CRANFIELD UNIVERSITY

FRANK G NOPPEL

CONTRAIL AND CIRRUS CLOUD AVOIDANCE TECHNOLOGY

SCHOOL OF MECHANICAL ENGINEERING

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SUPERVISOR: RITI SINGH

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Abstract

Civil aviation, providing transport to connect people, cultures and economies, is situated at the heart of globalisation. Since its earliest days, it has grown along with every other part of the industrialised society and experienced growth rates exceeding that of global GDP. Projections suggest that future air traffic emissions will play an increasingly important role in the contribution to global warming, which is regarded to be a serious threat to earth's socio-ecological systems.

Air traffic contributes to the overall anthropogenic radiative forcing, a metric denoting perturbations in the earth's radiation budget, by the emission of greenhouse gases and aerosols, and also by the generation of high ice clouds, commonly known as contrails. Recent studies suggest that the radiative forcing resulting from contrails is potentially higher than that of all other air-traffic pollutants combined.

In light of this, contrail avoidance is attracting increasing interest from the aeronautical community. An important contribution to the understanding of the problem in a wider context is made in this thesis, alongside proposals for short, mid and long term strategies for contrail avoidance. These are in particular the optimisation of the aircraft for contrail avoidance, the application of remotely induced heat to suppress contrail formation, and a novel engine concept that exhibits the potential for a reduction of all emissions simultaneously. Aircraft optimisation deals with the adaptation of existing technology for more environmentally compatible air transport, whereas the latter two approaches are breakthrough technologies of a more disruptive character covered by several patents resulting from this research.

Short and mid term strategies are accompanied by an increase in carbon dioxide emissions. A study examining the long-term impact of aviation carbon dioxide emissions relative to that of contrails suggests that in order to achieve more sustainable air transport, the avoidance of contrails is inevitable. However, as the short-term impact of contrails is less severe, postponing contrail avoidance until the associated increase in carbon dioxide emissions is less significant could be a better way to deal with the problem.

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Contents

List of Figures

List of Tables

Nomenclature

BF Block fuel (fuel/passenger).

λ Climate feedback parameter $[W/(m^2K)]$.

c_p Specific heat capacity $[J/(kgK)]$.

Δ Finite difference.

S Distance.

DTI Department of Trade and Industry (UK).

EI Emission index $[kg_{emission}/kg_{fuelburned}]$.

η Efficiency.

S Flight path length.

GDP Gross domestic product.

GTP Global temperature potential.

$GTPP$ Global temperature potential.

$GTPS$ Global temperature potential.

GWP Global warming potential.

h	enthalpy $[J/(kg)]$
HPC	High pressure compressor.
HPT	High pressure turbine.
ω	Humidity ratio (specific humidity) $[kg_{water}/kg_{air}]$.
IEA	International Energy Agency.
$IPCC$	Intergovernmental panel on climate change.
$ISAR$	Inverse specific air range $[kg_{fuel}/(kg_{payload}\ km)]$.
L/D	Lift to drag ratio.
LPC	Low pressure compressor.
LPT	Low pressure turbine.
m	Mass $[kg]$.
M	Molar mass ratio M/M.
q_{net}	Fuel net calorific value $[J/kg]$.
OPR	Overall engine pressure ratio.
P	Power $[W]$.
R	gas constant $[J/(kgK)]$
RF	Radiative forcing $[W/m^2]$.
ϕ	Relative humidity $p/p_{saturation}$.
RS	Ratio passenger weight to empty aircraft weight.

c_p Specific heat capacity $J/(kg\ K)$.

SKO Seat kilometres offered.

σ Slope of curve in a humidity chart [Pa/K].

T temperature [$K,\ ^oC$]

TAS True air speed [$km/h,\ m/s,\ knots$].

TET Turbine entry temperature [K].

Chapter 1

Introduction

1.1 Global warming

The earth's atmosphere is a protective layer of air enabling life in its form as we know it today. It shields cosmic radiation and holds elements crucial for the emergence of biologic life. Weather phenomena, which is the large scale movement of air and evaporation and precipitation of water, occur in the atmosphere. The scale and strength of weather events is primarily dependent on the amount of energy in the atmosphere. This energy is provided by the sun in the form of cosmic radiation, heating the planet's atmosphere. The heating occurs due to absorption and emission of thermal radiation by some of the air molecules. The dominant absorbers of solar radiation are CO_2 and water vapour. Without this warming effect, the earth's atmosphere would be much cooler, and unhabitable for the majority of species currently occupying the planet.

This warming effect was firstly recognised in 1827 by Jean-Baptiste Fourier, who observed it in greenhouses and drew parallels to the atmosphere. In a greenhouse, solar radiation is passing the glass almost unimpeded and is then absorbed by plants and the soil, which re-emit it in form of thermal infrared radiation. However, the infrared radiation is absorbed by the glass and scattered back into the greenhouse, which has the effect of keeping the temperature higher than without the surrounding glass. Based on this observation, the atmospheric warming was called greenhouse effect, and the radiation absorbing gases in the atmosphere are called greenhouse gases. Without greenhouse gases, the earth's atmosphere would be 21^oC or so lower. The blanketing due to naturally present greenhouse gases in the atmosphere, and the associated temperature difference, is known as the natural greenhouse effect.

An increasing greenhouse gas concentration would have an effect on the average global temperature because more thermal radiation would be absorbed. John Tyndall measured the absorption of infrared radiation by CO_2 and water vapour around 1860, and Arrhenius [1896] first speculated that changes in the levels of CO_2 in the atmosphere could substantially alter the surface temperature through the greenhouse effect. In 1940, Guy Stewart Callendar linked rising carbon dioxide concentrations in the atmosphere to global temperature. It is believed that he was the person who for the first time forecasted a global temperature rise due to increasing CO_2 concentrations as a result of burning fossil fuels. Revelle and Suess [1957] pointed out that the anthropogenic increase in CO_2 concentration would create an enhanced greenhouse effect, potentially causing significantly elevated global temperatures in the long term. The change in temperature would in return cause a change in variations of weather, known as climate change.

According to numerous studies, an increase in temperature will provoke a more hydrological cycle with more water vapour in the atmosphere and more severe weather events. While most areas expected to experience negatively associated

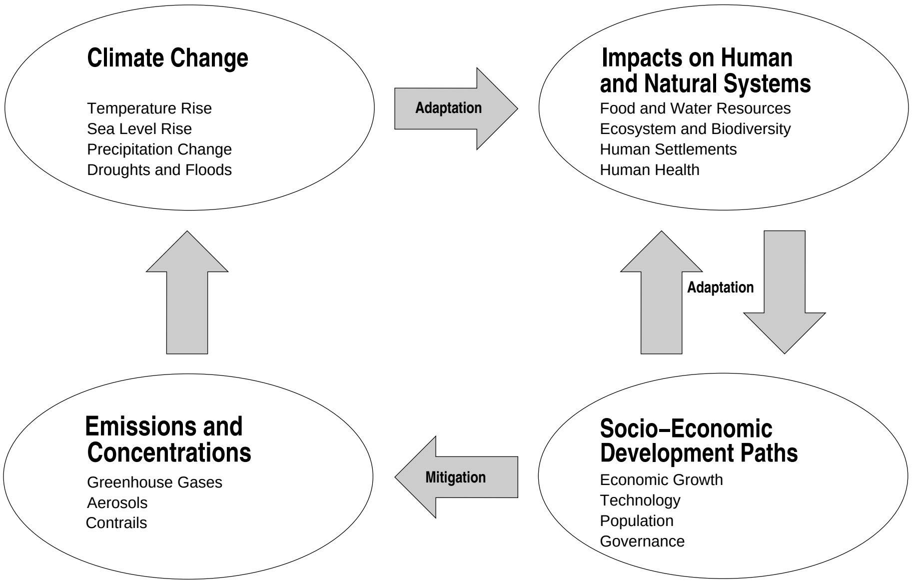


Figure 1.1: Climate change: source, impact and response [adopted from Houghton, 2004].

consequences such as more frequent and severe droughts or sea level rise, other areas might experience beneficial effects. But it is the abruptness of the change that is of greatest concern. If it occurred slowly enough, socio-ecological systems would be able to gradually adapt to it. A sudden change, as observed during the last decades, will have consequences that are hard to foresee. But most likely, human and natural ecosystems will find it difficult to adapt.

An integrated view of climate change is given in 1.1. Human activities in its various forms, such as emissions or deforrestration, impact the global climate. Climate change, in return, has an indirect impact on human or natural systems. Communities and natural systems can respond to changes in two ways: adaptation is aimed at reducing the effects due to climate change, and mitigation is aimed at reducing the cause of climate change.

The continually increasing demand in fossil fuels and projections regarding future emissions have led to the topic of global warming coming on top of political agendas. Governments are increasingly accepting the underlying science and thanks to the moral and economic pressure, cleaner energy sources are now anticipated to be put into place [The Economist print edition, 2007]. Policies and new regulations will require companies and private individuals to adopt more environmentally friendly technologies. Companies started realizing that although global warming is a cost driver, it may also provide new opportunities. New markets, technologies and businesses emerge, where revenues can be created. The change to alternative technologies, evoked through the introduction of policies, can occur in a disruptive manner. Sudden emergences of CO_2 reducing measures will be beneficial to companies that have positioned themselves well. It is believed that the firms which spent money on more environmentally friendly technologies are more likely to do well out of CO_2 emission constraints.

1.1.1 The fundamentals of global warming

Regarding earth as a closed system, solar incoming short-wave radiation is either absorbed or reflected back into space. Absorbed radiation is converted into heat energy, keeping the planet at a habitable temperature. Following the Boltzman law, a body of temperature above absolute zero Kelvin is radiating, whereas the intensity of the radiation depends on the body's temperature. Under equilibrium conditions, terrestrial infrared radiation due to the earth's temperature is offset by incoming solar radiation, and the energy fluxes of the ingoing and outgoing radiation are equal.

Pollutants, such as greenhouse gases, impose a perturbation on the equilibrium state by absorbing additional heat energy. The amount of energy absorbed is denoted by radiative forcing (RF), which is the amount of radiation forced to remain within system earth, i.e. the atmosphere, oceans and soil. As more and more heat is absorbed, the earth's temperature increases. The radiative forcing of a particular pollutant depends on its spatial distribution and its interaction with solar and terrestrial radiation [Shine and de Forsters, 1999]. A temperature rise will occur over time until the outgoing and the ingoing radiation are in equilibrium again. The expected steady state equilibrium temperature change due to a certain pollutant depends on the strength of its radiative forcing. A positive radiative forcing will cause a temperature rise, whereas a negative radiative forcing will cause a temperature drop.

Furthermore, the temperature change is also determined by the climate feedback parameter λ. It can be understood as a gain factor, accounting for three-dimensional atmosphere-ocean feedback mechanisms such as cloud or sea ice formation. The value of the climate feedback parameter varies from model to model. Despite vast improvements in climate modelling techniques, its quantification remains little improved and its uncertainty is often used by climate change sceptics to denounce climate change predictions [Lindzen et al., 2001].

1.1.2 Quantification of climate impacts

The quantification of the impacts of pollutants is fundamental for the assessment of global warming and its consequences. Metrics are used to identify and compare contributions from polluters on a global scale down to individuals. They support the development of pollutant abatement strategies and support decision-making processes. A metric can either represent the amount of pollutants released in the atmosphere or the impact they have on the environment, whereas the impact on the environment can be broken down into several levels. Regarding the impact of emission as a chain [Shine et al., 2005], the levels are: emissions $\rightarrow$ radiative forcing $\rightarrow$ climate impact $\rightarrow$ societal and ecosystem impact. Although the relevance of the impacts increases further down the chain, there is a corresponding increase in uncertainty and complexity in computational techniques. Ultimately, a metric reflecting the impact on the socio-economic development paths would be most desirable. In the following, the most important metrics that are used today will be introduced.

Radiative forcing

In a very simplified representation, the steady-state global mean surface temperature change due to perturbations in the planetary's radiation budget relative to a baseline temperature is defined as

$$\Delta T_s = \lambda RF \tag{1.1}$$

where ΔT_s is the temperature change, λ is the climatic feedback parameter and RF is the radiative forcing. Radiative forcing is expressed in terms of Watt per square meter, denoting the energy flux per unit earth's area forced to stay on earth. A positive forcing tends to warm the system, while a negative forcing tends to cool it. Efficacy is a term often associated with radiative forcing. It is defined as the ratio of the climate sensitivity parameter for a given forcing agent relative to the response produced by a standard CO_2 forcing from the same initial climate state [Hansen et al., 2005].

The radiative forcing of gaseous agents is dependent on their concentration, which is determined by the accumulated emissions in the atmosphere. Pollutants with long residence times, such as CO_2 cause a radiative forcing up to several decades after emission until they are absorbed by the natural environment. An immediate abatement of all carbon dioxide emissions would only result in a gradual decay of the CO_2 concentration and the associated radiative forcing. Radiative forcing is therefore a metric reflecting the current impact of past emissions. Other emissions, such as contrails, have much shorter residence times. They stay in the upper troposphere only up to some hours. Immediate avoidance would be followed almost instantaneously with the radiative forcing diminishing to zero.

Global warming potential

Global warming potential (GWP) is a metric for the contribution of a certain pollutant to global warming. It is a relative scale, comparing the environmental impact of a pollutant to that of the same mass of a reference gas, which is commonly CO_2 and has a GWP of one by definition. The definition of GWP is the “ratio of the time-integrated radiative forcing from the instantaneous release of 1kg of a substance relative to that of 1 kg of a reference gas.” In this case, the term “instantaneous” refers to a pulse emission of a certain amount of the pollutant. Quoting the GWP without specifying the length of the time period is meaningless. In the Kyoto Protocol, the time period is fixed to 100 years, although shorter and longer timescales are possible to calculate. Today, the time span of 100 years is commonly used as time period for calculating the GWP.

Unfortunately, the global warming potential is regarded to be not a suitable measure for the influence of aviation emissions [Rogers and Shine, 2005]. It is a metric that reflects the effect of one tonne of emitted pollutant gas, assuming the gas to be homogeneously distributed in the atmosphere and to have a reasonably long lifetime. However, aviation pollutants such as NO_x or contrails are more short lived, and their occurrence is more confined to certain regions and altitudes. Additionally, the environmental impact of some aviation pollutants is dependent on factors such their geographical location of release, the time when or also altitude where they were emitted.

Global temperature potential

Alternatives to the GWP for comparing the climate impact of emissions of greenhouse gases have been proposed by Shine et al. [2005]. Two different greenhouse gases, one strong with a short life-time and the other weak with a long live-time, can have the same GWP. At a given time, however, the temperature response due to a pulse emission might be different. Two metrics are proposed in Shine et al. [2005], both called the Global Temperature Change Potential (GTP), covering pulsed emissions (GTPP) and sustained emissions (GTPS). They represent the temperature change at a given time due to a pulse emission of a gas, making interpretation unambiguous as opposed to the GWP.

Both the GTPP and the GTPS are one step down in the chain on page 6. They are capable of modelling the influence of short-lived species, and are more applicable for quantifying the influence of aviation emissions on the global climate.

Other metrics

At the end of the chain of pollutants and their environmental impacts on page 6 are the societal and ecosystem impact. An assessment of pollutants regarding the societal and ecosystem impact would be most relevant, but due to their complexity, they are difficult to calculate. Attempts are made to measure the climate impact in terms of abatement cost or welfare loss applying empirical approaches, and is becoming more and more common to quote fiscal numbers. The use of fiscal numbers is particularly attractive for policy makers and in industry because climate change can be associated with a cost. As industry is profit driven, the association of climate change with a cost gives incentives to reduce their environmental footprint.

1.1.3 Trends

Carbon dioxide is the dominant mode through which carbon is constantly transferred in the natural environment between a variety of carbon reservoirs. Burning fossil fuels, which is one reservoir, means taking carbon from beneath the earth's surface, converting it to CO_2 and emitting it into the atmosphere. The accumulation of carbon dioxide in the atmosphere occurs due to the absence of sufficient natural carbon dioxide sinks. The atmospheric concentration of CO_2 and that of other pollutants are constantly recorded. Etheridge et al. [1996] derived the change in carbon dioxide concentration over the past from Antarctic ice core measurements. Results are shown in figure 1.2, showing an increasing trend of the atmospheric carbon dioxide concentration since the beginning of the industrial revolution. Especially during the last few decades, the atmospheric carbon dioxide concentration has increased sharply.

Human contributions to global warming are constantly assessed by the Intergovernmental Panel on Climate Change (IPCC), which has been established to improve the understanding of climate change, its potential impacts and options for adaptation and mitigation. Figure 1.3 is provided by the IPCC, summarizing the principal human induced mechanisms that force climate change. Not only the emission of greenhouse gases contributes to global warming, but also e.g. the alteration of surface reflectance by land use. The only forcing in figure 1.3 that is of non-human origin comprises the variations in the output of the sun. Some of the radiative forcing agents, such as such as CO_2, are homogeneously distributed over the globe. Other perturbations, such as aerosols, have more distinct regional signatures be-

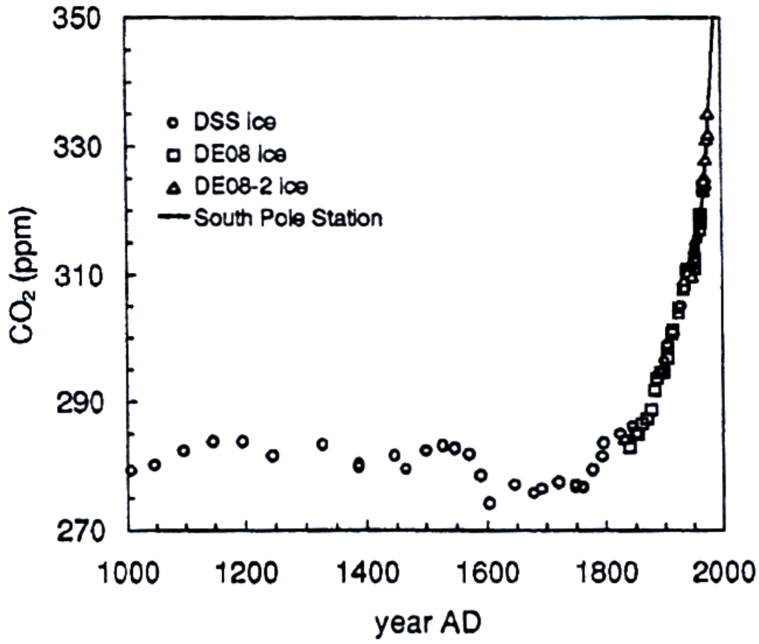


Figure 1.2: Global carbon dioxide concentration [adopted from Etheridge et al., 1996].

cause of their spatial distribution. Therefore, but also due to other reasons, the cumulative of all displayed radiative forcings cannot be expected to yield the net effect on the climate system.

As the atmospheric concentration or occurrence of a certain pollutant changes, so does its radiative forcing. For pollutants with relatively short lifetimes, an instant change in their emission rates, which could be measured in mass units or occurrences per unit of time, would then almost instantaneously provoke a change in their radiative forcing. Species with long life times, such as CO_2, accumulate in the atmosphere. Even if the emission of CO_2 was avoided instantaneously, it would take decades until all CO_2 of human origin was absorbed and the radiative forcing due to CO_2 settled to preindustrial levels.

Today, climate models are used to learn about likely climate change and beyond.

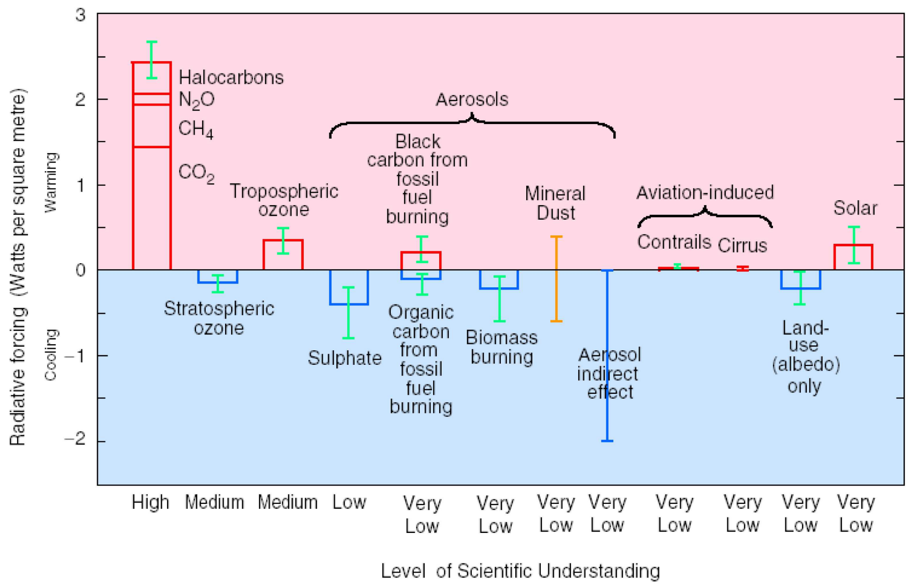


Figure 1.3: Global mean radiative forcing in 2000 relative to 1750 [adopted from IPCC Working Group 1, 2001].

Because of the uncertainty associated with simplifications in climate models and emission forecasts, the results of climate models are referred to as scenario projections rather than predictions. Emission scenarios, such as developed by the IPCC in IPCC [2000], are forecasts of emissions making assumptions regarding human behaviour and activities such as population, economic growth or energy efficiency. Based on the considered emission scenarios, estimates regarding the future global temperature can be made. Abatement strategies can be tested by implementing them into the climate model. Figure 1.4 shows a variety of temperature projections considering several scenarios. The calculated temperature change due to anthropogenic activities relative to the year 2000 is in the range between 1.5 and 4K.

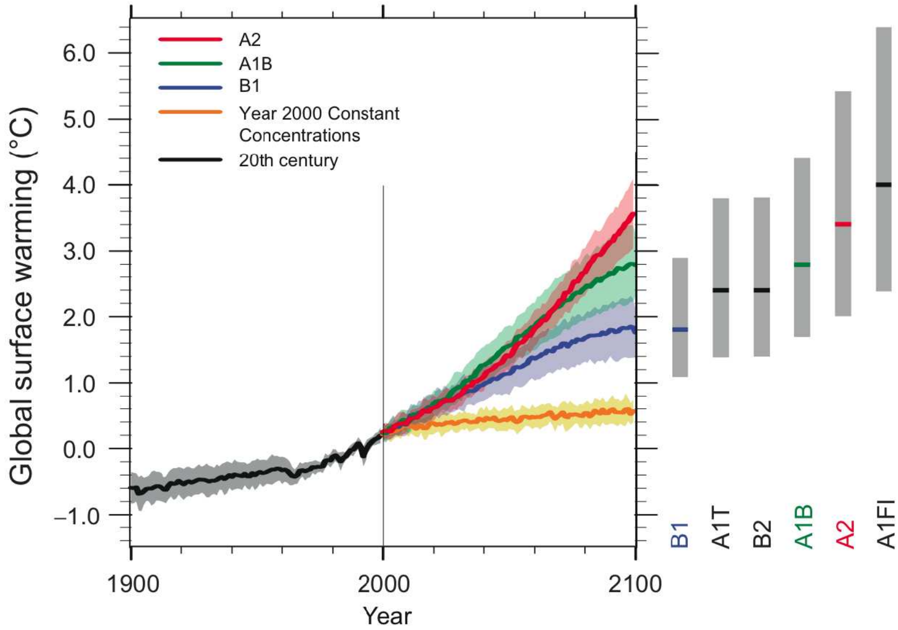


Figure 1.4: Global averaged and assessed ranges for surface warming [adopted from IPCC, 2007].

1.1.4 Mitigation

Because earth is the principal enabler for human life as a matter of principle, it becomes intuitively plausible to regard is as common property [Höffe, 2004]. And this property is shared over generations in equal measures. Justice teaches, and it is anchored in the genes of the human species, to provide an equally habitable environment for future generations. The principal driver in evolution has always been the desire to protect offspring. Global warming puts the global population at a risk, and it is our responsibility to react accordingly to changes in the global climate and the threats that come with it.

New technologies, both technological and operational, are being developed to reduce the environmental footprint of the international economies. Incentives are put into place where no natural desire for the implementation of cleaner technologies exist. This can usually be achieved through the introduction of policies, regulations, taxation or emissions trading, taking place globally, nationally or regionally, but also within more constrained borders such as companies or institutions. In the long term, a competitive advantage may exist for companies with cleaner technologies, especially if the education of the end consumer causes a paradigm shift. The complexity of the interactions of global warming with economic, political, social and technological processes imposes uncertainty and the risk of irreversibility on the decision making processes.

Climate change mitigation has a mutual influence on broader socio-economic trends such as development, sustainability or equity, and policies may promote sustainable development when they are consistent with broader societal objectives if they yield benefits outside their initially pursued area. An unequal distribution of resources among communities and between generations, as well as the cost that comes with mitigation, have to be taken into account during the analysis of climate change mitigation options.

1.2 Aviation and the global atmosphere

Aircraft pollutants are radiatively or chemically active substances which can reflect or absorb solar or terrestrial radiation or alter the chemical composition of the atmosphere. Kärcher [1999] provides a comprehensive review on aircraft emissions and their impacts. Figure 1.5, adopted from this publication, shows the regions of the earth's atmosphere that are impacted by aircraft emissions. The principal air-traffic pollutants in a global context are CO_2, water vapour, NO_x, soot, aerosols and contrails. The emission of NO_x in combination with CO and unburned hydro carbons leads to the tropospheric production of ozone, and stratospheric depletion

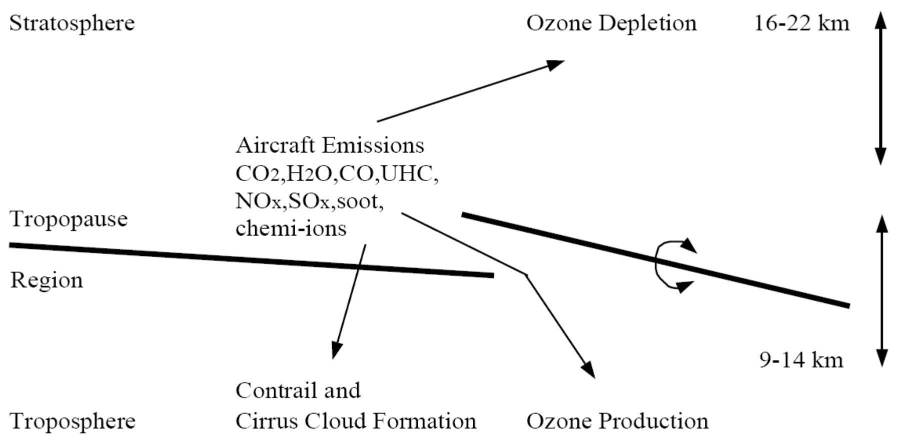


Figure 1.5: Influence of aircraft emissions on the atmosphere [adopted from Kärcher, 1999].

of ozone. Sulphur species, nitrogen species and water contribute to the formation of liquid particles, which can affect the tropospheric chemistry. Particulates and water vapour lead to the formation of contrails, which, because of their radiative properties, contribute to global warming.

