Access based module that is integrated into EUROCONTROL’s Advanced Emission Model AEMIII. It allows performing Particulate Matter estimations if it is desired by the user. It is programmed in VBA and SQL programming languages. The module is divided into several sub functions that are called up during the main calculation process at the corresponding position. In the following a detailed description of the functionality and the structure of the module AEM_PT as well as its integration into AEMIII will be shown. The source code can be found in the annex. The module consists of several sub functions that will be explained in the following section.

Alexander Kugele
LoadICAOSmokeNumber()
This function allows loading a new version of the ICAO Engine Exhaust Emission Data Bank, when pressing the button “Load New ICAO Database” in the AEMIII’s Engine Emission Maintenance dialogue (“Engines” → “Engine Emission Rates”). The dialogue is shown in Figure 81.

Figure 81: Aircraft Engine Emission Maintenance

The user is then asked to specify the location of the database. The actual version of the database is ICAO_Engine_Emissions_Databank-Issue_13.

Before loading a new version of the ICAO Engine Exhaust Emission Data Bank, some minor preliminary changes have to be done to avoid problems during calculation process:

- Rename the engine manufacturer “AO ‘Aviadgatel’ ” to “AO Aviadgatel”. The inverted comma is understood by Access as operator.
- Delete Excel sheets “Record of changes” and “Column description”. Alternatively move the sheet “ICAO databank” to the first position. This is necessary because of the limits in the “TransferSpreadsheet” function in Access.
The complete databank is saved in table *ICAO_database*. A detailed description of the function *LoadICAOSmokeNumber()* is illustrated in the following chart flow in Figure 82.

![Flowchart for LoadICAOSmokeNumber()](image)

The ‘clean’ database is then saved in table *tblICAOdbClean*.

When loading a new version of the ICAO Engine Exhaust Emission Data Bank, this function is followed by a function called *CalculateSmokeNumber()*, that contains the “fill-the-gaps-algorithm” to determine the missing Smoke Numbers.

*CalculateSmokeNumber()*

This function contains the “fill-the-gaps-algorithm” described in chapter 6.1.2. It determines the missing values of the Smoke Number for all engines listed in the ICAO Engine Exhaust Emission Data Bank. The following schematic flowchart in Figure 83 shows the basic steps.
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Figure 83: Flowchart of CalculateSmokeNumber()

The Smoke Numbers for each operation mode and engine type are written into the table tblEngineModeSmokeNumber.

CalcPMatSLS()
The function CalcPMatSLS() determines the soot concentration within the exhaust gas and the corresponding emission indices for the different types of Particulate Matter for the operation modes of the Landing- and Take-off cycle based on the "DLR-correlation" according to chapter 6.2 to 6.4. Following flowchart shows the basic structure of the function.

Figure 84: Flowchart of CalculatePMatSLS()
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

CalcPMatSLS_FOA()
This function determines the emission index of particulate Matter for the LTO-phases based on the “FOA-correlation” (chapter 5.2.1.1.5).

![Flowchart of CalcPMatSLS_FOA()](image)

Create_tblEnginePMLTOValues()
This function creates a table called tblEnginePMLTOValues that contains the emission indices for Particulate Matter for the four thrust settings of the LTO-cycle.

GetPMEmissions()
This function contains a SQL-query that determines among others the atmospheric data for the actual flight level, the operation condition, the Mach number and the fuel flow for each flight leg and engine for the flight phases climb, cruise and descent. These values are then transferred to the function dblPMnvEI(), that calculates the emission index of non-volatile PM. Using the conclusions from chapter 6.4 and 6.7 allows deriving the emission indices for volatile PM, PM10, PM2.5 and PM0.1.

dblPMnvEI()
This function calculates the emission index of non-volatile Particulate Matter for each flight leg. The following flowchart in Figure 86 shows the basic structure of this function.
Convert the soot emission index into a soot concentration (chapter 6.2)

Determine the actual thrust setting, the air-to-fuel-ratio and the Corresponding reference soot concentration (chapter 6.3)

Determine the actual combustor inlet temperature and pressure and the flame temperature for “in-flight” and “ground”

Apply the P3-T3-correlation (chapter 6.2)

Convert the soot concentration into a soot emission index

Figure 86: Flowchart of dblPMnvEI()
Create New Output Database and copy traffic and flight data

Create temporary aircraft and fuel burn tables

Match flight legs to table

Add virtual flight legs

Granulate Standard Atmosphere

Granulate BADA Fuel burn data

Correct granulated BADA fuel for climb and descent

Perform time cut

Match aircraft to engines

Figure 87: Flowchart of CalcOutput() and integration of AEM_PT (1)
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Calculate Fuel Burn