1.2.1 Carbon dioxide

Carbon dioxide emerges during the combustion of kerosene, and emissions rates can be related linearly to fuel burn rates. The emission index of kerosene for carbon dioxide is about 3.16, implying that for each mass unit of fuel burned, about 3.16 mass units of carbon dioxide are produced.

The present emissions of CO_2 from air-traffic are about 8.4% of the overall CO_2 emissions in the transport sector, or roughly 2% of all anthropogenic CO_2 emissions [Roger et al., 2002]. Figure 1.6 shows world greenhouse gas emissions by sector for the year 2002. The figure was composed from data from the International Energy Agency (IEA). Relative to other industry sectors, air-traffic carbon

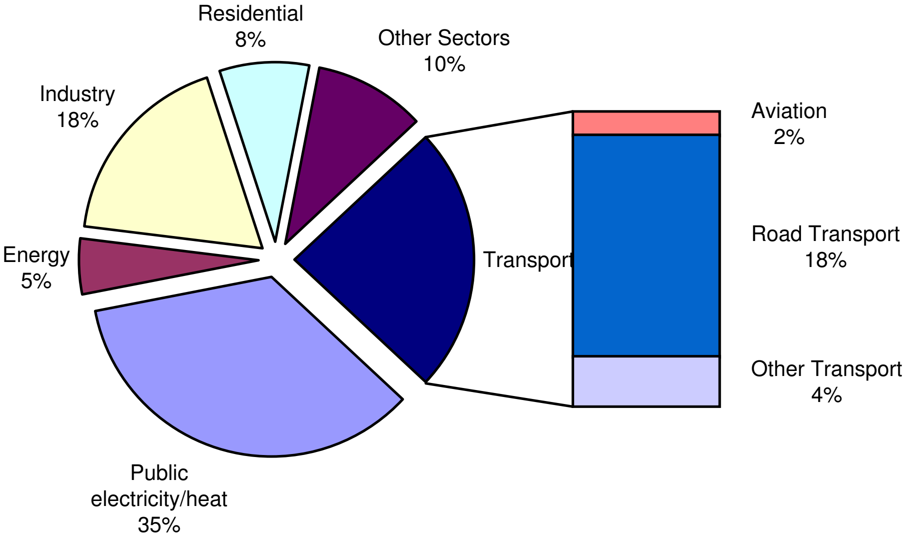


Figure 1.6: World carbon dioxide emissions by sector with data from the IEA.

dioxide emissions appear to be relatively low. However, it is the forecasted growth rates in air-traffic of 3-5% and the associated emissions that put pressure on the aerospace industry [Airbus, 2003, Eyers et al., 2004]. As air-traffic is growing, its emissions in terms of share and magnitude are considered to increase [Lee, 2004].

The radiative forcing of CO_2 from a particular industry sector is attributed to the accumulated amount of CO_2 in the atmosphere. In general, this is true for every pollutant. However, carbon dioxide has an atmospheric residence time of more than 100 years. Hence, the accumulated carbon dioxide emissions of a particular industry sector over the last 100 years are considered if the radiative forcing is calculated. Aviation became commercially viable during the last 70 years, and the radiative forcing from aviation CO_2 as shown in figure 1.10 is that of the accumulated CO_2 emissions during that time period.

1.2.2 Water vapour

Water, in vapour phase a relatively strong greenhouse gas, is also a combustion product. The emission index of water is about 1.28. Water emitted in the troposphere precipitates relatively shortly after emission, whereas stratospheric water can have longer residence times and hence a more significant radiative forcing. It has been calculated that air-traffic water vapour emissions account for about 5% of the observed increase in stratospheric water content [Danilin et al., 1998]. However, according to Schumann et al. [2001], the radiative forcing from stratospheric water vapour is marginal.

Water also plays an important role in the formation of contrails.

1.2.3 Soot and Aerosols

Atmospheric aerosol concentrations from air-traffic are relatively small compared to the contribution from surface sources. Even at the prevailing rate of air-traffic growth, the aerosol mass concentrations from aviation in 2050 are projected to remain small [Penner et al., 1999]. Soot emissions tend to warm the atmosphere, whereas sulfates have an opposite effect. Compared to other aircraft emissions, the direct radiative forcing of soot and aerosols is relatively small. Aerosols also play an important role in the formation of cirrus clouds that would not form in the absence of aviation, resulting in enhanced cloud formation and the modification of the radiative properties of natural cirrus clouds.

1.2.4 NO_x

The formation of NO_x, a generic term for the mono-nitrogen oxides NO and NO_2, occurs at high temperatures within the engine. Mainly atmospheric nitrogen oxidises to NO, which is quickly converted to NO_x both inside the engine and in the aircraft plume. Another nitrogen source is fuel, where it occurs in traces. NO_x emissions impact the global atmosphere in two ways. They produce ozone in the upper troposphere, which is an effective greenhouse gas. Ozone formation due to NO_x emissions in the upper troposphere is more effective than at the earth's surface. Apart from increasing tropospheric ozone concentrations, aircraft NO_x emissions decrease the concentration of another greenhouse gas: methane. A reduction in methane implies a cooling of the atmosphere.

Tropospheric ozone concentrations are affected by air-traffic mainly in the northern hemisphere, whereas the influence on methane concentrations is less spatially confined. On a global scale, the average radiative forcings due to ozone production and methane reduction offset each other partially, implying a relatively low overall radiative forcing due to aviation NO_x.

1.2.5 Contrails

Contrails are thin line-shaped ice clouds that can emerge in the wake of an aircraft (see figure 1.7). They were first observed during high-altitude flights in the 1920's, and air forces developed interest in contrails because they enhanced the visibility of their planes. The formation of contrails underlies many effects, such as chemical reactions in the aircraft plume, aircraft wake dynamics, ice microphysics, the state of the atmosphere within the flight corridors, atmospheric dispersion rates and engine technology. Depending on the atmospheric conditions, contrails can either

Figure 1.7: Photo of contrails of different ages.

evaporate shortly after formation, or persist for time periods of up to some hours.

In average, the backscattering of terrestrial radiation by the contrail's ice crystals is more effective than the reflection of solar radiation, creating a net positive radiative forcing. First concerns regarding air-traffic and their effect on the climate were made by Appleman [1966]. Back then, the announced introduction of a large fleet of supersonic transport aircraft, which has never happened, initiated first studies. Later, the topic was picked up again by Changnon [1980]. However, it was concluded that an increase in cloudiness could not be considered as proof of a jet-induced cirrus influence.

The potential effects of contrails on the climate were then again discussed by Schumann and Wendling [1990]. Sausen et al. [1998] presented first estimates regarding global contrail coverage, and the issue found its way into the IPCC special report [Penner et al., 1999]. Since then, a large number of studies have been performed to understand formation mechanisms of contrails and their impact on the global climate.

During the tragic events of the 11 September 2001, the airspace over the USA was shut down for commercial and personal air-traffic for a time period of about 36 hours, resulting in the absence of contrails over the USA. Although contrails

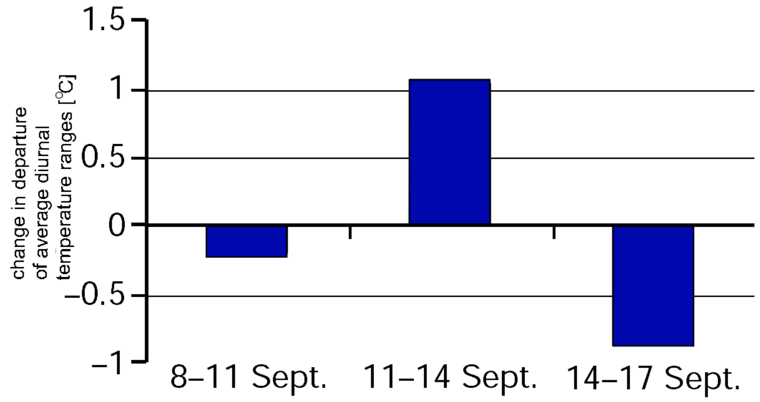


Figure 1.8: Departure of average diurnal temperature ranges from the normal values [adopted from Travis et al., 2002].

have a heating effect on the atmosphere on a global scale, they cause locally lower temperatures on the earth's surface during daytime and higher temperatures during nighttime [Ponater et al., 2002]. The average diurnal temperature range, which is the difference between the daytime minimum and nighttime maximum occurring temperature, is hence reduced in the presence of contrails. Travis et al. [2002] measured the average diurnal temperature range for the periods 8-11, 11-14 and 14-17 September 2001 and calculated its departure from the normal values derived from climatological data between 1971-2000 as shown in figure 1.8. The increase in the departure of average diurnal temperature during the 11-14 September 2001 is larger than it has ever been in the previous 30 years, and it is suggested that the anomaly occurred due to the absence of contrails during the shutdown. Simulations were carried out by Minnis et al. [2003] to explain the temperature anomaly. Although the results may explain the temperature anomaly, it was suggested to improve the calculation for more accurate results.

The IPCC reported a radiative forcing from linear persistent contrails of about 20.0 mW/m^2 for the year 1992, which was approximately 42% of the total aviation induced radiative forcing. A more precise estimate of the radiative forcing from

Figure 1.9: Photo of contrail cirrus cloud.

persistent linear contrails is given in Sausen et al. [2005] with 10.0 mW/m^2, representing approximately 20% of the total radiative forcing from air traffic. The future development of contrail cover and the associated radiative forcing has been investigated by Marquart et al. [2003]. Results suggest that annually and globally averaged total contrail cover and the associated radiative forcing approximately quadruplicates during the next decades due to the increase in air-traffic.

1.2.6 Contrail cirrus

Persistent contrails form where the ambient humidity is not high enough to facilitate natural ice-cloud formation. Depending on the atmospheric condition, persistent contrails can spread and form large area so called contrail cirrus clouds (see figure 1.9). The radiative properties of contrail cirrus are similar to that of contrails, and the overall radiative forcing of contrail cirrus is believed to be several times larger than that of contrails (see figure 1.10).

1.2.7 Secondary cirrus

Secondary cirrus can occur where soot and aerosol concentrations are elevated due to air traffic [Jensen and Toon, 1997, Stordal et al., 2004, Zerefos et al., 2003b]. Additionally, an indirect impact from aircraft particulates is possible when ice crystal size and number densities of natural cirrus clouds are modified [Kristensson et al., 2000]. The increase in both cloudiness and cirrus cloud modification are believed to cause a positive radiative forcing. Significant cirrus modification by black carbon particles, very likely also yielding a positive radiative forcing, cannot be excluded [Hendricks et al., 2005].

1.2.8 Summary

An estimate of all air-traffic emissions in terms of radiative forcing was first published in Penner et al. [1999]. An update on the report by Sausen et al. [2005] provides more accurate estimates. In figure 1.10, the radiative forcings from aviation as they appear in both publications are shown. **Although a precise estimate of the radiative forcing from contrails, contrail cirrus, secondary cirrus and cirrus modification is not possible at the current level of understanding, there is the potential they cause a radiative forcing exceeding that of all other air-traffic pollutants combined.**

1.3 The role of aviation in a global context

Aviation is playing an important role in the modern society [Thomas and Raper, 2000]. Mobility and economic development is going hand in hand. Aviation is a

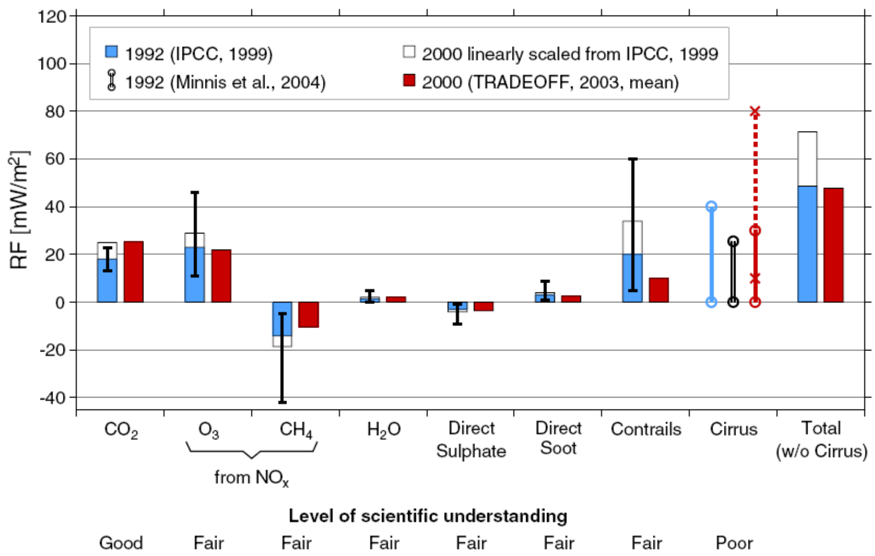


Figure 1.10: Radiative forcing from aviation for 1992 and 2000 [adopted from Sausen et al., 2005].

wealth creator, playing an integral role in business and commerce and supporting the operation and competitiveness of global, regional and local economies by facilitating rapid transport of people and goods over large distances [ACI, 1998]. The increase in services facilitates the development of societal, business and family networks, contributing to the mutual understanding of the different cultures [Nielsen, 2001]. Although it was believed that advances in information technology could level off the demand in transport, the continued growth in the aerospace sector in the recent years proves the opposite. The social and economic benefit from aviation is significant, and will probably become more important in future. In particular emerging economies will benefit from an integrated network, linking them to the major economic centres.

Since the advent of commercial air transport, the fuel efficiency of aircraft has been improved steadily, yielding lower carbon dioxide emissions per revenue passenger kilometer. In the past, however, the driving force for a better fuel economy was not the environment. More fuel efficient aircraft give a competitive advantage over less efficient aircraft as fuel drives direct operating cost, impacting profit margins of airlines. Figure 1.11 shows the change of the average energy intensity in MJ per revenue passenger kilometer of the commercial US aircraft fleet since the first commercial jets. Advances in airframe and engine technology, as well as improvements in air-traffic management, resulted in a decrease in average energy intensity of about 60% between 1970 and 2000.

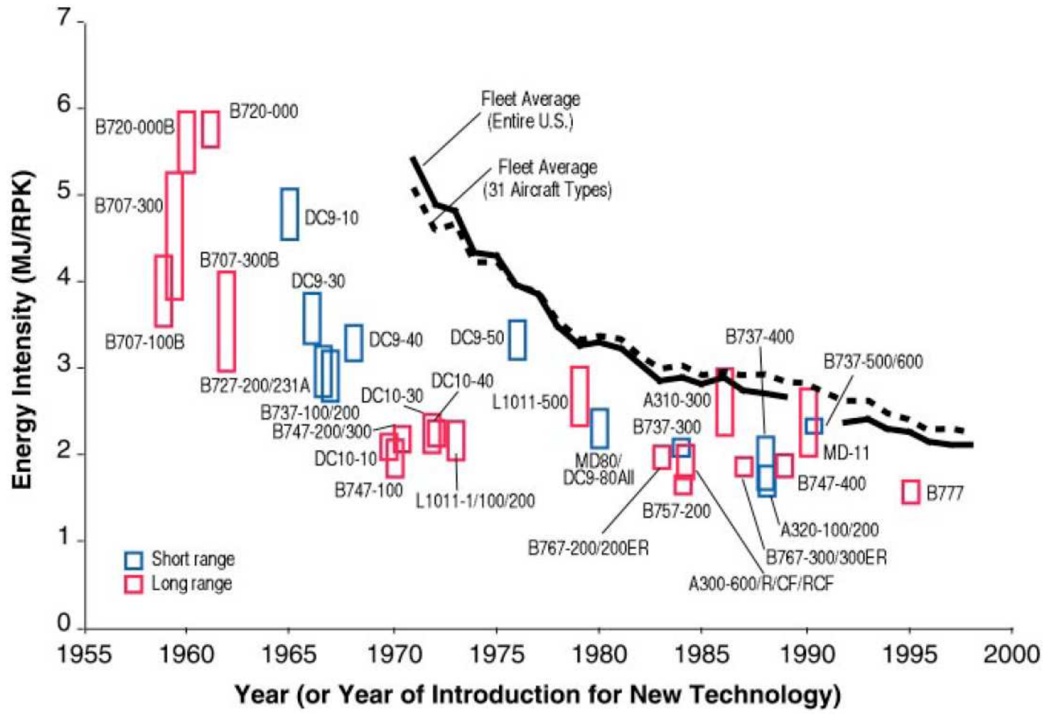


Figure 1.11: Historical trends of energy intensity of the commercial US aircraft fleet in terms of MJ per revenue-passenger kilometres [adopted from Lee et al., 2001].

Technological, physical and economical constraints, however, set limits to the nature and scale of improvements, and technologies start maturing. Further improvements are becoming more and more difficult to achieve, and are accompanied by higher capital cost. In terms of specific primary energy demand, a metric considering most of the measurable losses that occur in transport in general,

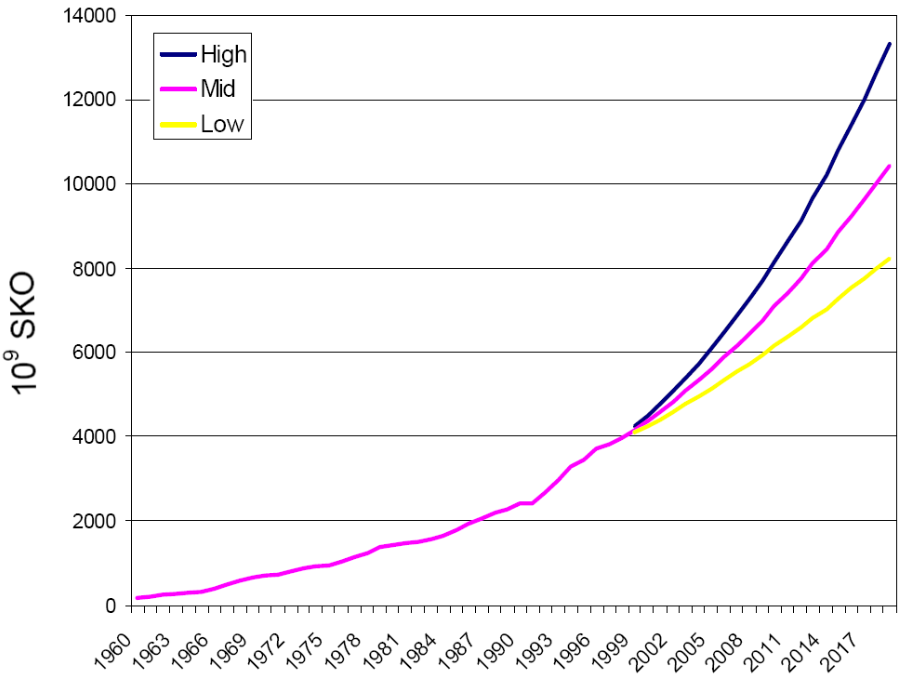


Figure 1.12: Aviation growth in terms of seat kilometers offered (SKO) [adopted from Roger et al., 2002; (with data from the DTI)].

Niedzballa and Schmitt [2001] have calculated that aircraft come second just after container ships, outperforming rail and road transport. Air traffic has seen growth rates exceeding that of global GDP despite the events on 11 September 2001. Figure 1.12 shows the increase in seat kilometres offered sine 1960, and a forecast for the next decade. Comparing figures 1.12 and 1.11, it becomes apparent that he improvement of aircraft technology is exceeded by the increase in passenger numbers, yielding in an overall increase in fuel consumption and hence carbon dioxide emissions.

As global warming and its consequences cause a paradigm shift, governments and interest groups are starting to demand action from stakeholders across all sectors. Particularly the aviation sector has been challenged because of the forecasted increase in emissions, and the aerospace industry, compared to just some years ago, is now changing from “farther, further, higher” to “leaner, meaner, greener”

[McMasters and Cummings, 2003]. Although the most important contributer to global warming in the aviation sector is regarded to be CO_2, this might change depending on the outcome of further studies on the environmental impact from contrails and cirrus clouds.

1.4 Thesis objective

The current trend in passenger number growth rates and the associated effect on the global atmosphere is believed to be unsustainable. Targets regarding the reduction of the environmental impact from air traffic, such as outlined in the ACARE goals [Advisor Council for Aeronautics Research in Europe, 2002], are increasingly established by policy makers and interest groups on national and international levels. So far, the impact from contrails and cirrus clouds has not been addressed in agendas, despite the potential of having a radiative forcing several times higher than that of all other air-traffic pollutants combined. Hence, it can be expected that the issue of contrail mitigation will be brought forward, and industry has an interest to take measures that help to prevent a confrontation with the problem without being unprepared.

In this thesis, the mitigation of the environmental impact from contrails and cirrus clouds is investigated. The principal aim is the identification and development of strategies and technologies that have the potential to reduce contrail and cirrus cloud forcings in future. First assessments of the strategies are conducted throughout the thesis that can assist in the development of an agenda for further research on this topic. Also, the long term impact of contrails and carbon dioxide emissions is compared, which helps to understand underlying issues that come with contrail avoidance.

1.5 Thesis structure

The remainder is divided into 5 chapters: the literature survey, contrail avoidance strategies, contrails vs. CO_2, discussion and conclusion. The literature survey reviews the physical key processes involved in contrail formation and their environmental impact. Based on the literature survey, contrail mitigation strategies and technologies are derived and described in chapter 3. Chapter 4 investigates the relative environmental long-term impact of contrails compared to CO_2. Conclusions are given in chapter 5, along with recommendation on further work. The appendix contains information on data and tools used, mathematical expressions, and provides a list of publications.

Chapter 2

Literature survey

This chapter reviews the literature relevant for the development of contrail avoidance strategies. Due to the multidisciplinary nature of the topic, it was inevitable to limit the content of this chapter to the fundamentals. References for a more comprehensive description are suggested throughout. For a better overview, already existing contrail avoidance strategies are not described in the literature survey but included in chapter 3.

2.1 Contrails

Generally, jet engines are thermodynamic machines utilising air as the working medium, which provide thrust to enable sustained flight of aircraft at high altitude and speed. Jet engines ingest air, which is then compressed, mixed with fuel, burned and expanded in the turbine and the nozzle. The turbine is delivering shaft power to the compressors, and some mechanical power is extracted to produce electricity in a generator.

The gases leaving the nozzle are a mixture of the incoming air and combustion products. For kerosene, the principal combustion products are water and carbon dioxide. For every mass unit of kerosene burned, approximately 1.25 mass units of water are produced, in addition to the water already present in humid air. Because of the restrictions set by the laws of thermodynamics, only a fraction of the chemical energy contained in the fuel can be converted into useful work. The unconverted part of the energy is contained in the form of heat energy in the engine exhaust. Hence, the jet efflux is hotter than the ambient air.

2.1.1 Thermodynamics

Depending on temperature and pressure, water can exist in three states: liquid, solid or gaseous. This dependency can be measured and represented in form of a phase diagram as shown in figure 2.1. If water in gaseous state is rapidly cooled or expanded, a phase change to either solid or liquid occurs. The phase transformation from gaseous to liquid involves the condensation of water in the form of droplets once saturation pressure, denoting the pressure at a given temperature for a particular phase change to happen under ideal conditions, is reached.

As droplets begin to form, the capillary attraction of the water molecules cause an increase in pressure inside the droplet. Capillary attraction is a result of the cohesion force, the molecular force between molecules of a single substance. The increase in pressure changes the state of the water back to gaseous, and the formation of droplets is prevented. This results in water being supersaturated, which is the state where water exists in gaseous phase although the prevailing pressure and temperature suggests liquid or solid phase. The amount of supersaturation can be

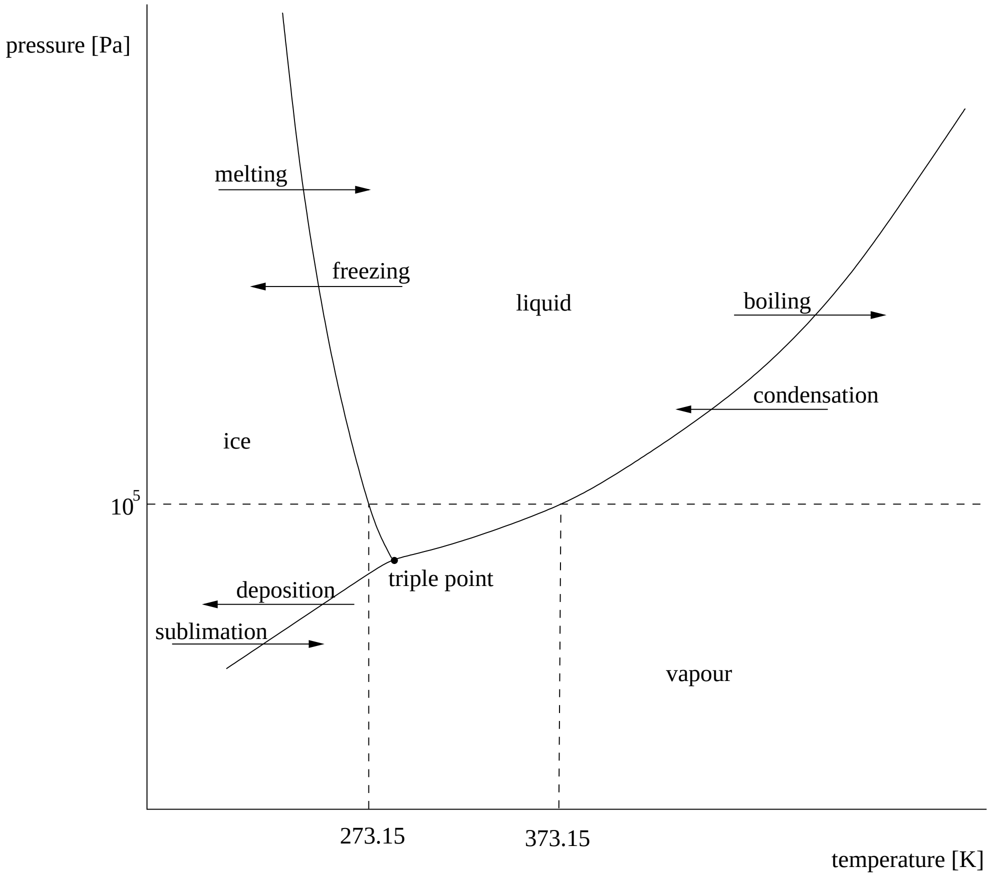


Figure 2.1: Phase diagram of water.

expressed in terms of relative humidity $P_{water}/P_{saturation}$. It can be measured with respect to liquid saturation pressure, or with respect to ice saturation pressure.

In the presence of small particles, so called condensation nuclei, condensation is facilitated by the adsorption force between water and the condensation nuclei if the adsorption force is larger than the cohesion force. In the atmosphere, where water is contained in the air, supersaturation is required for droplet formation to occur. The amount of supersaturation required to facilitate condensation typically depends on the the size and material of condensation nuclei; it can be calculated from

$$\phi_{droplet} = 1 + \frac{\sigma}{2\ R\ P_{w,\ s}} \tag{2.1}$$

where $\phi_{droplet}$ is the relative humidity required to form a droplet of radius R, σ is the surface tension of the liquid[1] and $P_{w,\ s}$ is the water saturation pressure. The typical droplet size for a rain drop is 2000 μm, for a cloud drop is 20 μm and for a cloud condensation nucleus is 0.2 μm.

If atmospheric air is only slightly supersaturated with respect to water or ice, condensation or ice formation is not facilitated. This is firstly due to the increase in pressure inside a droplet and hence the required level of supersaturation will be above the ambient supersaturation level. Secondly, droplet formation would cause a drop in the near-field supersaturation, resulting in a decrease of the ambient supersaturation level.

At the moment the moist and hot jet exhaust exits a jet engine, it mixes with ambient air in the aircraft wake. As the mixing proceeds, the specific humidity and temperature in the plume diminishes. Depending on ambient and exhaust temperature and water content, local humidity levels within the plume can elevate saturation levels during the mixing process to an extent that condensation of water is facilitated. For contrail forecast, it is desired to find the conditions at which supersaturation in the plume occurs that facilitates condensation of water.

First attempts of contrail forecast have been undertaken by Appelman [1953], which have later been reviewed by Schumann [1996]. The approach is based on a geometrical analysis of the mixing of the engine exhaust with ambient air on a phase diagram of water. The temperature and water partial pressure of both the jet exhaust and the atmosphere can be found on a phase diagram of water. For the engine exhaust, it is the stagnation temperature relative to the atmospheric frame of ref-

[1] $\sigma = 0.073\ N/m$ for pure water in air

erence. In figure, 2.2, the state of the atmosphere is labelled with B. The state of the exhaust gas, much hotter and containing more water than atmospheric air, is indicated as A and lies outside the area of interest in figure 2.2.

The mixing of the engine exhaust with ambient air can be displayed as a straight line, assuming the mixing taking place adiabatically and isobarically, and temperature and humidity mixing at equal rates. The line connecting the points A and B, representing the exhaust and the ambient air on the phase diagram, is generally referred to as the mixing line. It represents the intermediate states that occur during the mixing process. If the mixing line crosses the liquid saturation pressure line, the condensation of water, and hence droplet formation, is facilitated. This case is represented by the dashed line in figure 2.2. For exhaust gases that are hotter or contain less water, the mixing line will not cross the saturation pressure line, and the formation of contrails is not facilitated. This case is represented by the dotted line in figure 2.2.

It has been found that the slope of the mixing line $\sigma_{A,B}$ can be calculated without the knowledge of the plume stagnation temperature and water content. A dependency on several other variables exist, which reads

$$\sigma_{A,B} = \frac{c_p \, EI_{water} \, p_a}{q_{net} \, (1 - \eta_0) \, M} \tag{2.2}$$

where c_p is the specific heat capacity of air, EI_{water} is the water emission index, p_a is the ambient pressure, q_{net} is the fuel net calorific value, η_0 is the overall engine efficiency and M the molar mass ratio of water to air. See section A.1 in the appendix for the derivation of equation 2.2.

For given ambient conditions, contrail formation is facilitated if the mixing line slope exceeds the critical mixing line slope, known as the Appleman criterion.

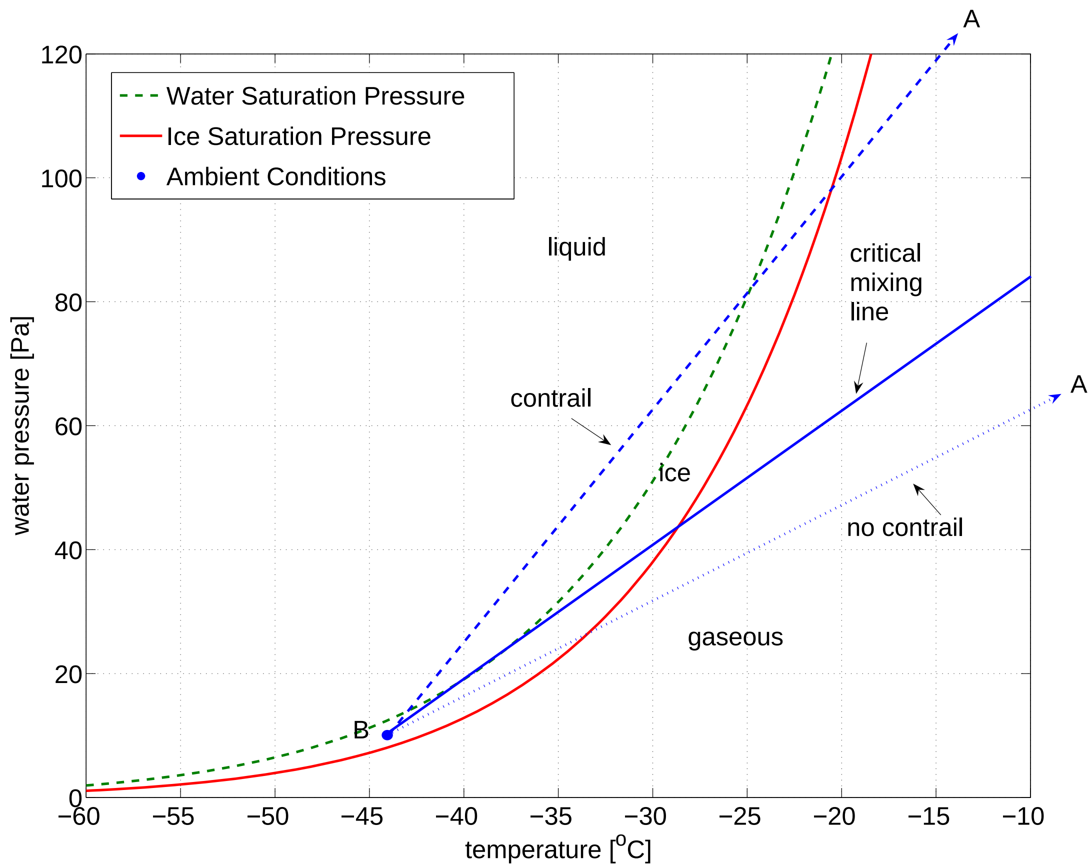


Figure 2.2: Geometrical analysis of contrail formation.

Originating at the state of the atmosphere, it is the slope of a tangent to the saturation pressure curve originating in B, represented as blue solid line in figure 2.2. The critical mixing line slope is dependent on ambient conditions and the quantitative determination of the critical mixing line slope is an iterative process. The temperature at which the critical mixing line slope is in contact with the saturation pressure line can be obtained from solving

$$\frac{p_{sat}(T_{crit}) - p_{ambient}}{T_{crit} - T_{ambient}} - \frac{\partial}{\partial T} p_{sat}(T_{crit}) = 0 \tag{2.3}$$

where $p_{sat}(T)$ is the saturation pressure at a temperature T, $p_{ambient}$ is the ambient pressure, T_{crit} is the temperature at which the critical mixing line is in contact with the saturation pressure line and $T_{ambient}$ is the ambient temperature. The saturation pressure line as function of temperature can be found in literature. A common approach to determine the saturation pressure is the Clausius-Clapeyron relation. In this work, polynomials fits to the saturation pressures according to Flatau et al. [1992] in the form $p_{sat} = a + b\ T + c\ T^2 + d\ T^3 + \ldots$ are used throughout. Solving equation 2.3 yields T_{crit}, from which p_{crit} can be calculated and finally the mixing line slope

$$\sigma_{A,B} = \frac{p_{sat}(T_{crit}) - p_{ambient}}{T_{crit} - T_{ambient}} \tag{2.4}$$

The geometric analysis for contrail forecast has been verified by numerous flight tests carried out in Europe and the US. Schumann et al. [2000] conducted in-flight experiments where ambient conditions and engine efficiency were recorded to compare theory against observation. Figure 2.3 summarizes contrail formation observations for a range of aircraft. It supports the assumption that contrails only form if liquid supersaturation is reached in the plume.

Once water condensation has occurred in the plume, it is typically followed by freezing as the temperature and humidity in the plume drops. If the atmosphere is not sufficiently supersaturated, the ice crystals evaporate shortly after freezing, and the contrail is very limited in its length. These kind of very short-lived contrails are called threshold contrails, which are considered not to contribute to global warming. The photo in figure 2.4 shows a typical example.

If the atmosphere is sufficiently ice-supersaturated, the ice crystals will remain in the air. The contrail then appears as elongated line shaped cloud following the flight path of the aircraft. Figure 2.5 shows a photo of a persistent contrail. The life time of the contrail is dependent on the ambient conditions, primarily the level of ice-supersaturation.

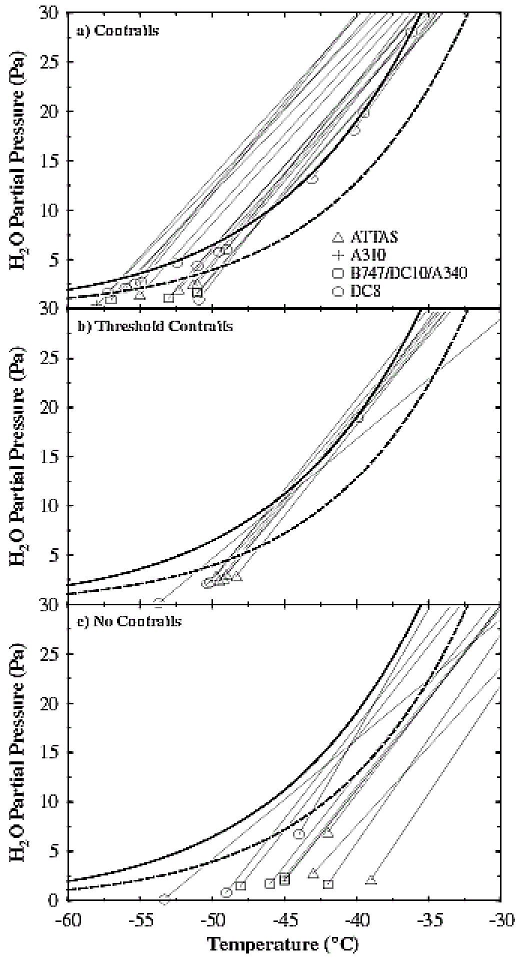


Figure 2.3: Contrail formation observations [adopted from Kärcher et al., 1998].

2.1.2 Plume chemistry

Contrail particles are ice crystals which nucleated on exhaust particles through the liquid state. The properties of contrails and the formation of cirrus clouds depends on the concentration and properties of particles that occur in the exhaust. Although particles are present in the atmosphere at typical cruise altitudes, contrail particles predominantly germinate on engine particle emissions. The various particles that can be found in the plume are of different chemical composition and size. If not

Figure 2.4: Photo of threshold contrail.

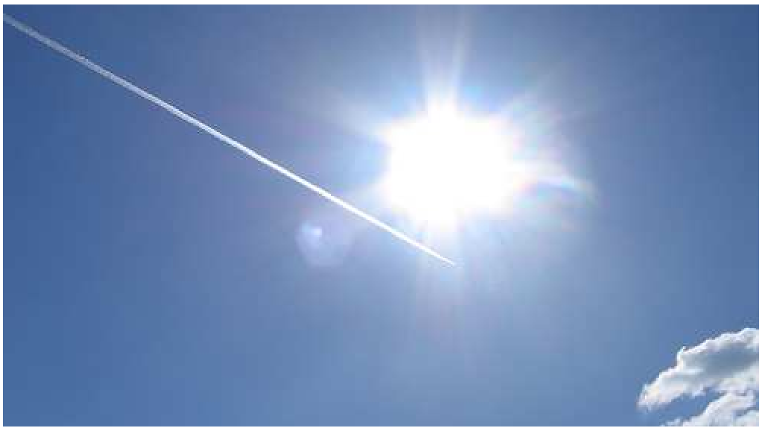


Figure 2.5: Photo of a persistent contrail.

already in the atmosphere and ingested by the engine, they emerge during during the combustion process of the fuel. Their properties can modify under atmospheric conditions.

Apart from acting as freezing or condensation nuclei, engine emissions can also alter the freezing capabilities of water or enhance the hydrophilicity of particles. The particles on which water condensation occurs during the contrail formation process are referred to as contrail precursors. In general, contrail precursors can be attributed to two groups: volatile precursors and non-volatiles precursors. The various contrail precursors as they can be found in the literature are summarized in the following.

Non-volatile precursors

Non-volatile precursors act as condensation nuclei for water in the plume. They include soot and metallic particles.

Metallic particles occur through abrasions within the engine, but can also be contained in the fuel. They occur in lower quantities than other precursors and play an insignificant role in the ice formation processes.

Soot, also called black carbon, in the form of small particles is an important contrail ice-particle precursor. Soot particles emerge during the combustion process and are produced in high temperature, fuel-rich regions inside the combustor. These regions typically lie in the primary zone close to the fuel ejector. The main factors in the formation of soot particles are pressure, fuel type and fuel atomisation.

Soot particles are of nearly spherical shape[2], exceeding dimensions of volatile particles. Soot characteristics are such size, nucleating and chemical properties, and freezing ability. In the plume, the distribution and concentration at the engine exit is also important. Several spherules may aggregate and form complex chain structures. Pure soot is naturally hydrophobic and require much higher levels of supersaturation to become activated than hydrophilic materials [Kärcher et al., 1996, Wyslouzil et al., 1994]. The rough-textured surface of soot particles or chemically active sites can alter its affinity to chemical reactions and amplify heterogeneous nucleation processes. A mechanism of reduction of the supersaturation required for

[2] therefore also referred to as spherules

heterogeneous water nucleation has been detected by Popovitcheva et al. [2001]. It facilitates the condensation of water in the young plume through the specific microporous structure and surface heterogeneity of young soot particles.

The hydrophilicity of soot is also altered through its immersion into hydrophilic substances or solutions [Petzold et al., 2005]. For almost pure carbon, only a fraction of soot particles is acting as condensation nuclei. In the plume, the prevailing activator of soot particles is sulphuric acid, H_2SO_4. Sulphuric acid emerges from fuel bound sulfur, and is discussed in the section covering volatile aerosols and particles on page 38. The soot immersion capability depends on its size. Soot hydration properties may also change after treatment with hydroxyl radicals (OH) and ozone.

The most important mechanisms for water condensation on soot particles are summarized in figure 2.6. Water condensation can be enhanced in the presence of sulphuric acid, but can also occur without a coating. Soot particles that get fully or partially coated by sulfuric acid solution typically grow to sizes $> 0.1\ \mu$m through water absorption. This is followed by freezing of the liquid drops, forming contrail ice-particles.

Volatile precursors

Volatile aerosols can exist in liquid or solid state. They serve as contrail ice particle precursors in the form of condensation nuclei or enhance the ability of water vapour to condense on particles. The most important volatile precursors are water vapour, sulfur species, chemiions, nitrogen species and hydrocarbons. Information on the origin and effects of the different volatile precursors is provided in the following.

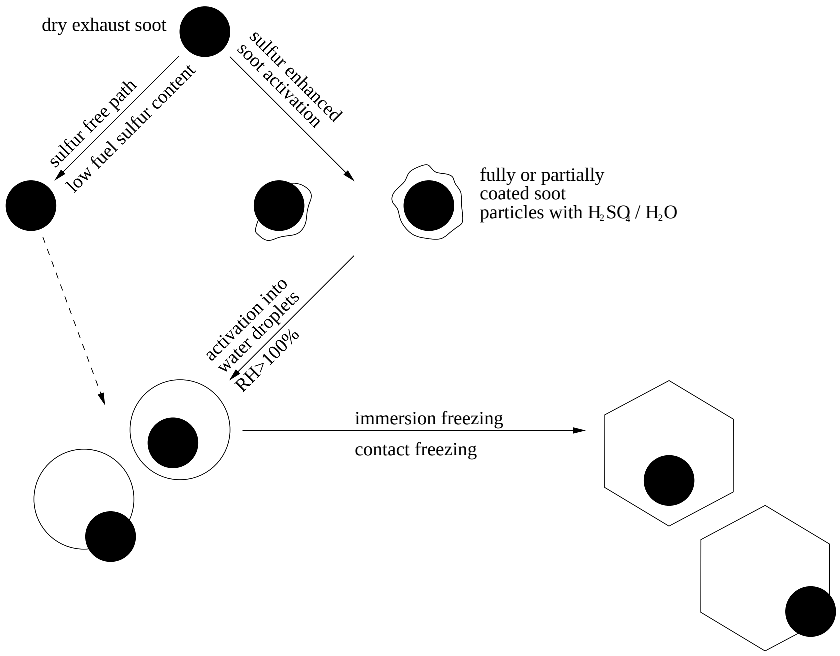


Figure 2.6: Soot activation and heterogeneous freezing model [derived from Kärcher et al., 1998].

Hydrocarbons are usually the result of poor fuel atomisation or insufficient burning rates in the combustor. They exist in the form of methane and non-methane hydrocarbons, such as alkenes, aldehydes, alkines or also aromates. Non-methane hydrocarbons can form aerosols, which can act as condensation nuclei, or alter hygroscopic properties and growth rates of other particles present in the engine exhaust.

Nitrogen species are present in the exhaust most commonly in the form of nitric oxide (NO) and nitrous oxide (NO_2), both commonly referred to as NO_x. NO_x is the result of the oxidation of NO in the presence of oxygen. There are four processes that promote the formation of NO.

- Thermal NO occurs though oxidation of atmospheric nitrogen in high-temperature regions within the combustor. Especially temperatures above 1850K facilitate NO formation. The main parameters in the formation of thermal NO are flame temperature and fuel residence time inside the combustor.

- The oxidation of atmospheric nitrogen to NO can indirectly lead to the formation of NO_2, known as the nitrous oxide mechanism.
- Prompt NO occurs in lean premixed combustors operating at low power settings.
- Fuel bound nitrogen can oxide to so-called fuel NO. Since nitrogen levels in aviation fuels are usually low, this contribution is therefore small.

NO_x can combine with hydroxy radicals (OH), forming nitrous acid (HNO_2) or nitric acid (HNO_3). These acids can be taken up by water soluble exhaust particles, enhancing their hydrophilicity.

Water vapour is the highest concentrated contrail precursor in the jet efflux and plays a role in almost all observed aerosol formation and nucleation processes. It enables the occurrence of supersaturation in the plume and participates in aerosol processes.

Sulfur enhances absorption characteristics of soot particles, alters the chemical reactivity of dry exhaust soot and provides volatile solid contrail precursors acting as condensation nuclei [Schumann et al., 2002]. Jet fuel contains sulphur to increase its lubricity, which is required to mitigate abrasion within the engine. High lubricity is especially required where highly loaded rubbing surfaces are in contact with each other and operate with mixed film lubrication. Particularly the fuel pumps of an engine are components where this is the case. In the plume, sulphur exists in the form of sulphuric acid, which is mainly resulting from the oxidation

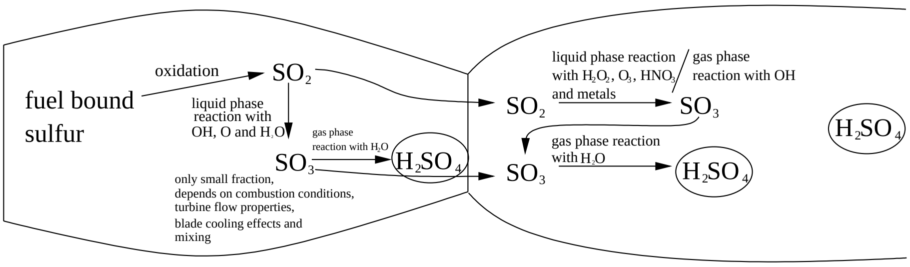


Figure 2.7: Model for the formation of sulfuric acid from fuel bound sulfur [derived from Kärcher et al., 1998].

of fuel bound sulphur. At the nozzle exit, most of the sulfur has already oxidised to SO_2 and SO_3, and further oxidation can occur within the jet regime of the plume [Starik et al., 2002]. The oxides, together with water, react to sulfuric acid, H_2SO_4. This can occur inside the engine, but predominantly takes place in the plume. The conversion fraction of fuel bound sulfur to sulfuric acid is between 1% and 20%, which is increasing with decreasing fuel sulphur content. Figure 2.7 summarizes the processes involved in the formation of sulfuric acid.

Water activation of soot may result from the formation of H_2SO_4 coatings. As the exhaust gases leave the engine, liquid coatings form on soot particles via binary heterogeneous nucleation[3] of H_2SO_4 and water, thereby enhancing their hydrophilicity. Once activated, the particle hydration behavior is consistent with hydration of H_2SO_4. This hydration behavior reduces the supersaturation required for water condensation and enhances the ability to act as condensation nuclei.

Once the critical H_2SO_4 concentration level for binary homogeneous nucleation[4] of sulfuric acid and water is reached in the plume, the formation of ultra fine volatile particles consisting of sulfuric acid and water is facilitated. These particles can freeze and act as condensation nuclei. The formation of these particles is dependent on the early concentration level of sulfuric acid and water. As the mixing of

[3]condensation on a surface of two distinct types of molecules

[4]formation of droplets by condensation of two distinct types of molecules

the plume progresses, concentration levels fall below levels that facilitate condensation.

Contrail particle number density increases downstream in the plume because homogeneous nucleation requires longer timescales than heterogeneous nucleation [Gierens, 2003]. An increase in abundance of ultra fine particles has been observed for an increasing fuel sulfur content. A lower sulfur content leads to predominantly heterogeneous nucleation (activation) and prevents the formation of volatile particles. High fuel sulfur content leads to more volatile particles [Petzold et al., 1997] whereas the number of volatile particles in the exhaust plume increases overproportionally with increasing fuel sulfur content [Schumann et al., 1996]. In the case of low sulfur fuel, non-H_2SO_4 volatile particles still constitute contrail precursors. It has been observed that a high fuel sulfur content facilitates contrail formation at slightly higher ambient temperatures (+0.4K) [Schumann et al., 1996].

Chemiions are in the exhaust due to high temperature chemical reactions. The presence of charged particles enhances coagulation processes due to electrostatic forces, promoting formation and growth of charged droplets containing sulfuric acid and water. Additionally, chemiions contribute to the formation of soot. Ion mode particles decrease in size if H_2SO_4 emissions decrease. Volatile droplets in the ion mode can be activated more easily than neutral mode droplets.

Ambient aerosols also provide contrail precursors. Their particle number concentration is far lower than that of engine produced aerosols. However, simulations suggest that even without the presence of engine produced contrail precursors, the formation of contrails would still be facilitated through the presence of ambient aerosols [Kärcher et al., 1998].

Particle growth

Activated soot and volatile particles grow through condensation and particle collision and attachment, know as coagulation [Schröder et al., 2000]. Particle growth rates are larger in cooler and more humid ambient air. As frozen volatile droplets differ in size and nucleation abilities, they become principal condensation nuclei, which is the case for very low ambient temperatures. If condensation nuclei are chemically identical, the larger particles tend to freeze first [Kärcher and Koop, 2004].

Contrail ice-particles can increase in size through several mechanisms. They can grow through deposition of ambient water vapour, known as the Bergeron process. Supercooled droplets can freeze through contact freezing when they come into contact with an ice nucleus. Once ice particles are formed, supercooled droplets can freeze onto ice particles. Two or more ice particles sticking together to form a larger particle is called aggregation.

Once ice crystals have consumed available water, supersaturation levels in the plume decline and further nucleation ceases. Large ice crystals may precipitate rapidly and cause a vertical spreading of the contrail. The ice crystal number concentration decreases as the plume dilutes.

Particle size

Contrail ice particles evaporate quickly if thermodynamic conditions are not sufficient for persistent contrail formation. Particle size and particle number density is not homogeneous over the plume cross section area. Variations can be found especially near the plume edges, where the mixing of the exhaust with ambient air

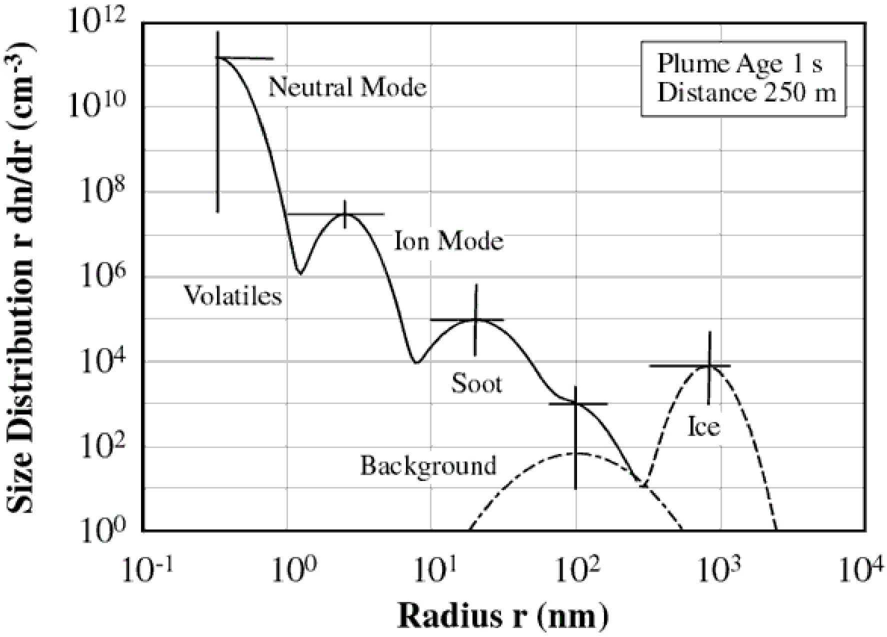


Figure 2.8: Size distribution of particles in the aircraft exhaust [adopted from Kärcher et al., 1998].

is progressing at a higher pace.

Figure 2.8 shows the size distribution of the particles occurring in plume as it occurs relatively close behind an aircraft [Kärcher et al., 1998]. The volatile particles predominate and have small dimensions, whereas non-volatile precursors (soot) are larger but occur less often. Background aerosols, indicated by the dashed line, are relatively large and have a lower number density than engine exhaust particles.