Calculate average engine Mach Number for cruise, climb, descent

If CalcPM = TRUE

Calculate Smoke Number()

If tblEngineModeSmokeNumber = NULL

Calculate PM at SLS
CalcPMatSLS()
CalcPMatSLS_FOA()

Reorganize emission data

CalcPMatSLS()

If CalcPM = TRUE

Create_tblEnginePMLTOValues()

Calculate fuel burn for LTO-phases

If CalcPM = TRUE

GetPMEmissions()
(non-LTO)

Calculate CO2, H2O, SO2 for all phases

Figure 88: Flowchart of CalcOutput() and integration of AEM_PT (2)
Aircraft Particulate Matter Emission Estimation through all Phases of Flight

Figure 89: Flowchart of CalcOutput() and integration of AEM_PT (3)
8 Conclusion

Within the framework of this diploma thesis a methodology was developed to determine the emissions of Particulate Matter from an aircraft through all phases of flight based on the ICAO Smoke Number. The fact, that the Smoke Number is incomplete requires an algorithm to handle this problem: the “fill-the-gaps-algorithm”. This algorithm allows to complete the Smoke Number in the ICAO Engine Exhaust Emission Data Bank and to calculate a concentration of non-volatile Particulate Matter and hence a corresponding emission index for each engine and each operation condition applying a method developed by the German DLR. Concerning the volatile fraction of Particulate Matter and those particles emitted by mechanical processes, information and assumption given by literature are applied. The described method was implemented into EUROCONTROL’s AEMIII as a separate MS-Access-based module called “AEM_PT”.

The comparison of the results concerning non-volatile Particulate Matter caused by the combustion process in aircraft engines showed a rather good agreement to measured and calculated data from other studies. Concerning the other fractions – volatile PM and Particulate Matter from abrasion of tyres, brakes and runways- no comparable data is available at present. Therefore a validation of these species is rather difficult.

Nevertheless, this method seems to be quite promising, at least concerning the emissions of non-volatile Particulate Matter by combustion. Especially its simplicity and expandability speak for this method. In terms of the other components the results of current and future research on Particulate Matter remains to be awaited.

This method must be considered as a temporary method. The Smoke Number is not very accurate, as smaller particles are not considered during measurement because of the limits of the filter. But it is until now the only information on Particulate Matter emissions from aircraft engines. Newer engines produce much smaller particles. Therefore new standardized measurement techniques and procedures are necessary to determine the amount of emitted Particulate Matter –its volatile and its non-volatile fraction- in terms of an emission index.
References


[2] EUROCONTROL Homepage: [www.eurocontrol.int](http://www.eurocontrol.int)


[37] DEFRA–Department for Environment, Food and Rural Affairs: *Methods of Measurement of Airborne Particles*, Expert panel on air quality standards,


[45] ICAO Annex 16, Volume II


Aircraft Particulate Matter Emission Estimation through all Phases of Flight


9  Annex

9.1  Performed changes in AEMIII

9.1.1  Tables

Changed tables
tbl2DGrid
tbl3DGrid
tbl4DGrid
tblAppConsts

New tables
PM_FlightPhasesSummary
PM_FlightSummary
PM_unknownEngines
tblEngineModePMConcentration
tblEngineModePMEmissionIndex
tblEngineModeSmokeNumber
tblEnginePMLTOValues
tblLTOSmokeNumberSootConcatSLS
tblPMValues
tblPressureRatio
tblTmpICAOdbCalcMissingSN
ICAO_database
tblICAOdbClean
tblTmpAvrgSN
tblTmpAvrgSN2
tblTmpICAOdbDoubleDeleted
tblTmpICAOdbEnginesGrouped
9.1.2 Queries

Changed queries
qryApplyFraction
qryViewFlightSummary
qryGetFlightPhaseSummary
qryGetFlightSummary

New queries
qryCalcPM
qryGet_PM_FlightPhaseSummary
qryGet_PM_FlightSummary
qryGraphPM
qryInsertFAAEngines
qryInsertFAAenginesIntoSNCalcAtSLS
qryUpdateLTOPM01
qryUpdateLTOPM25
qryUpdateLTOPM10
qryUpdateLTOPMnv
qryUpdateLTOPMv
qryUpdateLTOPMtot
qryViewFlightPM
qryViewFlightSummaryPM
9.1.3 Forms

Changed forms
- frmEngineEmissionMaintenance
- frmSubStudyWiz5
- frmStudyList

New forms
- Engine PM SmokeNumber
- frmAnalyseDataPM
- frmGraphPM
- frmViewFlightPhaseSummaryPM
- frmViewFlightSummaryPM
## 9.2 Engine groups

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9.3 **Source Code**

The source code for the AEM_PT module can be found in part two of this work.