Summary

Chemical processes in the plume play an important part in the formation of contrails and determine their radiative properties. Water emerging during the combustion process inside the engine and ambient water condenses on particles, followed

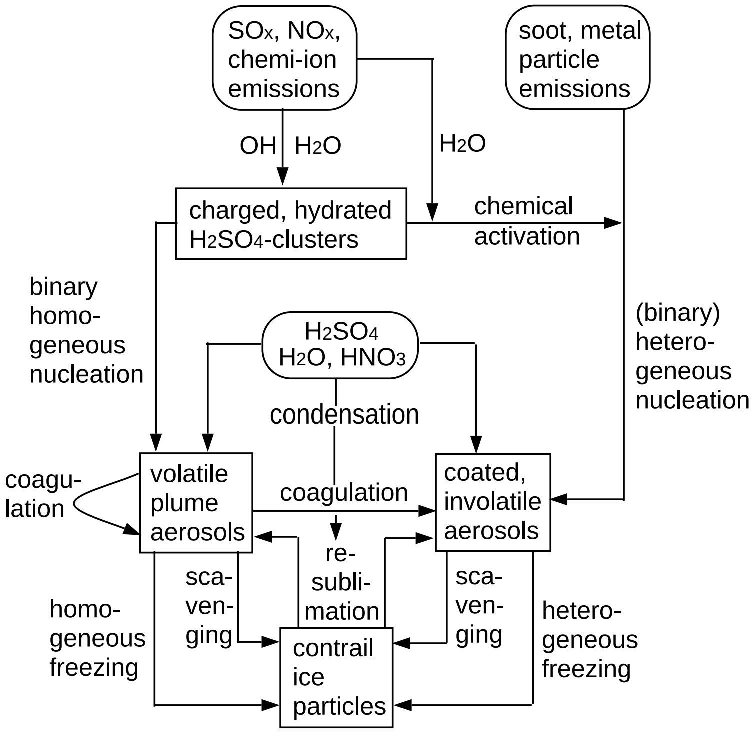


Figure 2.9: Schematic of aerosol dynamics in the aircraft exhaust [adopted from Kärcher, 2000].

by freezing. Soot particles, mainly activated by sulphuric acid, are the most important condensation nuclei. Sulphuric acid can form particulates that may also act as condensation nuclei. The amount of fuel sulphur determines the amount of sulphur particulates in the plume, and an increasing fuel sulphur content causes the formation of contrails with more but smaller particles. For a very low fuel sulphur content, contrail formation would still be facilitated because soot particles have altered hydration properties in the very young plume. Figure 2.9 summarizes the principal mechanisms for the formation of contrail and cirrus cloud precursors.

For perfectly clean combustion without the emergence of particles, contrail formation could still occur through the condensation of water on ambient particles and aerosols [Kärcher et al., 1998]. The activation and freezing of water on background particles would lead to contrails consisting of less but larger particles, and contrail formation would require slightly lower ambient temperatures.

2.1.3 Radiative forcing of contrails

Aerosols and contrails have direct and indirect effects on the climate. The direct effects include scattering and absorbing radiation, the indirect effects include modifying the formation of cloud particles and changing the properties of clouds.

In general, contrails are ice clouds with radiative properties similar to thin cirrus clouds. The radiative forcing of contrails can be broken down into shortwave radiative forcing RF_{SW} and long wave radiative forcing RF_{LW}. The short wave radiative forcing denotes the solar energy flux prevented from entering earth's upper troposphere. Long wave radiative forcing is the energy flux of terrestrial radiation prevented from leaving the earth. The net radiative forcing is the sum of both, longwave and shortwave radiative forcing.

$$RF_{total} = RF_{LW} + RF_{SW} \tag{2.5}$$

In Meerkötter et al. [1999], a one dimensional radiative transfer model was used to quantify the sensitivity of contrail parameters regarding its radiative forcing.

The short wave radiative forcing of ice clouds is determined by the solar zenith angle, the earth's surface albedo and its optical depth. It has a higher magnitude over dark surfaces than over deep blue oceans. Soot immersed in or attached to contrail ice particles may increase the absorption of solar radiation, thus reducing the albedo of contrails.

The longwave radiative forcing of ice clouds depends on the emissivity of its particles. It increases with the ice path, which is the product of contrail depth and ice water content. The longwave radiative forcing of ice clouds is maximum for clear sky conditions, a warm earth's surface and low humidity of the air below the contrail. Strong longwave radiative forcing can be found over tropic regions or oceans. Contrails with smaller particles tend to cause a stronger positive net radiative forcing, because small ice crystals enhance the cloud's albedo to a lesser extent than its emissivity. However, for contrails with very small particles, the effect is reversed.

Meerkötter et al. [1999] concluded that contrails cause a heating at the top of atmosphere for the majority of scenarios. An overall negative radiative forcing is possible for contrails over very cold surfaces with low ground albedo, or over a very humid but cloud free troposphere. The positive net forcing of ice clouds grows with increasing optical depth, but becomes negative with very large optical depth, larger than that of typical contrails. Contrails have the largest radiative forcing during night, when the short wave radiative forcing is not existent and only the long wave forcing remains [Stuber et al., 2006]. Over mid-latitudes, the radiative forcing of a contrail is larger during the summer than during the winter because of variations in the diurnal solar flux and the solar zenith angle.

The main parameter determining the global radiative forcing of contrails is the contrail cover, determining the amount of area covered by contrails. It is estimated that the global cover by line-shaped contrails is 0.1% [Schumann, 2002].

2.1.4 Wake dynamics

During cruise conditions, the aircraft wake is composed of vortices, and the two counter-rotating wing tip vortices are predominant. These interact with the engine exhaust jets, having an effect on the formation, dispersion and persistence of contrails.

The evolution of the interaction of the engine exhaust with the aircraft wake is categorized into three sequential regimes [Brunet et al., 1999, Jacquin and Garnier, 1996]: a) the jet regime, dealing with the near field of the engine jet, is equivalent to that of usual co-flowing jets (for two engine aircraft it is two jets); b) the deflection regime corresponds to the entrainment and capture of the jet by the wing tip vortices; c) the shearing regime, during which the plume is affected by shearing and convection as a result of the rotational velocity component inside the vortex cores.

Paoli and Garnier [2005], Paoli et al. [2004] combined a two phase flow and microphysics model to simulate the near field interaction of a trailing vortex with an exhaust jet during the deflection regime. Results suggest that cooling and vapor condensation are enhanced by the entrainment of the exhausts by the wing tip vortices.

Computational large eddy simulations were carried out in numerous studies to investigate the jet interactions during the shearing regime. In general, a pair of counter rotating vortices creates a flow field that results in the movement of the vortex pair. For wing tip vortices, the circulation field induces a downwards motion, resulting in quasi-adiabatic compression of the vortices as they descend to lower altitudes where higher pressures prevail. Aircraft vortices interacting with any ambient shear can also touch, reconnect and form descending vortex rings, a phenomenon known as Crow instability [Crow, 1969]. The compression causes an increase in temperature of the vortices, resulting in buoyancy forces that diminish the descent velocity of the vortex pair [Lewellen and Lewellen, 2001, Proctor et al., 1997]. Gierens and Jensen [1998] concluded that heating due to adiabatic compression of a falling vortex system can lead to significant ice crystal number depletion depending on the ambient ice-supersaturation, ice crystal number density and wake characteristics.

Huebsch and Lewellen [2006] calculated that in the presence of atmospheric turbulence, a marginally more effective mixing of ambient air with the aircraft exhaust takes place, whereas high turbulence levels in the atmosphere cause an increase in contrail ice crystal number and overall ice mass. Higher ambient temperature lapse rates, or stratification, prevent the descent of contrails, and hence diminish adiabatic heating, which results in more ice particles remaining in the contrail compared to the case where no stratification prevails [Huebsch and Lewellen, 2006, Lewellen and Lewellen, 2001]. Work by Huebsch and Lewellen [2006] and Chlond [1998] suggests that ice particle evaporation is only marginally affected by ambient wind shear. Lower levels of initial ice particle number density have the effect of the formation of larger particles, whereas higher levels of ice particle number density yield smaller ice particles [Huebsch and Lewellen, 2006]. If more but smaller ice particles exist in the plume, it is more likely that they will evaporate during the adiabatic heating associated with vortex descent.

The strength of the wing tip vortices determines the evolution of the contrail. An analysis of wake vortex decay mechanisms is given in Holzäpfel et al. [2003], where it was concluded that a decrease of the normalized spacing of two vortices may accelerate their decay, whereas increasing the vortex radii at constant spacing reduces their lifetime.

An effective entrainment of the engine exhaust jets enhances the vertical extension of a contrail, potentially increasing the probability for a contrail to cirrus transition. Unfortunately, contrail dispersion and ice particle evaporation are in conflict with each other. Huebsch and Lewellen [2006] found that engines placed placed further outboard lead to a lower ice crystal survival rate, but at the same time the horizontal extension of the contrail is enhanced. The opposite is true for placing engines further inboard.

2.1.5 Ice-supersaturated regions

Contrails can only persist under ice-supersaturated conditions. Since the Appleman criterion for contrail formation requires liquid phase [Jensen et al., 1998b], ambient ice supersaturation does not necessarily imply the formation of a persistent contrail.

Ice-supersaturated air masses are formed when ice-saturated air masses are lifted by atmospheric motion in the upper region of the troposphere. Ice-supersaturated regions are often cloud free, a phenomenon that occurs where the ambient humidity is insufficient for cirrus cloud formation or freezing abilities and number densities of ambient aerosols are too small for ice nucleation to occur [Heymsfield et al., 1998].

The occurrence of ice-supersaturated regions is altitude dependent [Gierens et al., 1999] and varies seasonally [Stuber et al., 2006]. Gierens et al. [1999] evaluated data from on board in situ humidity measurement devices installed on commercial airliners regarding ice-supersaturation along common flight routes. According to the results, the occurrence of ice-supersaturated regions is altitude dependent and the stratosphere contains less supersaturated regions than the troposphere. On average, it was calculated that commercial airliners flying in the troposphere encounter ice supersaturation during 13.5% of their journey, whereas for stratospheric flights the portion was only 2%. A mean ice supersaturation of 115% was calculated for the troposphere and 123% for the stratosphere.

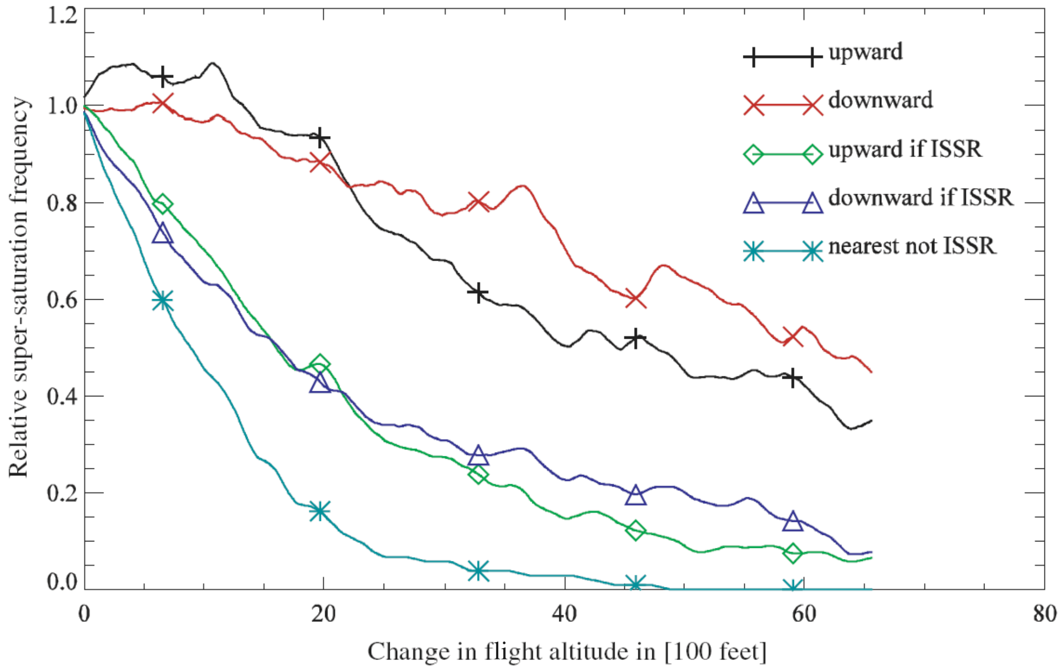


Figure 2.10: Relative ice supersaturation frequency [adopted from Mannstein et al., 2005].

The vertical extent of ice-supersaturated regions is relatively small compared to their horizontal extent. Radiosonde data was used in Mannstein et al. [2005] to calculate the relative ice-supersaturation frequency depending on a relative change in flight altitude. It was concluded that if aircraft encountering ice-supersaturation changed cruise altitude by less than 1000 metres toward the nearest ice-subsaturated altitude, 99% of ice supersaturation could be avoided. Figure 2.10 shows the ice-supersaturation frequency depending on a change in cruise altitude.

2.2 Contrail cirrus clouds

Contrails formed in a low ice-supersaturated atmosphere would persist but remain limited in size and lifetime [Schröder et al., 2000]. Contrails formed in regions with high prevailing ice-supersaturation may spread and transform into large area cirrus clouds, so called contrail cirrus [Jensen et al., 1998b, Minnis et al., 1998].

A line shaped contrail in an environment where the wind speed varies over altitude will spread as ice particles in the upper part of the contrail are carried away at a different speed than the ice particles of the bottom part of the contrail. The altitude dependent variation in wind speed, commonly referred to as wind shear, is the dominating effect in the horizontal spreading of contrails. The vertical extent of contrails also plays a role in the transition from line shaped contrails to contrail cirrus. For increasing vertical extent of the contrail, the difference in wind speed between the top and bottom part of the contrail becomes larger, resulting in faster transition rates.

The vertical spreading of the contrail results from the precipitation of larger ice particle to lower altitudes, updrafts caused by radiative heating inside the contrail, and aircraft wake dynamics. Ice-supersaturated regions are primarily linked to synoptic conditions that support vertical motions of air, also having an effect of the vertical extent of the contrail.

Large eddy simulations have been carried out by Jensen et al. [1998a] to simulate the evolution of a contrail. Results suggest that ambient supersaturation leads to increased contrail ice particle growth rates near the contrail's edges. Supported by vertical air motions, larger ice particles fall most rapidly resulting in a size sorting with height. Contrail spreading is less severe for low ambient supersaturation because it reduces ice particle growth rates and thus precipitation. The simulation of the vortex phase and dispersion phase of a contrail from a B747 aircraft is described in Gierens and Jensen [1998]. The study involves complex aircraft wake dynamics microphysics modeling to account for ice nucleation. The simulations suggest that the initial wing vortex pattern breaks up into two structures in which one structure is evaporating due to adiabatic heating during descent. The second structure extends downwards, and the surviving ice particles grow, forming a persistent contrail. The cold layer above the cloud causes buoyancy causing an ascent of the cloud in a warmer and stably stratified region. Thereafter, the cloud spreads out horizontally and breaks into several fragments, mixing into the dry air and finally evaporates.

The cloud coverage by cirrus clouds resulting from contrails has a considerable time lag behind the air traffic. In regions where air traffic is predominantly taking place during day time, contrail cirrus occurrences are shifted to night hours where only the long wave radiative forcing remains [Mannstein and Schumann, 2005].

It is suggested that the radiative forcing caused by aviation induced cirrus clouds has the potential to be several times stronger than that of line shaped contrails.

2.3 Secondary cirrus clouds

Kärcher and Lohmann [2003] concluded that aviation can cause an increase of soot particle number concentration by more than 30% in regions highly frequented by aircraft. Soot and also aerosol emissions from aircraft have the potential to cause the formation of cirrus clouds where no cirrus clouds would form naturally. An evaporated contrail ice particle can leave traces of ice attached to the condensation nucleus unless exposed to a dry environment for a long time. These particles are more likely to re-nucleate under supersaturated conditions, an effect known as preactivation [Kärcher and Lohmann, 2003, Pruppacher and Klett, 2000]. Preactivation enhances the freezing ability of aircraft soot particles that acted as threshold contrail condensation nuclei.

Satellite and surface observations show a statistically significant dependency between cirrus cover and air-traffic density [Minnis et al., 2001, Stordal et al., 2004, Zerefos et al., 2003a]. Cirrus clouds nucleating on aircraft particle and aerosol emissions occur independently from contrails and contrail cirrus and would not form in the absence of air traffic. They are commonly referred to as secondary cirrus clouds and contribute to the overall cloud cover, yielding a positive radiative forcing.

2.4 Natural cirrus modification

Aircraft emissions may also cause an indirect climate forcing by changing particle size and ice particle number density of natural cirrus clouds. It has been observed that the effective ice crystal diameter decreases and the ice crystal number density is enhanced in cirrus clouds perturbed by aircraft soot [Kristensson et al., 2000]. These modification impact the micro-physical properties of cirrus clouds, the ice particle size, geometry and cloud life-time. According to Meerkötter et al. [1999], perturbed natural cirrus clouds can have a stronger radiative forcing. Natural cirrus modification by aircraft emissions depend on the nucleation ability of the exhaust particles. The effect is less severe in regions where the formation of natural cirrus clouds occurs on more efficient ice nuclei than that of the aircraft exhaust particles.

2.5 Aerodynamic contrails

Pressure disturbances around the lifting surfaces and turbulence in the aircraft wake can initiate condensation of water on particles. In the case of ambient ice supersaturation, this will cause a persistent linear contrail with similar radiative properties to that of engine induced contrails.

Gierens and Ström [1998] calculated that adiabatic cooling as it occurs within the complex flow field of an aircraft wake can triggering homogeneous freezing nucleation. The results suggested that the formation of aerodynamic contrails occurs more likely for aircraft with increased wing span. Especially heavy, slow, wide-body aircraft would favour the formation of aerodynamically induced contrails.

Chapter 3

Contrail avoidance strategies

In this section, contrail avoidance strategies are presented. In the majority of cases, the strategies were derived from the literature survey and developed during the work programme in several studies, whereas some strategies could be found in the public domain in the form of journal publications or patents, in which case sources are referred to appropriately.

In order to develop strategies that have the potential to mitigate the radiative forcing of contrails, an integrated framework for the identification of strategies was deduced from the literature survey. It is subdivided into four levels of coherency: radiative forcing → contrail occurrences and radiative properties → physical principles → technological and operational enablers. The radiative forcing of contrails on a global scale can be directly linked to both contrail occurrences and their radiative properties, whereas the principles determining contrail occurrences or radiative properties can be attributed to one of the following identified categories:

Particles & **aerosols:** particles and aerosols provide condensation nuclei for contrails and secondary cirrus clouds, and activate hydrophobic particles. They affect the formation and the radiative properties of contrails.

Wake dynamics: near field and far field interaction of the engine exhaust with the aircraft wake facilitates the mixing of the exhaust with ambient air. The evolution and interaction of the wake with the atmosphere has an effect on the development of the contrail and its transition into a contrail cirrus. Wake dynamics influence the formation of aerodynamic contrails.

Contrail potential: the condensation of water occurs only in the case of liquid supersaturation occurring within the plume, facilitated through the mixing of the exhaust gases with ambient air or triggered by humidity, pressure and temperature variations in the aircraft wake.

Air-traffic distribution: the radiative forcing of contrails, contrail occurrences, and contrail persistence depend on the temporal and spatial distribution of aircraft routes.

Operational and technological enablers are engineering tools that enable the reduction of the environmental impact from contrails. They function according to at least one of the afore-mentioned principles and can be attributed to at least one of the following groups:

Engine architecture: includes all possible modifications to the propulsion device, or novel and revolutionary concepts.

Flight path: modifications to the spatial and temporal characteristics of the flight path trajectory of a single aircraft, the air traffic for a region or the air traffic on a global scale.

Fuel and combustion: addresses emission control, the type of energy source used to power the propulsion device, and the conversion method of stored energy into any other form of energy required to obtain a propulsive force.

Airframe and engine integration: all modifications to current technology or novel concepts regarding the airframe and the engine integration method.

Supplementary devices: devices which prevent by any means the formation of contrails, contrail cirrus or aviation induced cirrus clouds.

A graphical representation of the framework for the identification of contrail avoidance strategies is given in figure 3.1. A change in the radiative forcing from contrails (green) can be achieved via the technological enablers (blue), which according to the different physical principles (yellow) have an impact on the radiative properties or occurrences of contrails (red). Connections where an interdependency can be assumed but has not been proven yet are indicated by a dashed line.

3.1 Adjustment of air traffic

The underlying idea is to adjust air traffic to avoid regions which support the formation of persistent contrails or which because of their geographical location cause a positive radiative forcing of contrails. In a preliminary study, the geographical distribution of regions facilitating contrail formation was investigated. Therefore, the probability for contrail formation was calculated on a global scale using MetOffice weather data. The data, containing records for the year 2005, comprises information regarding temperature and humidity in a 6 hour interval on a global grid. A description of the data can be found in the appendix on page 157. For each grid

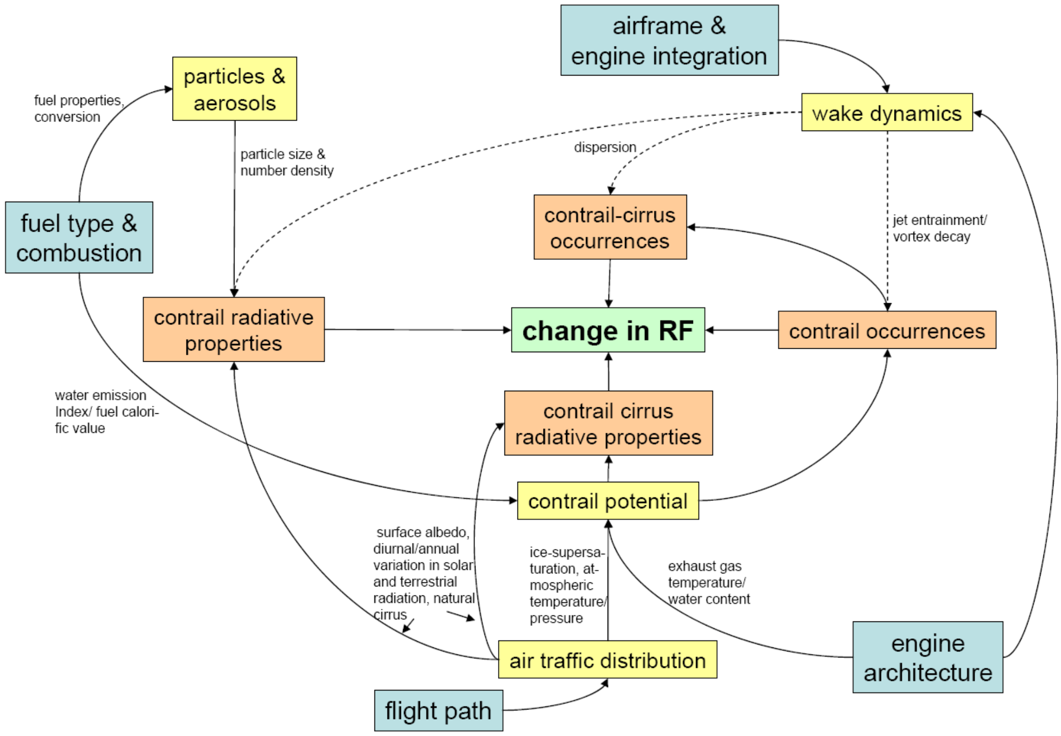


Figure 3.1: Integrated framework of interdependencies in the contrail formation process to identify contrail avoidance strategies.

cell and time interval, it was computed whether the formation of a persistent contrail was facilitated by testing for ice supersaturation and whether the Appleman criterion, as described in section 2.1.1, is satisfied. Events where the formation of persistent contrails was facilitated were counted and divided by the number of time intervals, yielding the probability for contrail formation for each grid cell. Results presented hereafter are based on calculations where an aircraft overall efficiency of 0.4 was assumed.

Figure 3.2 shows the probability for contrail formation at different pressure levels. It can be seen that at low altitudes, contrail formation is more likely to occur towards the poles, whereas at higher altitudes, the probability for contrail formation is increasing towards the equator. According to the results, contrail formation is most

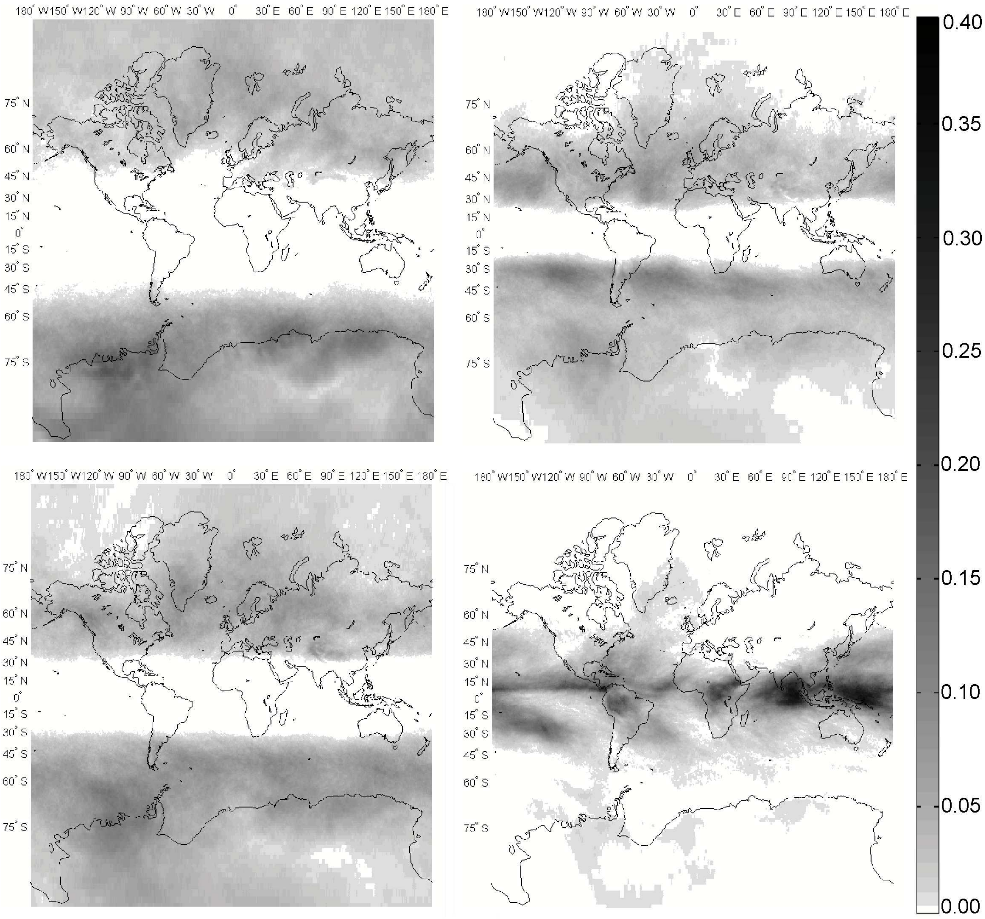


Figure 3.2: Probability for contrail formation for different altitudes (annual average): 400hPa (7185m) top left, 300hPa (9164m) bottom left, 150hPa (10363m) top right, 200hPa (11775m) bottom right.

likely to occur at high altitudes over the equator, with a probability as high as 40% in some regions. In the mid latitudes, over the Eurasian and North American continent (30^{o}N-60^{o}N), and for altitudes between 7185m-13509m (400hPa-150hPa), the mean mean probability for contrail formation was calculated to be 2%. It has to be noted that this probability represents the volumetric probability for contrail formation, i.e. that for a given location and altitude the formation of a contrail is facilitated.

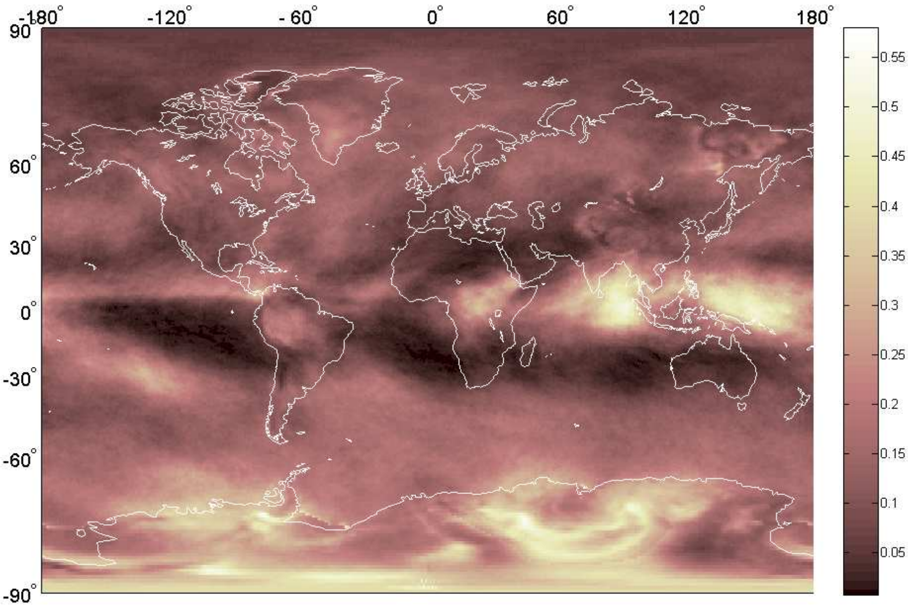


Figure 3.3: Areal probability for contrail formation for an overall engine efficiency of 0.4.

engine efficiency	0.3	0.4	0.5
probability	11.8%	12.9%	14.5%

Table 3.1: Global average area probability for contrail formation.

The area potentially being covered by contrails, also referred to as the potential contrail cover, is regardless of the altitude at which the contrail occurs, and the global average area probability that contrail formation is facilitated was calculated in a separate set of computations. As it varies depending on the assumed overall engine efficiency, it was carried out for different values of overall engine efficiency. Results are given in table 3.1, and the potential contrail cover was calculated to be 11.8-14.5%, depending on the overall engine efficiency. Figure 3.3 shows the potential contrail cover assuming the overall engine efficiency to be 0.40. For the northern hemisphere over regions with high air traffic density, the potential contrail cover was calculated to be in the range of 17%.

Considering that the occurrence of regions facilitating the formation of contrails varies geographically, temporarily and with altitude, the spatial or temporal adjustment of air traffic could lead to the reduction of contrail occurrences. Furthermore, as described in section 2.1.3, the radiative forcing of contrails is dependent on the ground albedo and daytime. Hence, the spatial or temporal adjustment of air-traffic could not only yield a reduction of contrail occurrences, but also a reduction in the radiative forcing of contrails independently from their occurrences. In the light of this fact, the adjustment of air traffic in its various ways was investigated.

3.1.1 Temporal adjustment of air traffic

Temporal adjustment of air traffic to reduce the environmental impact from contrails can be applied to either avoid aircraft flying through regions in the atmosphere that facilitate the formation of persistent contrails or to cause contrail occurrences when their radiative forcing is minimum.

The radiative forcing of contrails varies over the day because of diurnal variations in solar radiation at a particular location on the globe. During night times, in the absence of solar radiation, only outgoing long wave radiation is affected by contrails. Since the overall radiative forcing of contrails is the sum of both longwave and shortwave radiation, and the solar forcing is negative, the overall radiative forcing is increased during night. Stuber et al. [2006] concluded that night-time flights during winter are responsible for most of the contrail radiative forcing and according to Myhre and Stordal [2001], an increase in air-traffic density around sunrise and sunset would reduce the radiative forcing of contrails. However, this might be in conflict with the fact that secondary cirrus from contrails formed during evening hours persist during night when they cause a stronger radiative forcing [Mannstein and Schumann, 2005], an effect that was not considered by Myhre and Stordal [2001]. Although the approach exhibits environmental benefits in terms of contrail radiative forcing, it implies the limitation of air traffic to morning and evening hours, which from an economical point of view is regarded to be impractical. Air traffic is currently taking place during the entire day, and limiting air traffic to certain periods would not be in the interest of airline customers and very likely yield airport and air corridor congestion during the times when air traffic is taking place. Hence, this approach was not pursued further.

3.1.2 Spatial adjustment of air traffic

Similar to the temporal adjustment of air traffic, spatial adjustment of air traffic or individual flights could be applied to either avoid aircraft flying through regions in the atmosphere where the formation of contrails is facilitated, or to cause contrail occurrences where their radiative forcing is minimal.

As the surface albedo determines the radiative forcing of contrails, contrails over regions with low ground albedo would reduce their radiative forcing [Meerkötter et al., 1999]. Hence, avoiding flights over regions with high ground albedo would reduce the radiative forcing of contrails. As regions with an albedo required to reduce the environmental impact of contrails cannot be found near all airports, the approach is impractical as it can only be applied to limited amount of flight routes. It has also to be taken into account that contrails, once formed, can travel over large distances, depending on the high wind speed at high altitudes. Hence, although a contrail might have formed over a region with low albedo, it could be found over a region with high albedo after some time has passed. Furthermore, in order to divert flights over regions with low albedo, the flight path would be artificially prolonged, leading to fuel burn penalties and and increase in journey time. In the light of these disadvantages, the approach was seen as impractical and has not been investigated in more detail.

Apart from adjusting air traffic to reduce the radiative forcing from contrails, contrail occurrences could be reduced by preventing aircraft from flying through regions in the atmosphere that facilitate the formation of persistent contrails. Regions susceptible to the formation of contrail cirrus have distinguishable characteristics and could be avoided independently.

An aircraft approaching a region that facilitates contrail formation could avoid it by either changing altitude or diverting from the flight path horizontally. The horizontal deviation from the flight path would imply an increase in flight length, leading to higher block fuel consumption, and as the aircraft performance is dependent on flight altitude, a change in cruise altitude would also imply an increase in fuel burn. The most fuel efficient altitude of a conventional commercial aircraft increases as the journey progresses. Calculations were performed to calculate the effect of a change in cruise altitude on fuel consumption and contrail formation. Therefore, TURBOMATCH and the ESDU aircraft performance were embedded in a MATLAB script. A description of the codes can be found in the appendix on page 156. The aircraft type considered in the study is a modern long-haul medium-size commercial transport aircraft, as described in the appendix on page 157. The baseline is used in all calculations throughout this thesis. Figure 3.4 shows the relative change in specific block fuel consumption in fuel per passenger-kilometre, also known as inverse specific air rnage (ISAR), depending on altitude and cruise speed for different aircraft weight and ISA temperature deviation scenarios. Displayed true air speeds correspond to a Mach number range of 0.75 to 0.85. The ISAR is minimum for a certain altitude-speed combination. For higher/lower speeds and altitudes, the aircraft operates outside the most fuel efficient conditions, and the most fuel efficient cruise altitude is increasing as the fuel weight decreases (from left to right in figure 3.4).

The horizontal lines in figure 3.4 denote altitudes for persistent contrail formation according to the Appleman criterion. At low altitudes below the dash-dotted line, contrail formation is not facilitated. For altitudes between the upper dashed and lower dash-dotted lines, contrail formation depends on the ambient humidity, denoted by the dashed lines in between: 140% (bottom), 120% (middle) and 100% (top). Contrail formation is always facilitated for altitudes above the top dashed line.

Changing to lower speeds has an impact on the overall engine efficiency. Figure 3.5 shows the absolute change in engine efficiency. Although the associated loss in overall engine efficiency could be seen as a method to avoid the formation of contrails, the decrease in engine efficiency is marginal, at most 3% for the range shown in figure 3.5, with almost no effect on contrail formation.

Hence, changing cruise altitude would be more effective for avoiding contrail formation. However, the specific block fuel consumption of the considered aircraft type is minimum for altitudes where contrail formation is facilitated. This is especially the case for a negative ISA temperature deviation and low aircraft weight. In order to avoid contrail formation thermodynamically, an aircraft would have to change to lower cruise altitudes where the ambient temperature and the specific block fuel consumption is higher. In the case of zero ISA temperature deviation and 66% fuel in the tanks, an aircraft operating at its most fuel efficient altitude/cruise speed combination (250m/s at 10750m) would have to descend by 1500 metres to avoid contrail formation. This would be accompanied with an increase in specific block fuel consumption of about 5%. However, formation of persistent contrails is only facilitated if the ambient atmosphere is ice supersaturated, and ice-supersaturated regions can have a vertical extent that would be lower than the required altitude change to avoid contrail formation thermodynamically, resulting in a less severe increase in block fuel consumption.

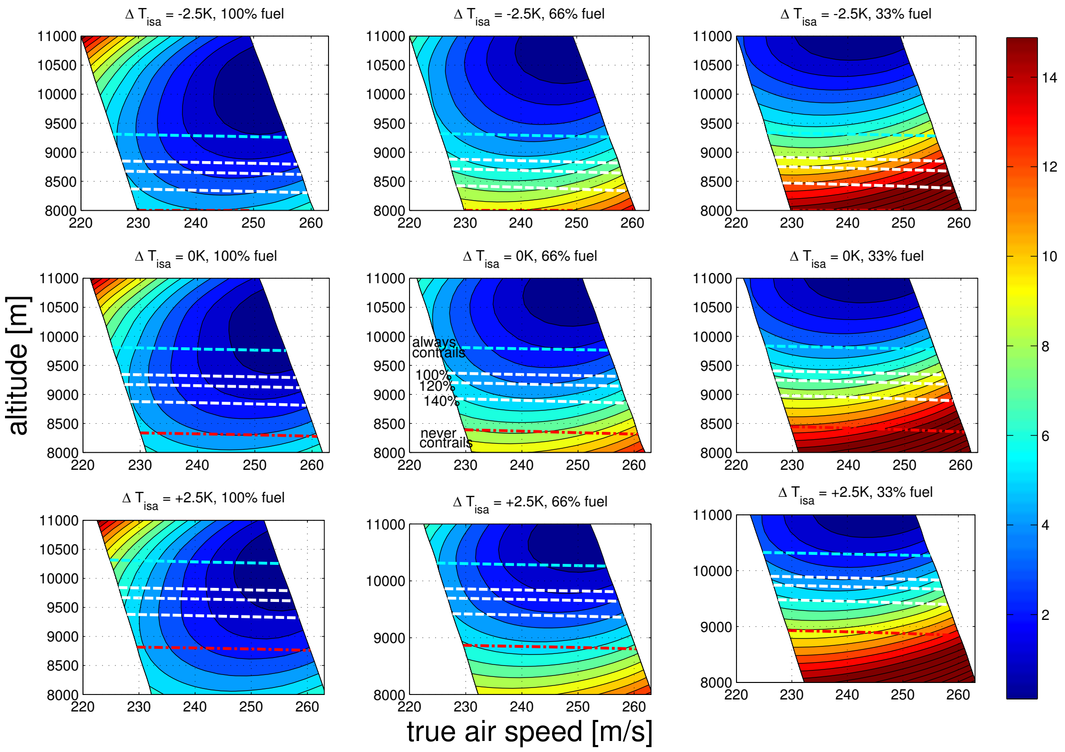


Figure 3.4: Relative change in inverse specific air range relative to most fuel economic value [%].

Three distinct approaches were identified that can be used to mitigate the formation of contrails by spatially adjusting air traffic: (a) change cruise altitude on a global scale [Fichter et al., 2005]; (b) restrict cruise altitudes based upon atmospheric conditions for certain regions over a certain time period [Williams and Noland, 2005]; (c) change aircraft cruise altitude during flight depending on ambient conditions [Mannstein et al., 2005]. These approaches are discussed in the following.

(a) change cruise altitude on a global scale

Ambient temperature, pressure and humidity depend on altitude and differ geographically. If air traffic was shifted upwards or downwards relative to current

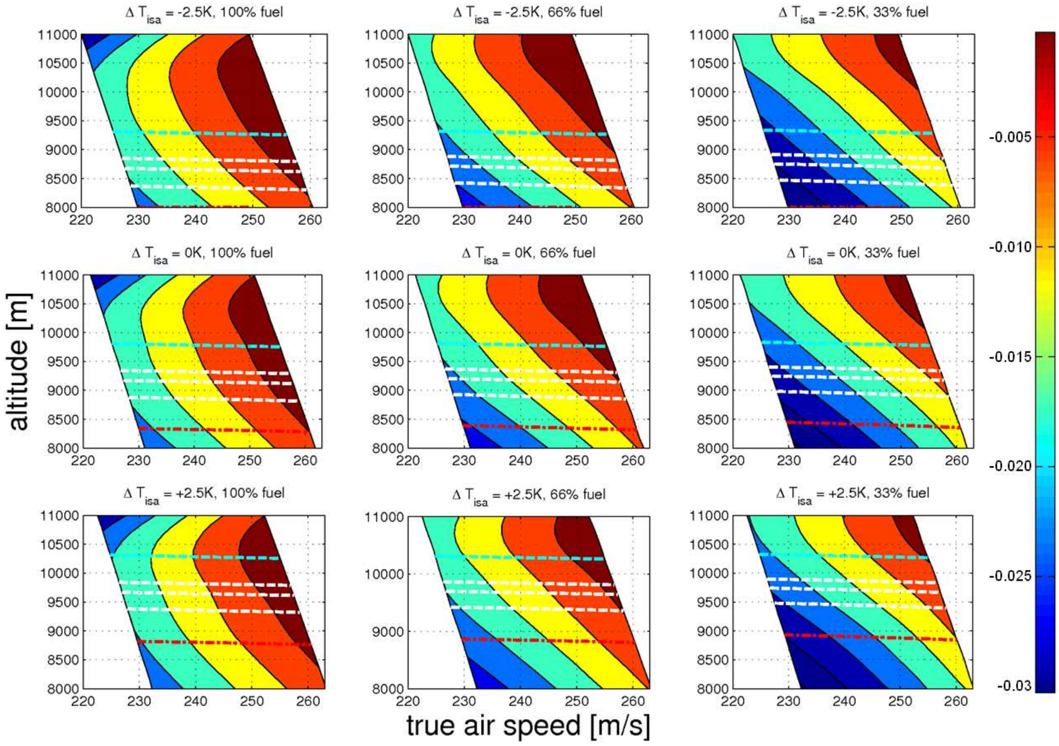
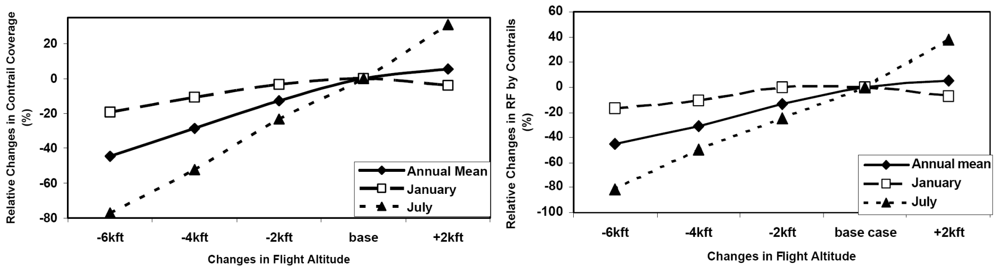


Figure 3.5: Absolute change in overall engine efficiency.

typical cruise altitudes, a change in contrail occurrences, and hence radiative forcing, should be observable. The stratosphere e.g. is much drier than the troposphere [Gierens et al., 1999], and stratospheric air traffic would reduce contrail cover considerably. However, other considerations would have to be taken into account. There are concerns about ozone depletion by nitrogen oxides due to stratospheric air traffic.

In Fichter et al. [2005], a parametric analysis of the radiative forcing from contrails depending on a shift of air traffic to different altitudes is presented. In that study, the global radiative forcing of contrails was calculated by means of a global circulation model for different air-traffic scenarios. It was calculated that a downwards displacement of the flight corridors on a global scale would result in a decrease in global contrail coverage and radiative forcing, especially during the winter months.



(a) Contrail cover. (b) Radiative forcing.

Figure 3.6: Change in contrail cover and radiative forcing from contrails by changing flight altitude [adopted from Fichter et al., 2005].

An increase in contrail cover would occur in regions with prevailing high altitude air traffic in the mid-latitudes. The opposite would be true for an upwards shift of the flight corridors. Figure 3.6 shows the change in contrail cover and the associated radiative forcing for different altitude scenarios. An increase in fuel burn of 6.3% was calculated for the case of shifting air traffic 6,000 feet downwards.

In general, aircraft are designed for a particular mission in terms of cruise speed, payload and journey length. Depending on the technology, the most economic cruise altitude results from the initial specification. If an aircraft designed for a particular altitude is flying above or below that altitude, more fuel is required to complete the journey and hence more carbon dioxide is emitted. In addition, some journeys would not be feasible due to the limited fuel capacity and minimum climb requirements during take off. However, aircraft especially designed for different altitudes might offset the fuel burn penalty, an issue investigated in section 3.3.1.

(b) restrict cruise altitudes based upon atmospheric conditions for certain regions over a certain time period

In this approach, air traffic is shifted to different flight corridors for defined regions and over a certain time period. Williams and Noland [2005] carried out simulations for air traffic over Europe. In the simulations, air-traffic corridors were relocated in 6 hour intervals depending on atmospheric conditions, and the formation of contrails was assessed using atmospheric data. Results suggest that (b) leads to a decrease in contrail cover of 65-95%, associated with a fuelburn penalty of 2.6-7.0%.

However, air-traffic management and safety issues associated with this contrail avoidance method may impede its application. Currently, aircraft are allocated certain flight altitudes to avoid collision with other aircraft, and the allocated flight altitudes can be found within certain flight levels. Aircraft changing altitude in flight would cause a rise in traffic on other flight levels, increasing the risk of collision. Especially regions with heavy air traffic would be affected. Williams and Noland [2002] studied the increase in air traffic associated with this contrail avoidance method and found that the required minimum separation between aircraft could not then be maintained due to the reduced number of available flight levels. In a following study, [Noland and Williams, 2003] concluded that this could be alleviated by redesigning air-traffic sectors.

(c) change aircraft cruise altitude during flight depending on ambient conditions

Regions that facilitate the formation of persistent contrails could be avoided by changing cruise altitude in flight. This technique is already applied by military planes to suppress their visibility. Since the deviation from the most fuel efficient cruise altitude would be for a relatively short time period, the fuel burn penalty is expected to be lower than for (a) and (b).

The flight path could be planned already prior to take off. Weather forecast data or in-flight measurements of preceding aircraft could be used to determine the flight path that facilitates a reduction in contrail formation. If forecast data or in flight measurements lack the required accuracy, an alternative approach would be on-board sensors, which can detect the formation of contrails behind the aircraft. Humidity, pressure and temperature measurements could complement measurements to enable effective decision-making by the pilot whether to change altitude or not. As for (b), this contrail avoidance method could lead to an increasing risk for aircraft collision. More sophisticated flight tracking and collision avoidance systems would be required for an introduction of this contrail avoidance strategy.

The fuel burn penalty that comes with changing altitude during flight was assessed in a study as part of the PhD project. Therefore, a MATLAB script was developed that allows the optimization of a flight path between a specified departure and destination point for minimum contrail formation. Starting with the great circle route, the flight path was parameterized subdividing it into equally long portions. A horizontal and vertical offset of waypoints from the great circle route could be defined, yielding in a flight path differing from the great circle route. Fuel consumption along the flight route was calculated considering change in aircraft weight as fuel is consumed and the change in performance of the aircraft depending on altitude was taken into account. Therefore, engine performance response surfaces were created with TURBOMATCH. The response surfaces were used in the ESDU aircraft point performance code, which was embedded in the MATLAB script. For each waypoint, the ESDU aircraft point performance code was called to get the fuel flow rates. Time integration of the fuel flow rates yields overall block fuel consumption. In between the major waypoints, additional waypoints could be defined to increase the accuracy of fuel burn figures. In order to account for contrail formation, the probability for persistent contrail formation was calculated for each month using the 2005 operational weather analysis data of the MetOffice unified model. Defining departure and destination coordinates, the geographic location and altitude was known for each waypoint. The MATLAB script reads the probability for contrail formation at each waypoint, which allowed the calculation of the fraction of the flight path where contrail formation is facilitated. Linear interpolation was applied in between the available grid points.

Varying the offsets of the waypoints from the great circle route would result in both a change in fuel burn and the fraction of the flight path where contrail formation is facilitated. The MATLAB script was connected to a commercially available simplex optimisation algorithm. The objective of the optimisation was to minimize fuel burn and reducing the fraction of the flight path where contrail formation is facilitated. Therefore, an objective function was selected which combines both fuel consumption and contrail formation in the form

$$OBJ = m_{fuel} \ [c_w \ p_i + 1] \quad (3.1)$$

where m_{fuel} is the mass of the fuel burned during the journey, c_w is a weighting factor and p_i the fraction of the flight path where contrail formation is facilitated. In this study, the flight path was defined by 8 major waypoints, and the considered departure and destination points were London and New York, stretching over a distance of approximately 5600km. In the first instance, the fuel burn and amount of contrail km formed was calculated for the great circle route without taking into account contrails formation, i.e. $c_w = 0$. Fixing the weighting factor to 6, optimisations were then carried out for each month. Figure 3.7 contains results regarding the fraction of the flight path where contrail formation is facilitated for the contrail

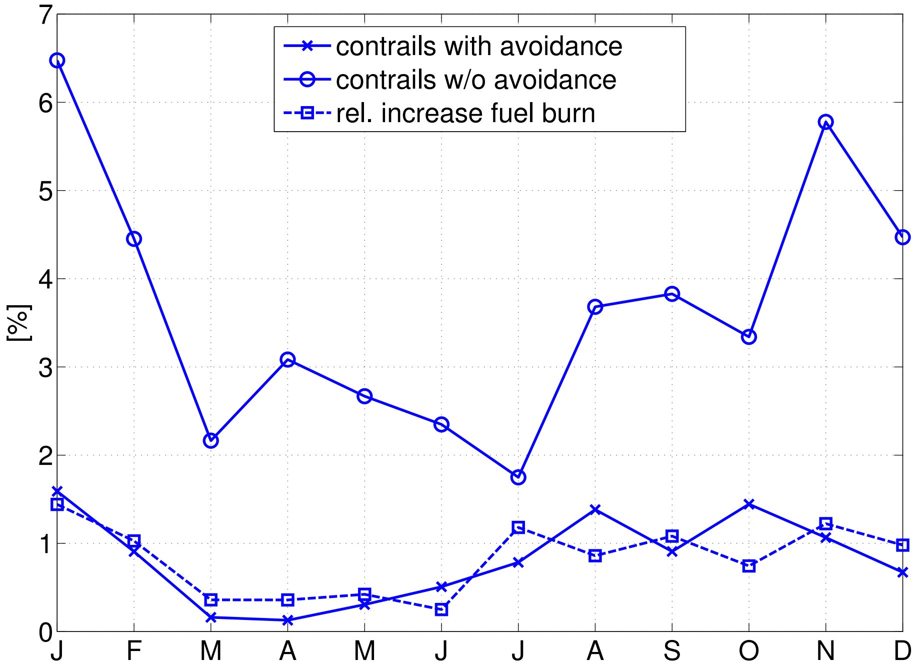


Figure 3.7: Annual variation in contrail formation along the flight path with and without avoidance and the relative increase in fuel burn.

avoidance and non-avoidance scenario, and the associated increase in fuel burn. According to the results, the annual mean of the fraction of the flight path where contrail formation is facilitated is 3.7%. Numbers peaked during the winter months and were lower during the summer months. Applying flight path optimisation, a reduction in contrail formation was possible but associated with a fuel burn penalty. The new mean fraction of the flight path where contrail formation is facilitated was calculated to be 0.8%, which is a 78% decrease in contrail occurences in absolute terms. The relative increase in fuel burn was calculated to be 0.8%.

Allowing the change of cruise altitude in flight, also called free flight, does not only have advantages because the formation of contrails could be avoided. It would also allow continuous climb, an approach often suggested to reduce fuel burn, and hence CO_2 emissions. Free flight has been established as one of the most commonly mentioned approaches for contrail avoidance [Dings and Peeters, 2000]. But it is,

EI	c_p	M	q_{net}
1.25	1004J/(kgK)	0.622	43MJ/kg

Table 3.2: Parameters for minimum engine efficiency calculations.

however, associated with severe implications regarding air-traffic management and safety. Otherwise its introduction would have probably already happened as it exhibits the potential to reduce fuel burn, which would not only reduce CO_2 emissions but also reduce airline direct operating costs.

3.2 Engine technology

For a given ambient temperature, pressure and humidity, the minimum engine efficiency required for contrail formation can be calculated solving equation 2.3. Ambient temperature and pressure is a function of altitude, described by the International Standard Atmosphere (ISA) atmospheric model. Hence, the minimum engine efficiency required for contrail formation can be calculated specifying altitude and ambient ice-supersaturation and, if desired, a temperature deviation from the ISA atmosphere. Calculations were conducted combining equation 2.2 with the standard atmosphere model. The parameters used for the calculation are given in table 3.2, and results for different overall aircraft efficiencies are shown in figure 3.8. They can be used to determine the minimum overall engine efficiency required to facilitate the formation of contrails. For example, at an altitude of 8500 metres and a local ice-supersaturation of 140%, aircraft with an overall efficiency of 0.4 or more would cause the formation of contrails. With a negative ISA temperature deviation, the minimum overall engine efficiency required for contrail deviation decreases and the opposite is the case for a positive ISA temperature deviation.

In general, the minimum engine efficiency required to facilitate contrail formation

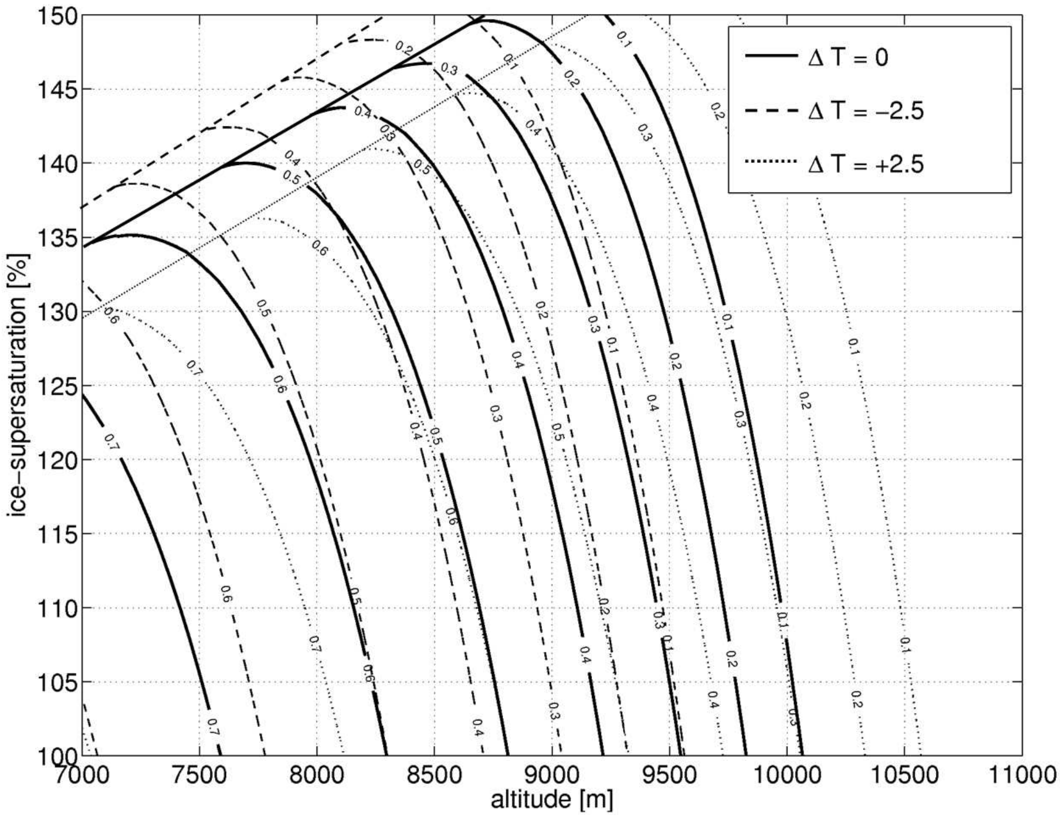


Figure 3.8: Minimum engine efficiency required for contrail formation for standard temperature deviations ±2.5K.

increases for altitudes and levels of ice-supersaturation. Current aircraft, typically operating with overall efficiencies of 0.30-0.35, do not facilitate contrail formation for altitudes below 9500 metres assuming an ice-supersaturation below 130%. Aircraft designed with higher overall efficiencies, say 0.5, would cause no contrails if they flew below 8300 metres (7750m if the ISA temperature deviation was -2.5K). However, it is important to note that the occurrences for ice-supersaturated regions is altitude dependent, and lower altitudes does not necessarily mean less contrails on a global scale.

Referring to equation 2.2, lower values of the mixing line slope σ, reducing the potential for contrail formation, can be obtained by either decreasing its numerator or increasing its denominator. The variables in the numerator are c_p, EI_{water} and p_a, and the numerator decreases if one of the variables decreases. The specific heat capacity of air, c_p, is a natural constant and cannot be modified to suppress contrail formation. Ambient pressure, p_a, is altitude dependent, decreasing for higher altitudes. The water emissions index EI_{water} is fuel dependent. The impact of fuels on contrail formation is discussed in sections 3.4.

The denominator in equation 2.3 has q_{net}, $(1-\eta_0)$ and M. Increasing the individual terms would cause the desired decrease in the mixing line slope σ. The molar mass ratio M is a natural constant and cannot be modified, whereas q_{net} is fuel dependent and discussed in section 3.4, and η_0 depends on the engine technology. Further improvements in overall engine efficiency considering current technology are constrained by restrictions set by the stoichiometric combustion temperature and theoretically achievable propulsive efficiency of open rotor devices [Green, 2003]. According to Green [2003], the theoretical limit of overall efficiency for conventional engine architecture is 0.56, assuming open rotor technology, ultimate component efficiencies, a stoichiometric turbine inlet temperature and an overall pressure ratio in excess of 80. In effect, contrail formation would be facilitated at lower cruise altitudes, and potentially more contrails could occur. The change in regions where the formation of contrails is facilitated switching from an overall engine efficiency of 0.35 to 0.56 was calculated using the 2005 MetOffice weather analysis data. The world map in figure 3.9 is a snapshot of 1st of January 2005 at 6 am, showing regions where contrails would form if the engine efficiency was either 0.35 or below (grey) and between 0.35 and 0.56 (dark) using the MetOffice data set, i.e. for an engine efficiency of 0.56 contrail formation would be facilitated in both the grey and dark shaded regions. As it can be seen, more regions exist where contrail formation is facilitated for an increasing engine efficiency. A quantitative analysis was carried out, and a MATLAB script was therefore developed that counted occurrences in the MetOffice data set if the ice supersaturation was in excess of 100% and the Appleman criterion was met. The script was run for an engine efficiency of both 0.35 and 0.56. In general, more occasions were counted in case of a higher engine efficiency. The ratio of the occasions where contrail formation was facilitated for an engine efficiency of 0.35 over the case where the engine efficiency is 0.56 is given in figure 3.10 for different altitudes. At low altitudes, the ratio is 0.48, implying that the switch to more efficient engines would also cause an increase in regions facilitating persistent contrail formation. At high altitudes, the effect is less severe, and over 13000 metres there would not be any difference. This effect should be considered if next generation aircraft operate with higher engine efficiencies and are designed for lower altitudes.

The particle size, their microphysical properties, particle number density and the presence of aerosols in the exhaust plume have an effect on the radiative properties of contrails. Changing the radiative properties of contrails could reduce the overall radiative forcing from contrails. Hence, it might be desirable to either control particle and aerosol properties or increase/decrease particle concentrations in the exhaust. Even for a perfectly clean exhaust without aerosols, contrail formation would still be facilitated in the presence of ambient aerosols. Without additional particles in the exhaust, contrail ice particles would be larger in size, possibly leading to a lower radiative forcing [Ström and Gierens, 2002]. Hence it might be desirable to reduce particle emissions. Engine emissions emerge during the combustion process and may be tackled either during the combustion process itself or post combustion via exhaust clean-up by means of filter systems. A trend for less particle emissions can already be seen as it is part of the common business for engine manufacturer to continuously increase the combustion efficiency of combustors. However, a significant reduction of particle emissions would be necessary, and it

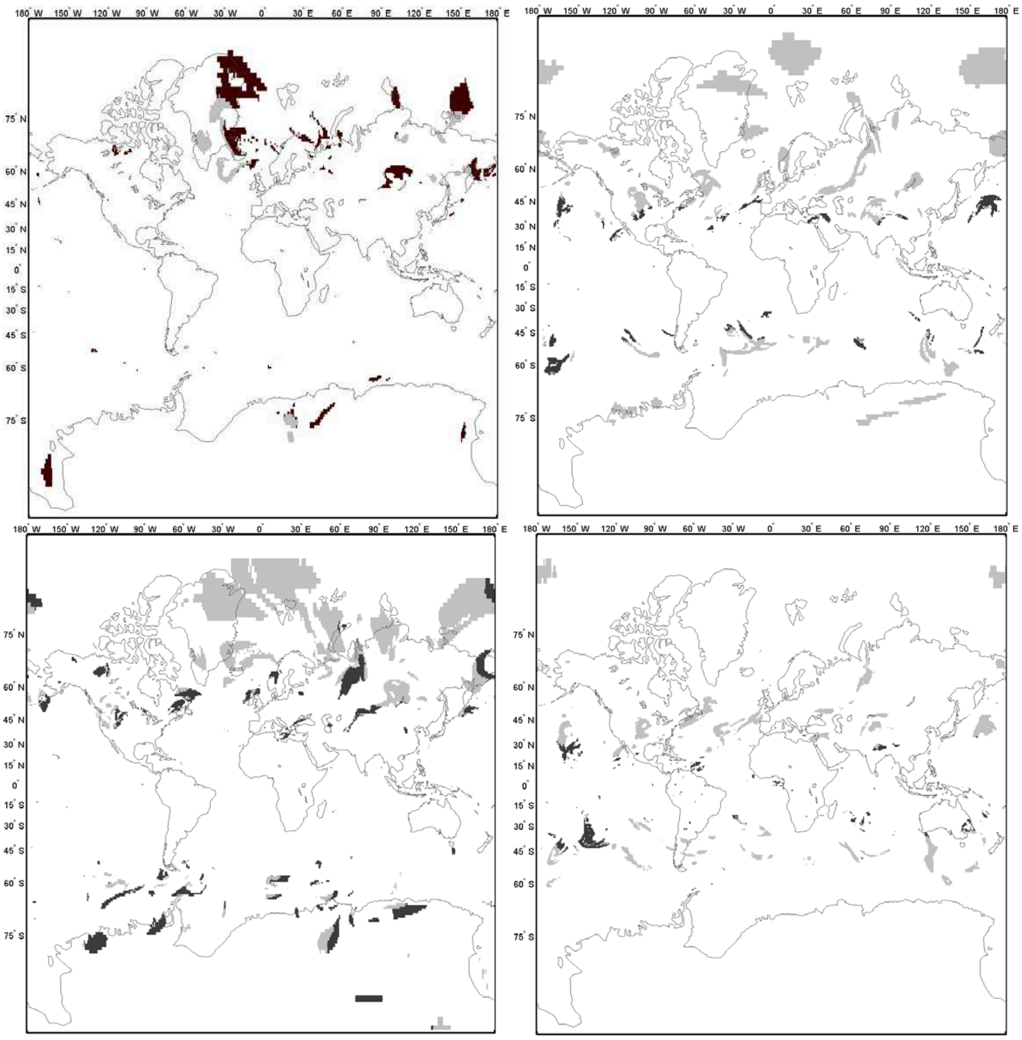


Figure 3.9: Snapshot for 1 January 2005 showing areas where the formation of contrails is facilitated at different altitudes. Top left: 400hPa (7185m), bottom left: 300hPa (9164m), top right: 250hPa (10363m), bottom right: 200hPa (11775m). Dark: $\eta_0 \leq 0.35$; grey: $0.35 \leq \eta_0 \leq 0.56$.

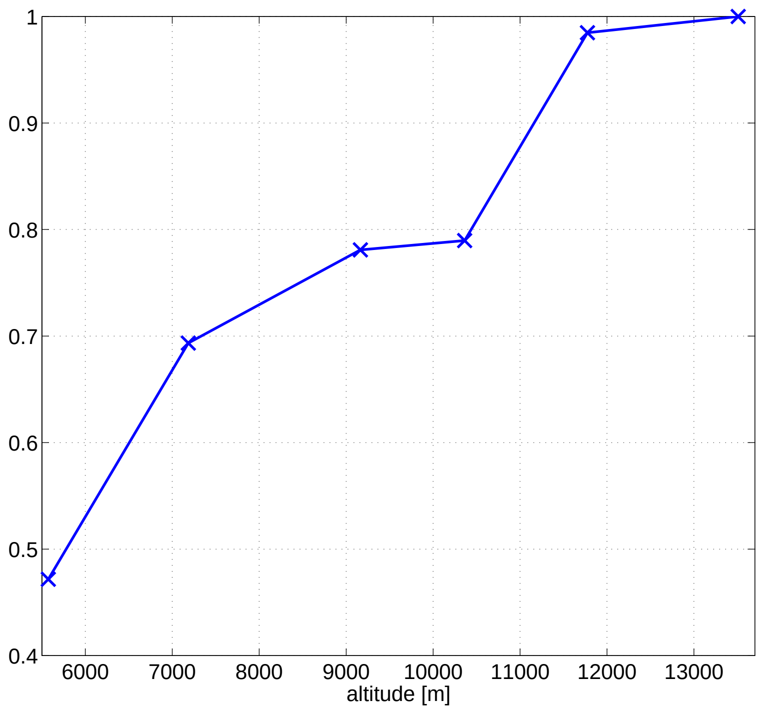


Figure 3.10: Ratio occurrences where contrail formation is facilitated for an engine efficiency of 0.35 over occurrences where contrail formation is facilitated for an engine efficiency of 0.56

might be questionable whether that will ever be achievable without additional filter systems.

3.2.1 Distributed propulsion and remotely driven fans

A novel engine concept discussed in the aeronautical community is distributed propulsion [Campbell, 2003, Sehra and Whitlow, 2004] in the form of mini-gas turbines or remotely driven fans. Mini-gas turbines have the potential to reduce block fuel consumption but might operate with a lower overall efficiency compared to current designs [Ameyugo et al., 2006]. The decrease in the overall efficiency could cause a reduction in the potential for contrail formation. Smaller plume diameters might lead to a smaller vertical band of the contrail thus reducing the chance for contrail cirrus formation. A distributed exhaust along the lifting body could possibly also have an effect on the jet entrainment. The effects of distributed propulsion on contrail formation would have to be studied if this propulsion method became a serious alternative to common engine practice.

Distributed propulsion in the form of remotely driven fans could be a disadvantage in terms of contrail formation. If the core of the propulsion device is a gas turbine producing power to drive the fans, the jet of the fans and the exhaust of the core would be physically separated. This would have an impact on the humidity/temperature ratio distribution in the plume. For common turbofans, the engine exit conditions in terms of temperature and humidity as considered in the Appleman theory for contrail formation are a weighted average of both engine core and bypass. If both are separated from each other, it could be assumed that both jets mix independently from each other with ambient air. In figure, 3.11, the mixing lines for core and fan are separately shown, together with the mixing line assuming both streams mixing prior to mixing with ambient air. The core exhaust, containing the entire combustion water and hence being extremely humid, would facilitate contrail formation even at very warm temperatures. The bypass air, containing no additional water, would not contribute to contrail formation.

3.2.2 A clean exhaust engine concept

Since the introduction of jet engines for commercial air traffic, there has been steady improvement in their fuel economy. Whilst the reason for better fuel economy of early aircraft was to extend the accessibility to air travel for a larger fraction of population, environmental aspects have become the main reason for cleaner technologies. First jet engines suffered from poor component efficiencies, restricted

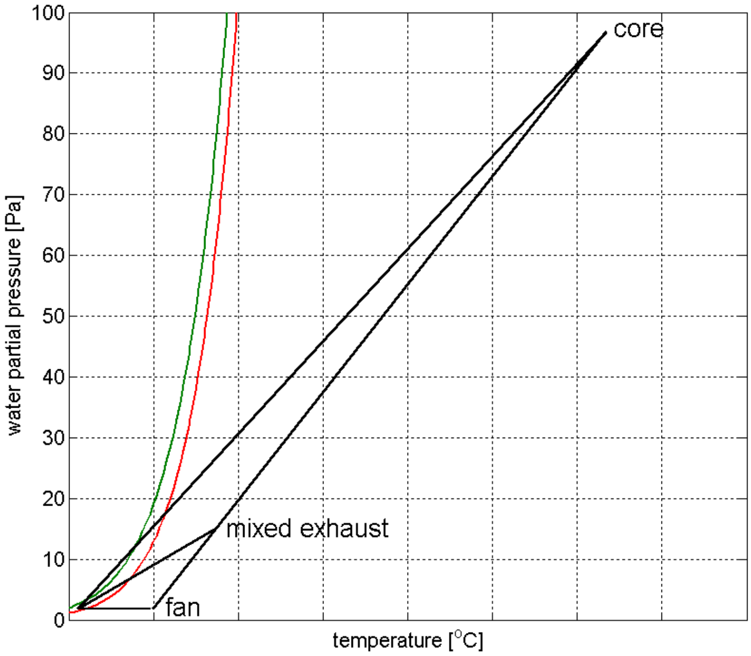
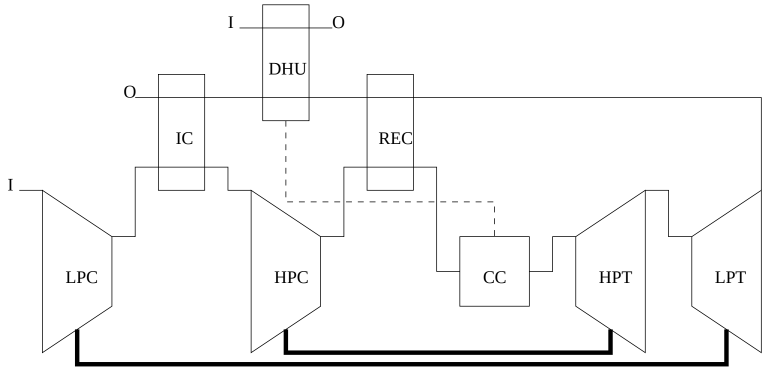


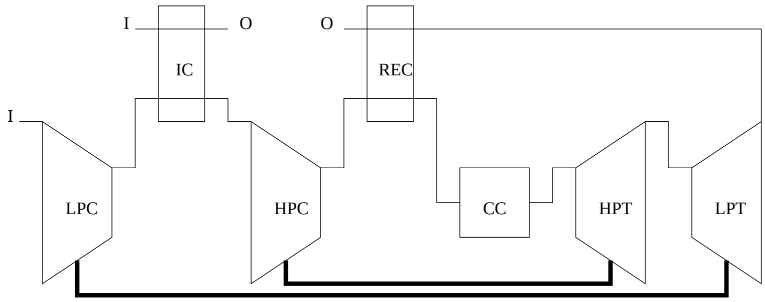
Figure 3.11: The effect of remotely driven fans on contrail formation.

turbine inlet temperatures, low achievable pressure ratios and low thrust to weight ratios. The advent of advanced combustor technology, higher component efficiencies, new materials, blade cooling techniques, higher pressure ratios thanks to multi spool arrangements and large bypass ratios improved the engine performance. Future developments considering current engine architecture have the potential for further improvements. However, they are incremental, take place on a subsystem level and are associated with increasing technological and financial investments.

Maclin and Haubert [2003], Sehra and Whitlow [2004] and Seidel et al. [2001] state that only revolutionary changes in engine design can lead to the significant advances in engine fuel economy and environmental compability required in the light of the annual growth rates in air traffic. Although approaches utilising fuel cells and similar mechanisms may be feasible [Alexander et al., 2002], they require significant deviation from current gas turbine practice. Hence it would be more desirable to provide a revolutionary solution with respect to existing gas turbine technology that can also operate with any available hydro or hydrocarbon based fuel. In this section, an engine concept is presented that, apart from suppressing contrails, has also the potential for lower emissions. The following requirements were set on a novel engine architecture: higher thermal efficiency, and a reduction in water vapour, soot and aerosol emissions to avoid the formation of contrails and cirrus clouds, and lower NO_x emissions. Generally, the formation of contrails could be avoided by reducing the water content in the exhaust gases of a jet engine. A temperature drop of the exhaust gases would be necessary to facilitate water condensation inside the engine, which could be achieved with heat exchangers. The water condensate could be stored either on board the aircraft or released into the atmosphere in the solid or liquid state for precipitation. The clean exhaust engine concept, patented in Noppel et al. [2007], is a derivative of the standard intercooled and recuperated engine cycle with a condensation stage. The intercooled-recuperated engine cycle, which is shown in figure 3.12(b), enables a substantial improvement in thermodynamic work potential, ultimately leading to lower fuel consumption [Boggia and Rüd, 2005]. A reduction in NO_x is possible through the reduction in fuel flow and lower pressures inside the engine, yielding lower levels of NO_x formation during combustion. The intercooler is a heat exchanger, typically placed between the low pressure compressor LPC and high pressure compressor HPC. The flow on the cold side of the heat exchanger is usually bypass air. Intercooling reduces the work required for the compression of the air in the HPC. The hot gases leaving the LPT are used to heat the pre-combustor air in the recuperator, so more heat is used to generate useful work. In this arrangement, the thermal efficiency does not increase for higher pressure ratios, but is maximum for a specific pressure ratio. The overall effect can be a significant improvement compared to conventional gas turbine cycles at lower OPR and TET.



(a) Novel concept based on a intercooled recuperated engine cycle.



(b) Intercooled recuperated engine cycle.

Figure 3.12: Novel engine concept vs. intercooled recuperated engine cycle.

Contrails form in the exhaust plume of an aircraft if the ratio of water partial pressure to temperature in the exhaust, denoted by the slope of the mixing line σ, is below a certain value. Equation 2.3 assumes that all water emerging during combustion is contained in the engine exhaust. The ratio could be artificially lowered by removing the water from the exhaust inside the engine. This could be achieved if the temperature after the LPT is reduced so water condenses within the engine. A temperature reduction down to some 10 K above ambient temperature would be required to facilitate water condensation inside the engine. However, reducing the flow of the exhaust by simply transferring heat energy outside the engine without utilising it would cause a reduction is engine efficiency.

An intercooled and recuperated cycle in a novel arrangement exhibits the potential for water condensation within the engine without compromising engine efficiency. The recuperator redirect heat energy into the engine core flow, where it is not wasted. The temperature of the flow exiting the recuperator, already cooled to a certain degree, is further reduced by applying an additional heat exchanger. In the following, the additional heat exchanger is referred to as condensation stage. It operates with bypass or ambient air on the cold side. For sufficiently low temperatures, this will cause condensation of the water contained in the exhaust within the engine. The dry and cold air leaving the condensation stage contain less water, but what is required for contrail avoidance is a dry and relatively hot exhaust. Thus, the flow exiting the condensation stage is used in the intercooler to chill the flow between the compression stages. This has the effect of increasing the exhaust temperature, further reducing the potential for contrail formation and increasing the engine efficiency simultaneously. A gas path diagram of the clean exhaust engine concept is given in figure 3.12(a). The major differences between the clean exhaust engine concept and the conventional intercooled recuperated cycle is that the clean exhaust engine concept has an additional heat exchanger, the dehumidifier, and that the intercooler operates with core air only.

Figure 3.13 shows the water partial pressure on a phase diagram of water for different stations within the engine and in the exhaust plume. Static flow temperatures and pressures are considered for the stations within the engine, whereas stagnation properties relative to the atmosphere frame of reference are considered in the plume. Mixing is assumed to take place adiabatically and isobarically. The water saturation pressure is calculated considering clean water condensing on a flat surface [Flatau et al., 1992]. The flow exiting the LPT, being relatively hot and humid, is cooled by about 400K. The decrease in water partial pressure in the recuperator occurs due to the pressure loss within the heat exchanger as a decrease in absolute pressure does also imply a decrease in the partial pressures of the flow constituents.

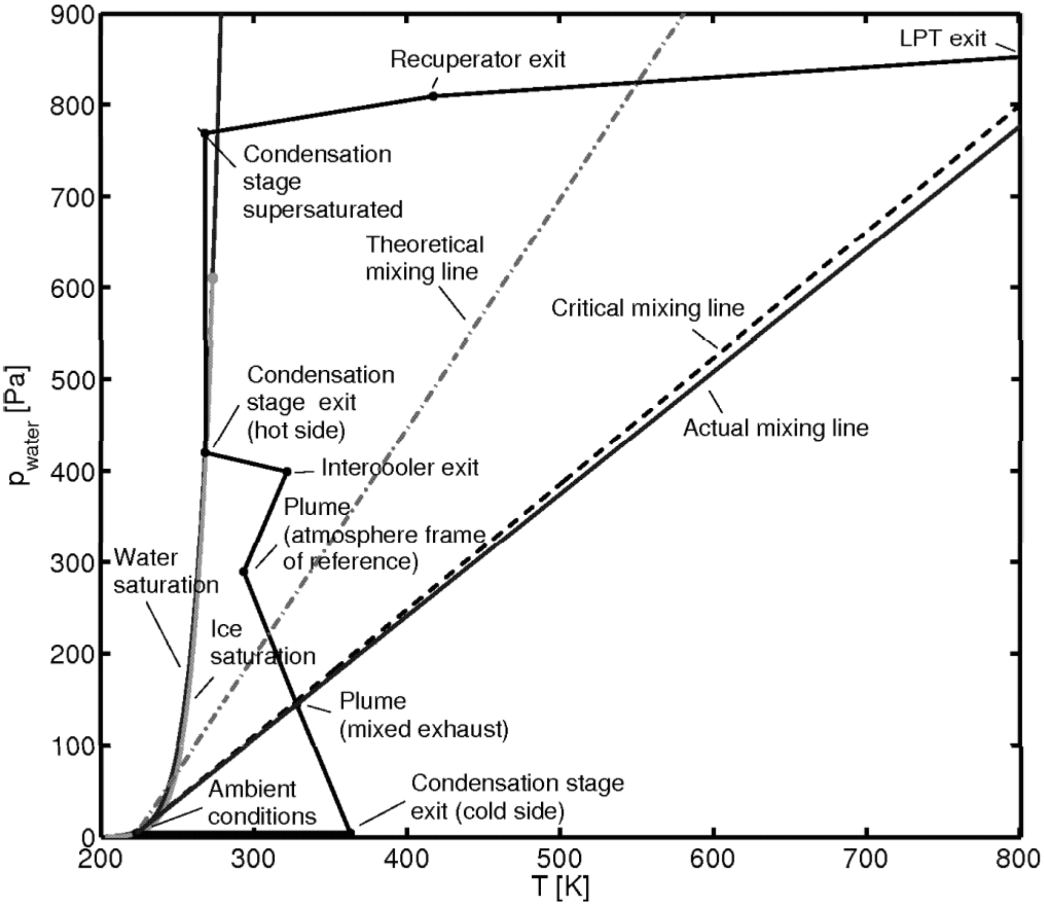


Figure 3.13: Engine stations on a phase diagram of water.

At the condensation stage exit, the flow has a temperature low enough for water to exist in the liquid state. Assuming condensation of water, the partial pressure at the condensation stage exit is then determined by the liquid saturation pressure at the prevailing temperature. The exhaust gas temperature increases again in the intercooler. Again, the drop in partial pressure is caused by the overall pressure loss in the heat exchanger. The temperature of the exhaust gases exiting the cold side of the condensation stage and the cold side of the intercooler was calculated to be the flow stagnation temperature relative to the atmosphere frame of reference. The exhaust flow from the cold side of the intercooler contains no additional water. The mixing of the two flows can take place inside the engine or in the plume. In this study, it was assumed that the mixing takes place outside the engine and it was assumed that they mix prior to the mixing with ambient air. The actual mixing line in figure 3.13 represents the mixing of the mixed exhausts with ambient air. Furthermore, the critical mixing line is shown, which is indicating whether contrail formation is facilitated or not. It is a tangent to the water saturation pressure line originating from the ambient state of the atmosphere. If the actual mixing line is below the critical mixing line, the formation of contrails is not facilitated, because contrails form only if the actual mixing line surpasses the region for which water is present in the liquid phase in a phase diagram as mentioned in previous sections. Additionally, the theoretical mixing line is shown. It represents the mixing line of the mixed exhausts with ambient air if no dehumidification took place. The actual mixing line and the theoretical mixing line would coincide if no dehumidification occurred within the engine.

The condensation of water can be expected to occur on the walls of the heat exchanger, but also on the particles that are contained in the exhaust. This would result in the scavenging of particles and aerosols from the exhaust, leaving the engine exhaust free from particles and aerosols. The condensed water, present in the liquid state, could be partially redirected into the combustion chamber. An 80% reduction in NO_x emissions is possible injecting water into the combustor as shown in figure 3.14 [Lefebvre, 1983]. Water injection during takeoff and climb conditions has been successfully demonstrated in the lab by Daggett et al. [2004]. With this engine concept, NO_x reduction would become feasible during the entire journey.

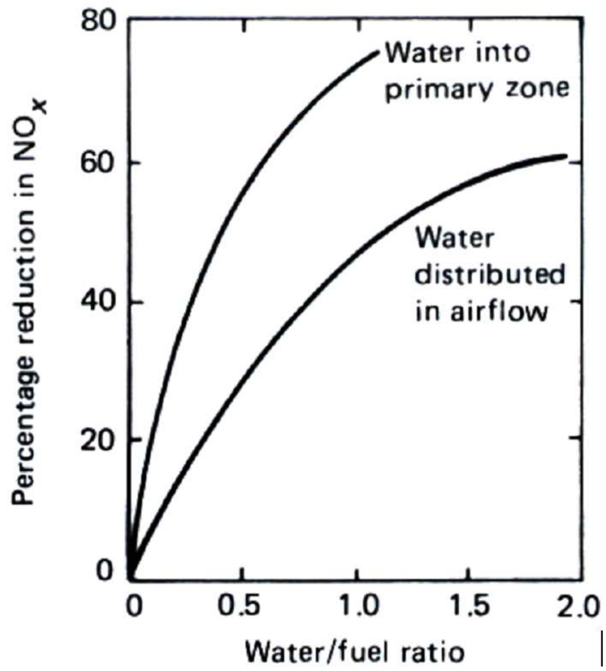


Figure 3.14: NO_x reduction through water injection [adopted from Lefebvre, 1983].

Cycle optimisation

A set of optimisations was performed to calculate the cycle performance. Therefore, a mathematical representation of the cycle was developed as part of an MSc project by Lucisano [2007]. The performance model was linked to a contrail forecast model. Phoenix Model Center, a commercially available genetic optimisation algorithm computer programme, was used to calculate the combination of design parameters that yield in maximum engine efficiency. The design variables were overall pressure ratio, fan pressure ratio, bypass ratio and the ratio of the high pressure compressor ratio to the low pressure compressor ratio.

Three sets of optimisations were carried out considering a range of turbine entry temperatures between 1600K and 2200K. In the first set, the objective of the optimisation was to calculate the most efficient cycle regardless of its ability to suppress contrails. In subsequent runs, the objective was to calculate the most efficient cycle that would allow the suppression of contrails. As it was discovered that the optimum cycle performance also depends on the ambient ice-supersaturation, 2 different levels of ambient ice-supersaturation were taken into account: 115% and 130%. Ambient conditions where held at 33,000 feet (10,058 metres) and Mach 0.8 during all optimisations. Component efficiencies represented latest technology levels. The heat exchanger effectiveness' of the intercooler and recuperator were assumed to be 0.90, and 0.95 for the condensation stage, as relatively low temperatures close to ambient are required to facilitate water condensation inside the engine.

Optimisation results are given in figures 3.15 to 3.19. In general, cycles with higher TET result in better specific fuel consumption. For a given TET, it was calculated that the specific fuel consumption is higher for cycles where contrail suppression is considered than for the baseline cycle where contrail suppression was not taken into account during the optimisation process, whereas the higher the levels of ambient ice-supersaturation cause larger drawbacks in terms of specific fuel consumption. In terms of overall engine efficiency, as shown in figure 3.16, the cycles were all between 0.44 and 0.52, which is well above what is achieved with current engines and close to what is theoretically available with conventional technology (see section 3.2 on page 75). Higher component efficiencies, lower pressure losses in the heat exchangers or higher TET yield overall engine efficiencies above what is possible with conventional engine architecture. According to the results, the optimum overall pressure ratio is increasing with TET as shown in figure 3.17. It is lowest where contrail avoidance is not considered during optimisation and is increasing for higher levels of ambient ice-supersaturation. The optimum bypass ratio shown in figure 3.18, is increasing with TET. No significant influence of ice-supersaturation on optimum bypass ratio was found. However, the results suggest that this engine

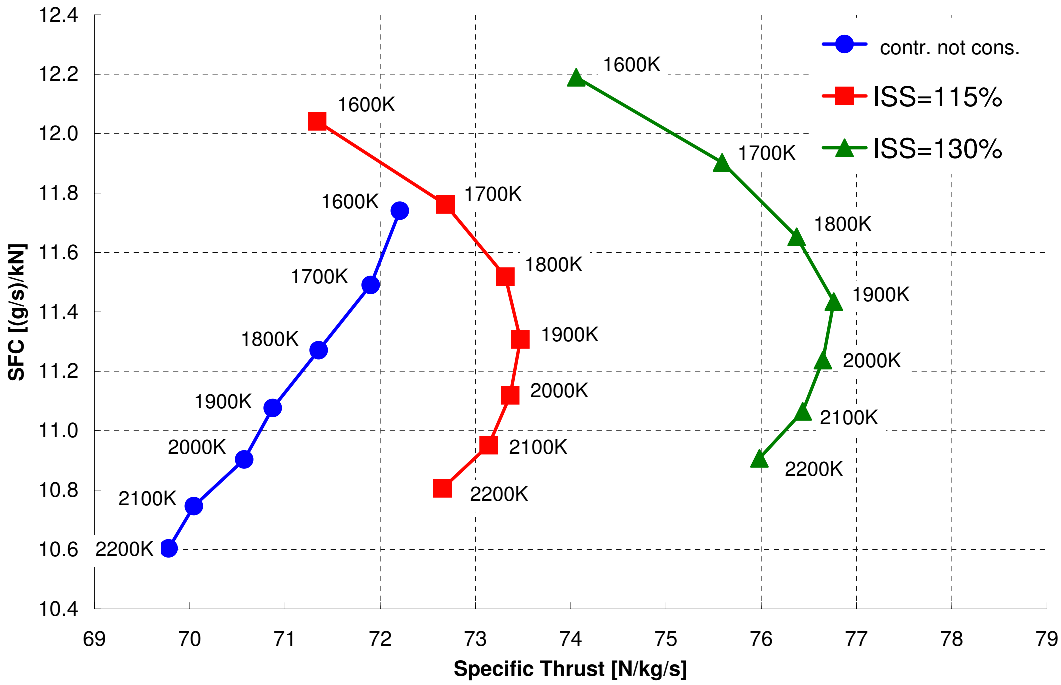


Figure 3.15: SFC vs. specific thrust.

concept requires very high bypass ratios to be efficient, exceeding what is common with conventional turbofan configurations, which is about 10 for modern engines. Hence, this engine concept would be more suited for propulsors where the bypass ratio can be designed to be very large, such as unducted fans or remotely driven fans. The optimum fan pressure ratios are shown in figure 3.19, indicating fan pressure ratios around 1.30, which is below that of current conventional engines and what can be achieved with unducted fans. For the case that contrail avoidance is not considered during optimisation, the optimum fan pressure ratio is not affected by the TET. In the other cases, the optimum fan pressure ratio is increasing with TET and is lower for higher levels of ice-supersaturation.

In general, heat exchanger size is predominantly dependent on the mass flow, heat exchanger effectiveness and the desired temperature change. The cycles respond

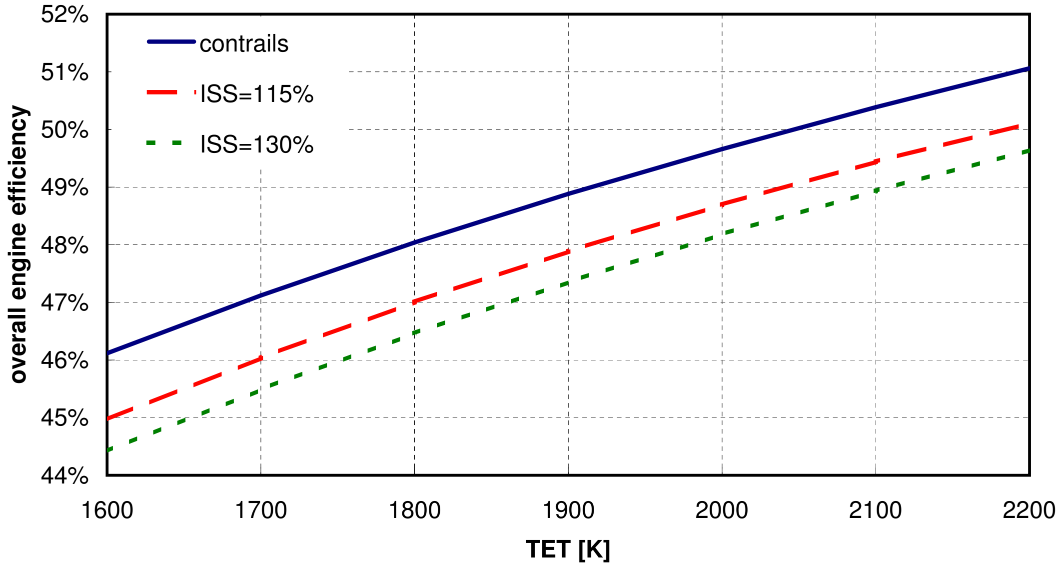


Figure 3.16: η vs. TET.

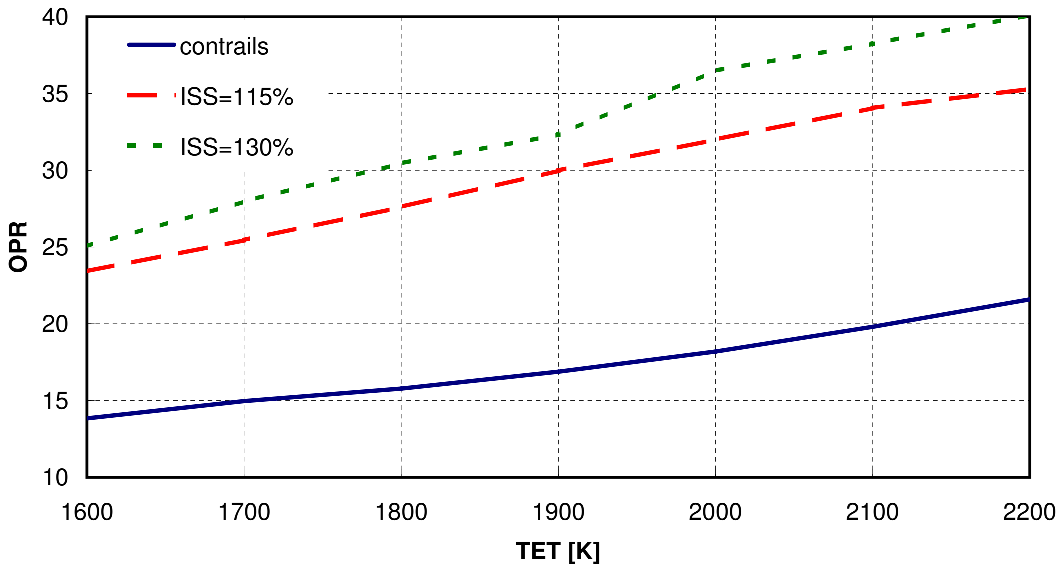


Figure 3.17: OPR vs. TET.

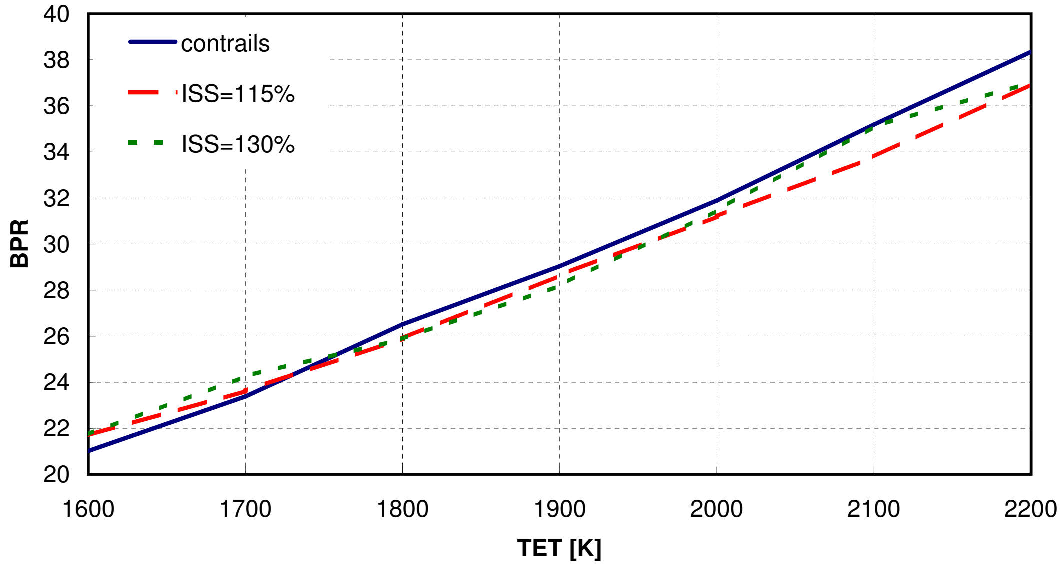


Figure 3.18: BPR vs. TET.

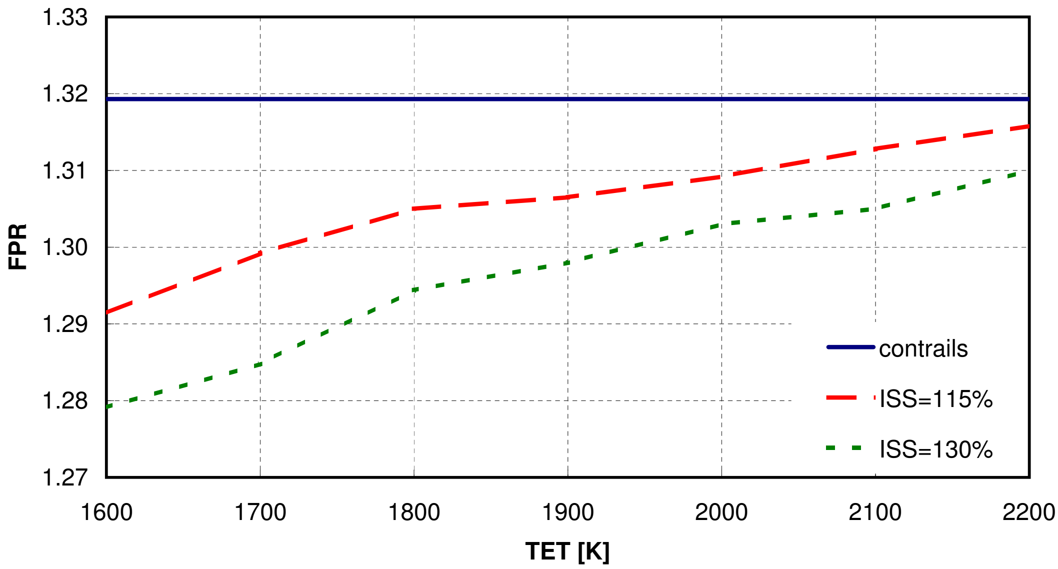


Figure 3.19: FPR vs. TET.

with an increase in the overall temperature change to a decrease in heat exchanger effectiveness', potentially causing the heat exchanger to be even larger. A relatively high effectiveness in the condensation stage is crucial in order to achieve a low temperature within the engine that facilitates water condensation. This temperature is within the ambient temperature range, so the temperature difference between the flows that exit the condensation stage at the core side and enter at the bypass side is relatively small, requiring a relatively high heat exchanger effectiveness.

Hence, it can be concluded that advanced heat exchanger technology in terms of effectiveness, weight, and pressure loss is essential for the feasibility of this concept. Super conducting heat transfer material is being investigated and similar materials could be available in the future [Qu, 2000]. Because the required temperature in the condensation stage is determined by the temperature at which water condensation occurs, a reduction in water saturation pressure would cause a reduction in the required temperature difference. A reduction in the water saturation pressure required for condensation could be achieved by applying curved surfaces within the heat exchanger (Kelvin effect) or advanced materials with very good hydration behaviour.

3.3 Aircraft technology

This section deals with methods for contrail avoidance through modifications in the airframe.

3.3.1 Aircraft optimisation

In general, aircraft are designed to serve a particular market and to maximise the earning capacity for the manufacturer. Factors driving the aircraft design are such as payload, range, the prevailing air-traffic infrastructure, and the aircraft's competitive advantage in terms of economical performance. The design process typically yields a configuration that meets the design requirements within the constraints imposed by regulations regarding safety, performance, and environmental impact. As in particular the environmental impact of contrails is increasingly emphasized, regulations might be introduced with the objective of contrail mitigation. These regulations will either affect the current aircraft fleet, e.g. how aircraft are operated, or influence the design of next generation aircraft. Airlines would have to deal with the former approach, whereas the manufacturer would have to respond to the latter as it might cause a shift of the design requirements.

Fichter et al. [2003] concluded that contrail formation could be mitigated if air-traffic took place at lower altitudes on a global scale. As discussed in previous section, both fuel consumption and contrail formation of a particular aircraft are dependent on cruise altitude, and the shift of the air-traffic corridors would come with a fuel burn penalty. The fuel burn penalty could be reduced optimising the aircraft for altitudes where contrail formation could be mitigated, and once decided how to position an aircraft in the market in terms of payload, range and cruise speed, its optimisation in terms of cruise altitude could yield an acceptable compromise between fuel burn and contrail formation. An approach dealing with the aircraft optimisation for minimal environmental impact is given in Antoine and Kroo [2004]. However, contrails were not taken into account in that study, and aircraft optimisation in a more global context is given in the following, describing how the design processes could be adapted to meet new design requirements regarding contrail formation. Therefore, a methodology was developed that considers contrail formation during the aircraft design process, which was applied for the optimisation of the baseline aircraft configuration. The methodology can be broken down into two parts. One part predicts the performance of the aircraft configuration, which depends on design variables, technology parameters, and mission requirements. The aircraft performance can be optimised varying the design variables. Combining the calculated performance with air-traffic data, the fuel consumption can be calculated on a global scale. The second part includes the calculation of the environmental impact from contrails. As the calculation of the radiative forcing from contrails is not straightforward, this study considers the amount of contrails formed only. It is measured in contrail-km, which is the cumulative sum of the fractions of flight paths where the formation of contrails is facilitated on a global scale. This is facilitated by combining air-traffic data with historical meteorological data. A representation of the overall procedure is given in figure 3.20.

NASA's Flight Optimisation System (FLOPS) was used for performance calculation and multidisciplinary optimisation of a particular engine and aircraft configuration. The code computes airframe weight, airframe aerodynamics, engine weight and engine performance according to the airframe and engine related parameters and design variables, from which the block fuel is calculated. The part covered by FLOPS is framed with a dashed line in figure 3.20.

Ideally, optimisation of the aircraft configuration is carried out considering contrail formation already during the optimisation process. The figures of merit, block fuel and contrails, would then be combined in the objective function, represented by the dashed arrow in figure 3.20. In this study, the aircraft was optimised for minimum block fuel, and the resulting configuration was then subsequently assessed in terms of contrail formation. This would allow a comparison between different configurations regarding fuel consumption and contrail formation. The aircraft design

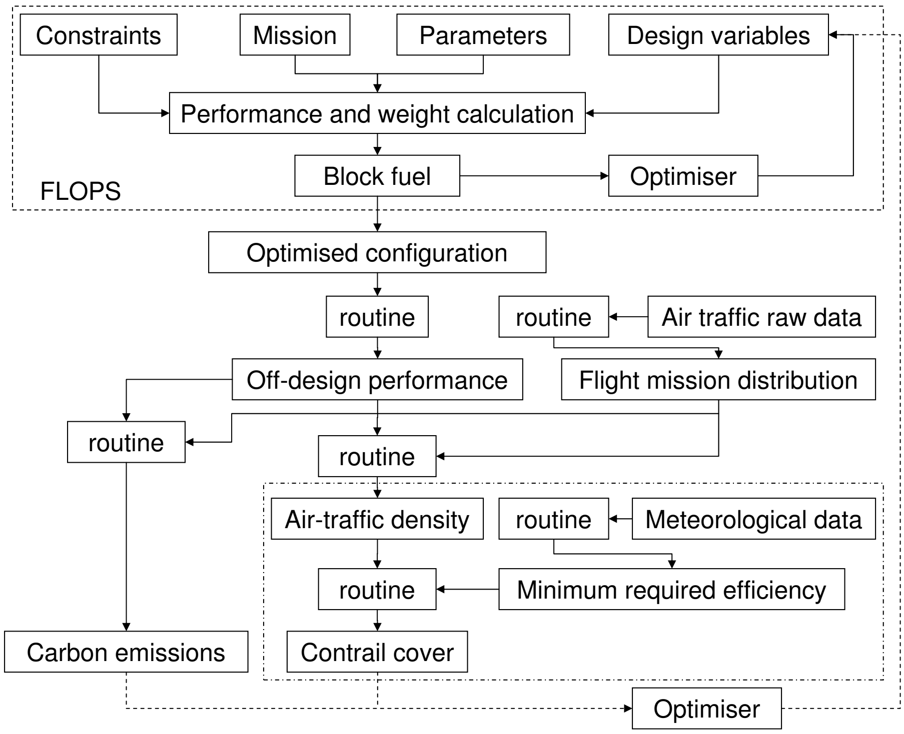


Figure 3.20: Layout of aircraft design process where contrail formation is taken into account.

variables were wing area, thickness to chord ratio and sweep angle; engine design variables were bypass ratio and take-off thrust.

The design point mission was defined by range, cruise speed in terms of true air speed, and initial cruise altitude. Block fuel is calculated considering continuous climb during cruise. Defining a minimum and maximum cruise altitude, the aircraft is enforced to not fly within a certain altitude band for both design point and off-design point missions. Mission requirements in terms of landing and take off field length, minimum rate of climb during initial climb (one engine off) and approach speed were taken into account according to the FAA regulations. During cruise, the engine is allowed to operate with at most 90% throttle setting. These requirements were considered as constraints and accommodated in the objective function, im-

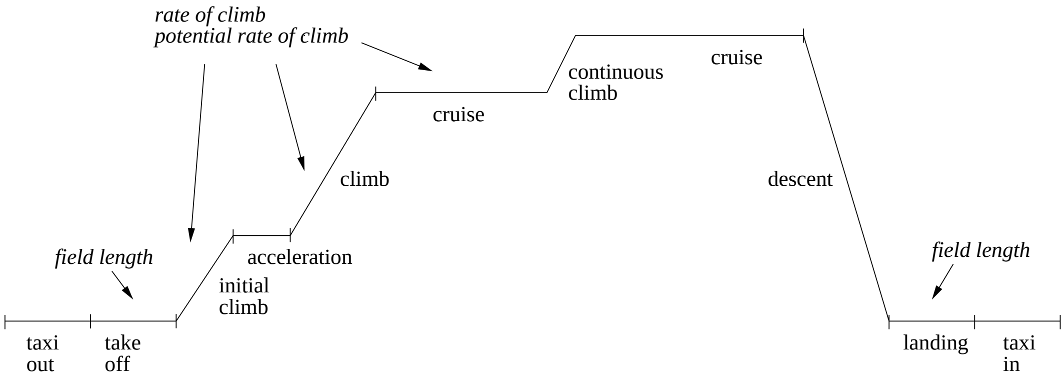


Figure 3.21: Mission definition and constraints.

pacting the airframe and engine design optimisation. Figure 3.21 shows a typical flight mission as applied in FLOPS. Constraints are indicated in italic letters.

Air-traffic density, defined as the sum of distances flown by aircraft within a certain volume over a given time period, was calculated from a database provided by Cranfield University's Department of Air Transport. The database holds information of national and international scheduled commercial flights. Knowing departure, destination, departure time and flight duration of each scheduled flight, the air-traffic density could be calculated assuming the flights to follow great circles. Calculating the intersections of the flight path with the map grid, it could be dissected into several fractions ΔS, as shown in figure 3.22. The areas A, known as spherical quadrangles, are defined by the intersecting grid lines. The ratio of the fractions of the flight path ΔS and the areas A yield the air-traffic density $\Delta S/A$. The air-traffic density resulting from several flights can be calculated by taking the sum of the air-traffic densities resulting from the individual flights.

Only the flights that would be undertaken by the considered aircraft class are of interest when calculating air-traffic density and fuel burn on a global scale. An extensive market research would be necessary to make an accurate assumption regarding the routes on which the aircraft is going to operate. In this study, it was

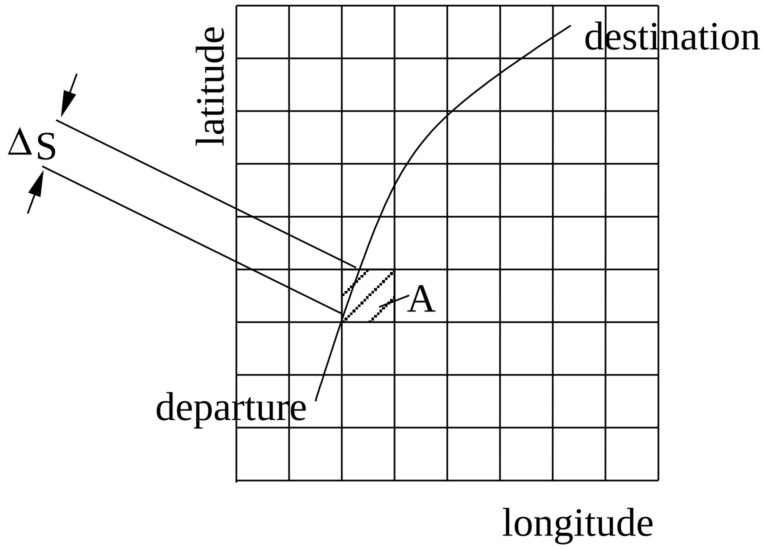


Figure 3.22: Schematic of calculation of air-traffic density.

assumed that the aircraft would operate on routes that are contained in the database with between 200 and 250 passengers and a maximum range of 8000nm. The resulting distribution of journey length of flights with aircraft between 200-250 seats is given in figure 3.25.

As the optimisation of the aircraft was carried out considering the journey to take place within a certain altitude band, it was necessary to calculate the air-traffic density in three dimensions. Therefore, the initial cruise altitude, the final cruise altitude, and the fractions of the journey for climb and descent were calculated using the off design capabilities of FLOPS and stored in the form of response surfaces for each altitude scenario. Also, the diurnal variability in air traffic was taken into account when the air-traffic density was calculated. Knowing departure time and destination time for each flight, sections of the flight paths could be attributed to different times. Four air-traffic density maps were computed for each altitude scenario, covering the time periods 0-6h, 6-12h, 12-18h, and 18-24h (Universal Time). The resulting maps, as shown in figure 3.23, are the sum of the air-traffic density

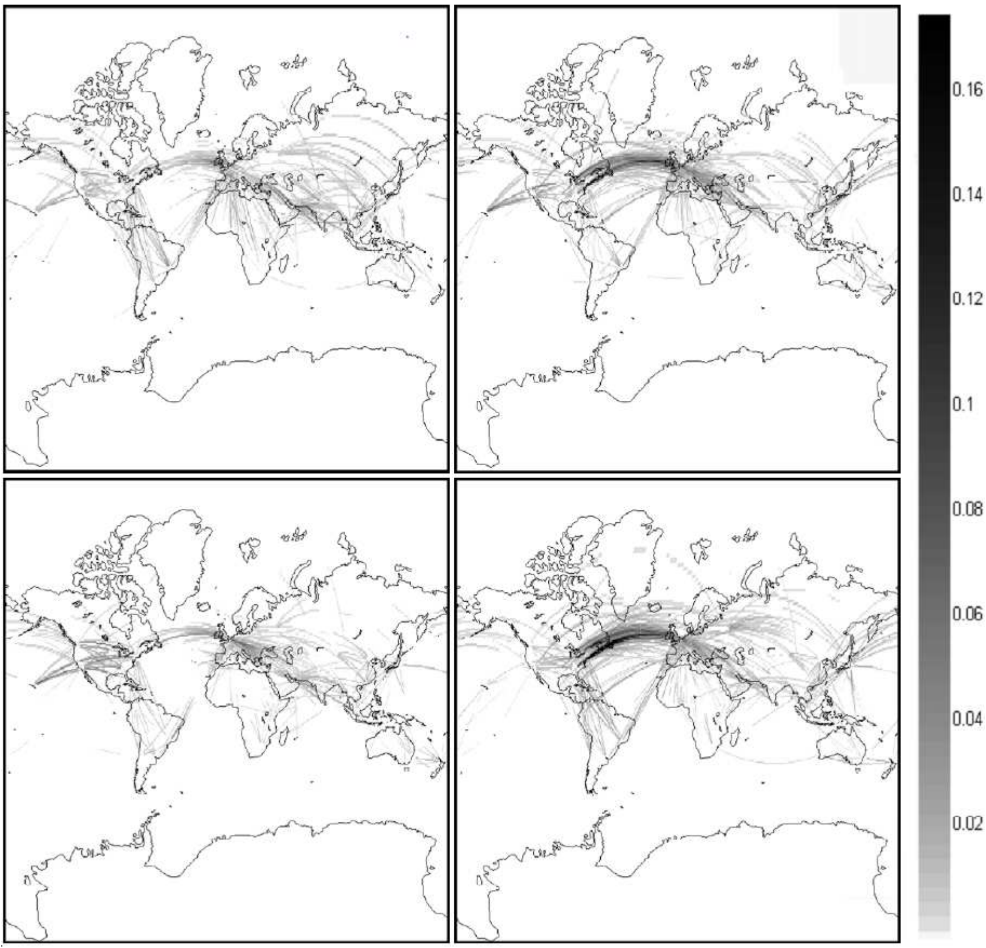


Figure 3.23: The cumulative air traffic density over all altitudes in km/(km^2 hour) considering 200-250 seater only. 00-06h (top left), 06-12h (bottom left), 12-18h (top right), 18-24h (bottom right)

of all altitude levels.

Regions that facilitate the formation of contrails are determined by local ice-super-saturation, altitude, ambient temperature and engine efficiency. The operational weather analysis data from the MetOffice unified model of the year 2005 as described in the appendix on page 157 was evaluated regarding contrail formation applying the Appleman criterion. As the engine efficiency is an aircraft related parameter in the Appleman criterion, the minimum engine efficiency required for

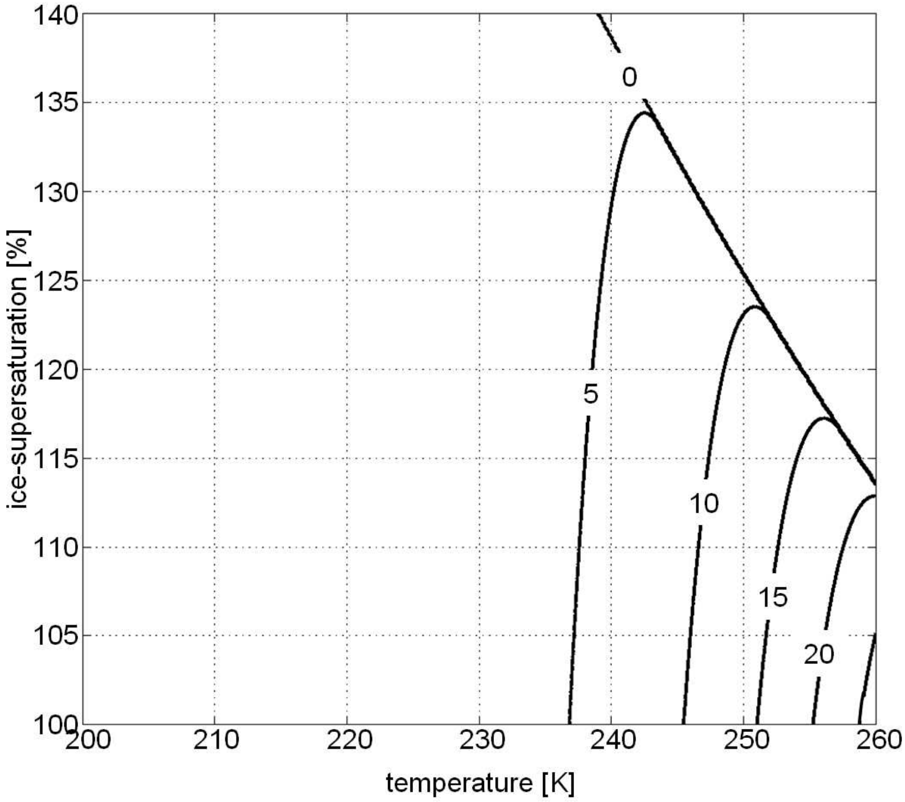


Figure 3.24: Critical mixing line slope as function of ice-supersaturation and temperature.

contrail formation was calculated in the first instance for each time interval of the MetOffice data. In order to speed up the calculation, a look-up table was computed of the critical mixing line slope σ depending on ambient temperature and ice-supersaturation. This would make the time consuming iteration of equation 2.3 redundant. Figure 3.24 is based on the look-up table and shows the isolines for the critical mixing line slope on a temperature-ice-supersaturation chart.

In the second instance, the amount of contrails formed was calculated in terms of contrail-km for each time interval for each altitude scenario combining air-traffic density data and the data containing minimum required engine efficiency for contrail formation. As aircraft optimised for different altitudes cruise with different overall efficiencies, the calculation of contrail occurrences was carried out with different overall engine efficiency for each altitude scenario.

The aircraft type considered in this study was based on the baseline aircraft as described in the appendix on page 157. Altitude scenarios were chosen to be in 1,000 feet (305m) steps with 34000 feet (10.36km) as baseline. Best estimates for future engine and aircraft related parameters were made accessible by industry and could be derived from information available in the public domain. Airframe technology related parameters, determining primarily material weight and aerodynamic wing performance, and engine related technology parameters such as maximum turbine entry temperature, overall pressure ratio, fan pressure ratio or parameters related to the mechanical integrity of the turbomachinery, were held constant for all altitude scenarios.

The differences in block fuel consumption compared to the baseline configuration was calculated for both the design mission and on a global scale. The resulting distribution of journey length of flights with aircraft between 200-250 seats is given in figure 3.25. Most of the flights occur for legs less than 3000nm. The database holds virtually no entries for flights above 6250nm. This is because there is currently no aircraft with 200-250 seats that can serve this range. Aircraft with 200-250 seats and a maximum a range of 8000nm would serve an emerging market of long haul services away from hub-to-hub towards point-to-point.

Figure 3.26 shows the change in fuel consumption relative to the baseline configuration. The block fuel consumption ultimately increases as the aircraft is designed to fly at both lower or higher altitudes. According to the results, an aircraft of the considered class optimised for 31,000 feet would consume 2.4% more fuel at its design point than an aircraft optimised for 34,000feet. On a global scale, the fuel burn penalty would be 1.0%. The difference in fuel burn for aircraft designed for

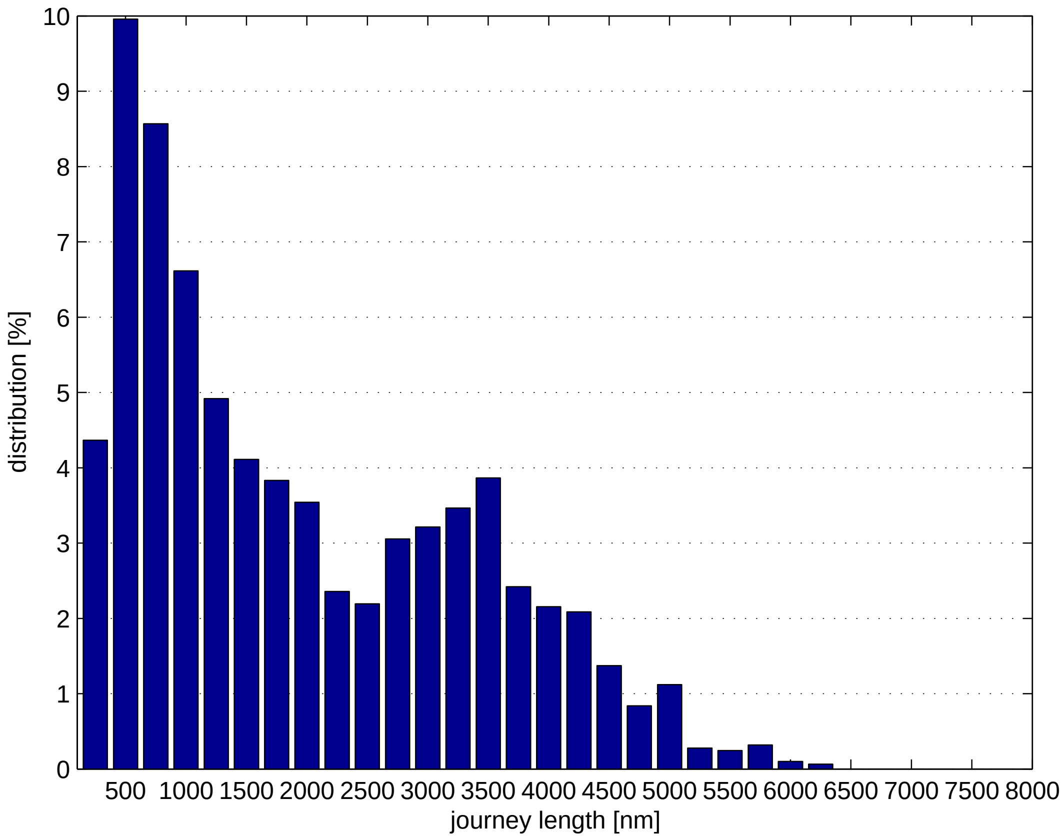


Figure 3.25: Journey length distribution for aircraft with 200-250 seats.

37,000feet is calculated to be 4.8% at the design point, and 5% on a global scale.

Figure 3.27 shows the relative change in the design variables for the different altitude scenarios. Thrust and bypass ratios are calculated at sea level static. The results suggest that aircraft optimised for higher altitudes have higher thrust requirements, larger wing areas, but smaller bypass ratios. The effect is not inversed for aircraft optimised for lower altitudes. The results suggest that the optimum bypass ratio is increasing for aircraft designed for lower altitudes, thrust requirements would be lower and the wing area would also be larger.

The aircraft configuration resulting from an optimisation is dependent on various factors. It is, however, mainly affected by the change in air density at higher al-

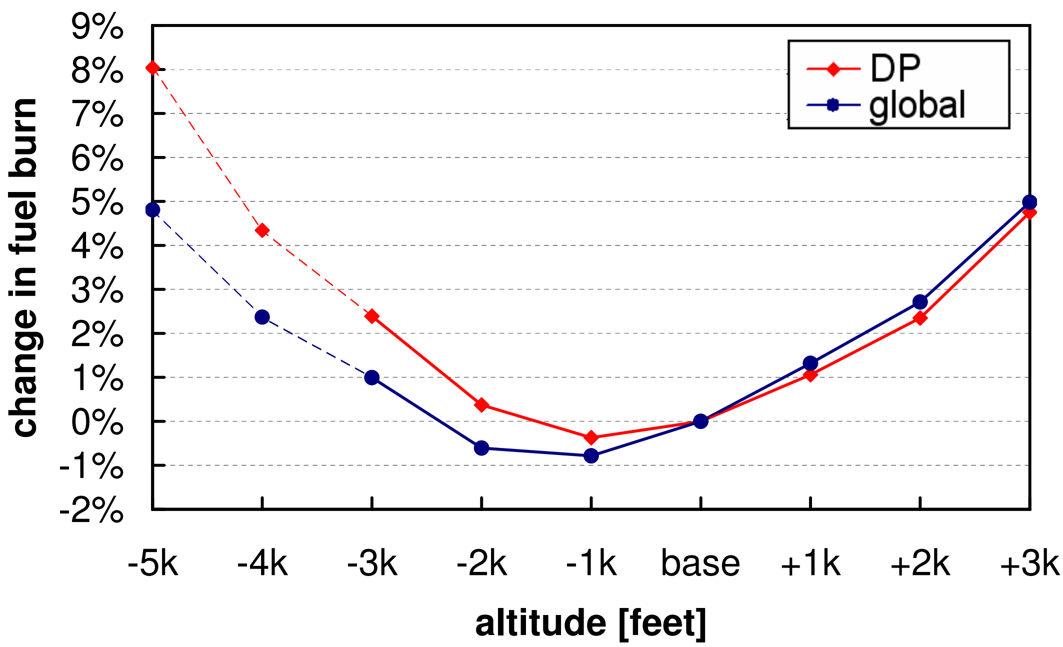


Figure 3.26: Fuel burn penalty relative to baseline configuration (34,000feet).

titudes, impacting lift, drag and engine performance. Additionally, design constraints impact the final design of aircraft. The fuel consumption and hence aircraft weight depends primarily on the thrust requirement during cruise and the engine efficiency. At high altitudes, where the air density is lower, larger wings are needed to obtain enough lift, impacting aircraft weight and drag. At the same time, the mass flow through the engine needs to be increased in order to obtain enough thrust. An ever increasing engine diameter can, however, not be accommodated due to limited space below the pylon, engine weight and increasing nacelle drag. Hence, the engine exit velocity is increased to provide enough thrust, which is achieved through a lower bypass ratio. This, in effect, negatively affects the overall aircraft efficiency. As a result of increasing wing area and decreasing engine efficiency at higher altitudes, the block fuel consumption is increasing.

Aircraft optimised for lower altitudes can be designed with larger bypass ratios, allowing better overall engine efficiencies. This is because the higher air density at

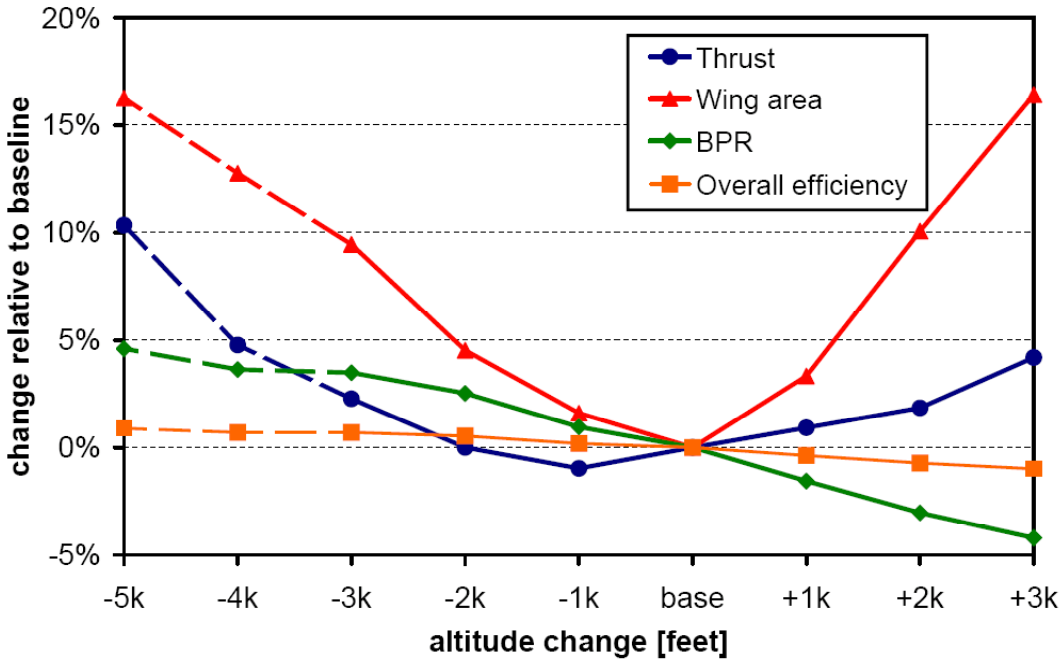


Figure 3.27: Relative change in design variables relative to baseline (34,000feet).

lower altitudes allows sufficiently large air mass flows through the engine without increasing its diameter. At low altitudes, however, the higher air density causes an increase of the parasitic drag, impacting fuel consumption. Minimum climb requirements for one engine off conditions at 1500 feet altitude also result in larger wing areas, having an increasing effect on block fuel consumption.

The overall relative change in contrail formation for each altitude scenario on a global scale, measured in terms of contrail-km, is given in figure 3.28. Aircraft of the considered class optimised for lower altitudes tend to cause more contrails, whereas higher cruise altitudes indicate a decrease in contrail formation. According to the results, almost 58.0% more contrails would form if the aircraft was designed for 31,000 feet instead of 34,000 deet, but 10.1% fewer contrails would form if the aircraft was designed for 37,000feet.

The persistence of contrails, and ability to spread to contrail cirrus, is primarily

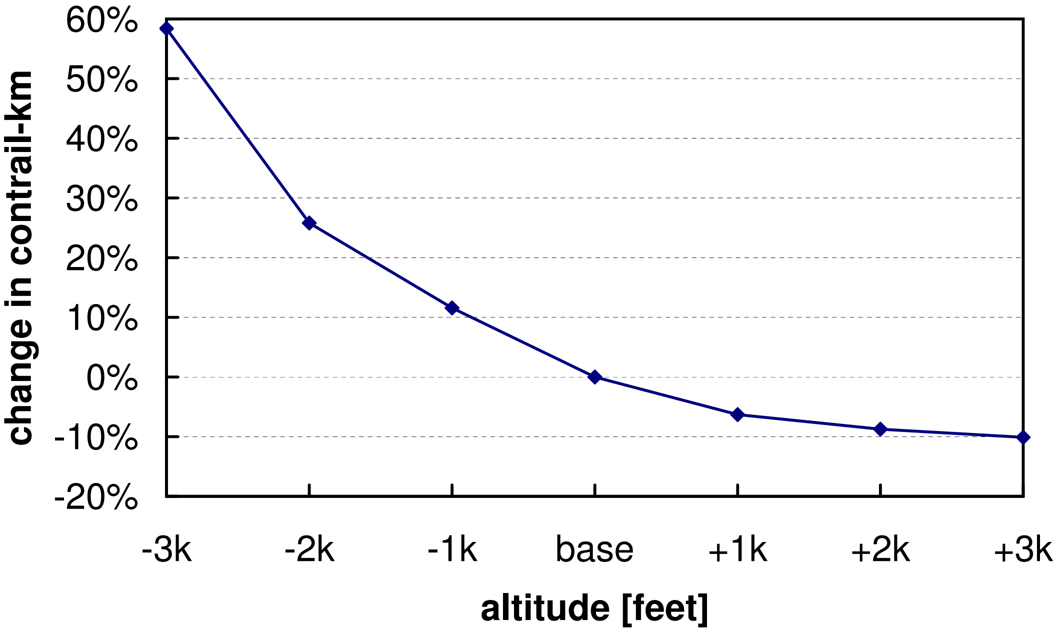


Figure 3.28: Change in contrail formation relative to baseline configuration (34,000 feet).

dependent on ambient ice supersaturation. Therefore, the increase in contrail formation for different levels of ice-supersaturation was calculated: results are shown in figure 3.29. Configurations optimised for lower altitudes would particularly increase contrail formation under relatively high ice-supersaturated conditions.

The results suggest that aircraft of the considered aircraft class designed for lower altitudes would produce more contrails and would ultimately consume more fuel. If designed for higher altitudes, the fuel burn would also be higher but fewer contrails would be produced. This is in contradiction with Fichter et al. [2005], where results suggest that cruising at lower altitudes would reduce contrail occurrences (see section 3.6 on page 68). The difference is that in this study only one particular aircraft class and its associated contrail occurrences are considered. There is an altitude at which contrails are most likely to form, and aircraft can either cruise above or below it. As the optimum cruise altitude in terms of fuel consumption

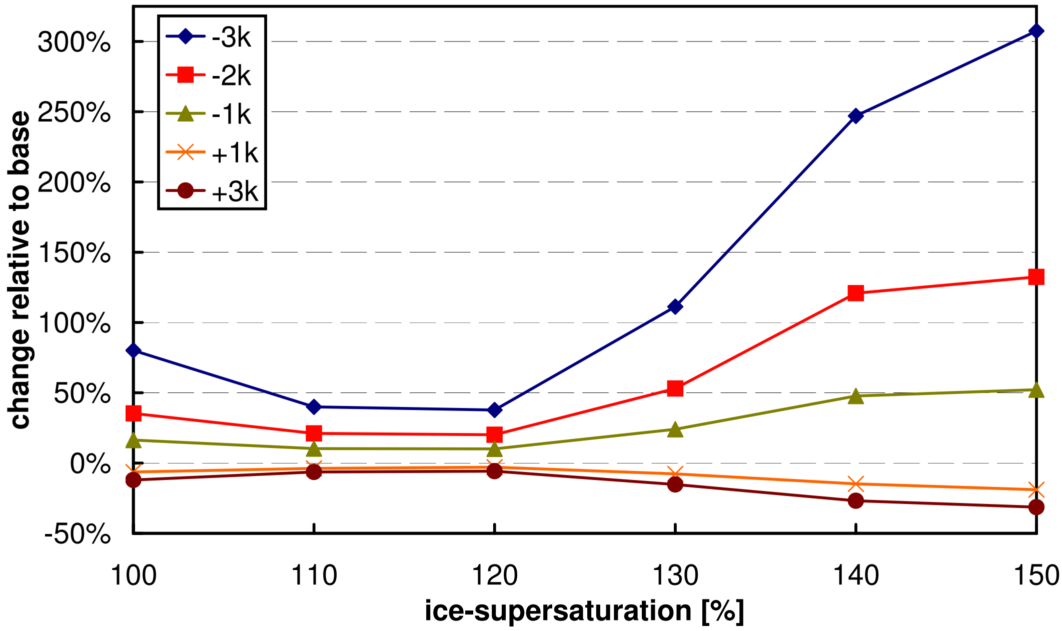


Figure 3.29: Change in contrail formation relative to baseline configuration (34,000 feet) for different levels of ice- supersaturation (altitude variation in feet).

is dependent on various parameters such as payload, cruise speed and technology, individual optimisation of aircraft for minimum contrail avoidance would shift the air-traffic towards altitudes where contrail formation is mitigated. This would not necessarily imply that all aircraft would be designed for lower altitudes. If contrail formation is most likely to occur for a particular altitude, then contrails could be avoided by designing aircraft for both higher or lower cruise altitudes, depending on the design requirements and the technology. It has to be taken into account, however, that contrails and carbon dioxide are not the only pollutants from air traffic. The environmental impact of other emissions, such as NO_x, varies with altitude and would have to be taken into account for a more integrated analysis.

Further reducing cruise altitude of this aircraft class would probably make sense in terms of contrail formation, because for much lower altitudes, contrail occurrences would diminish again. However, the fuel burn penalty would be over proportionally larger. New technologies, such as propfans or compromises in terms of aircraft speed, could alleviate the fuel burn penalty. A study in the form of an MSc project as part of this work programme was carried out by Faupin [2006], comparing the performance of unducted fans and turbofans on medium haul routes. Fuel savings utilizing unducted fans relative to the turbofan configuration are given in figure 3.30. If aircraft were designed to operate at lower cruise altitudes, the switch to unducted fans seems to be promising. According to the results, the unducted fan configuration consumes between 10% and up to 22% less fuel at lower altitudes relative to the turbofan configuraiton, depending on the design cruise Mach number. Hence, unducted fans could be a way to reduce both fuel consumption and contrail occurrences at the same time.

3.3.2 Airframe and engine integration

Aircraft geometry has an effect on the vortex structure and intensity. The relative position of the jet exhaust to the vortices determines its entrainment. The formation, evolution and radiative properties of a contrail are affected in two ways [Lewellen and Lewellen, 2001]: a) a more effective jet entrainment causes ice particle evaporation due to vortex descent and the associated adiabatic heating and b) less effective jet entrainment prevents vertical spreading of the contrail, reducing the chance for contrail cirrus formation and leading to less effective mixing of the exhaust gas with the ambient air.

Configurations with a larger gap between exhaust and wing tip vortices (e.g. fuselage mounted engines) might reduce the probability of contrail dispersion and thus contrail cirrus. A more effective jet entrainment could be achieved by placing the jet closer to the vortices.

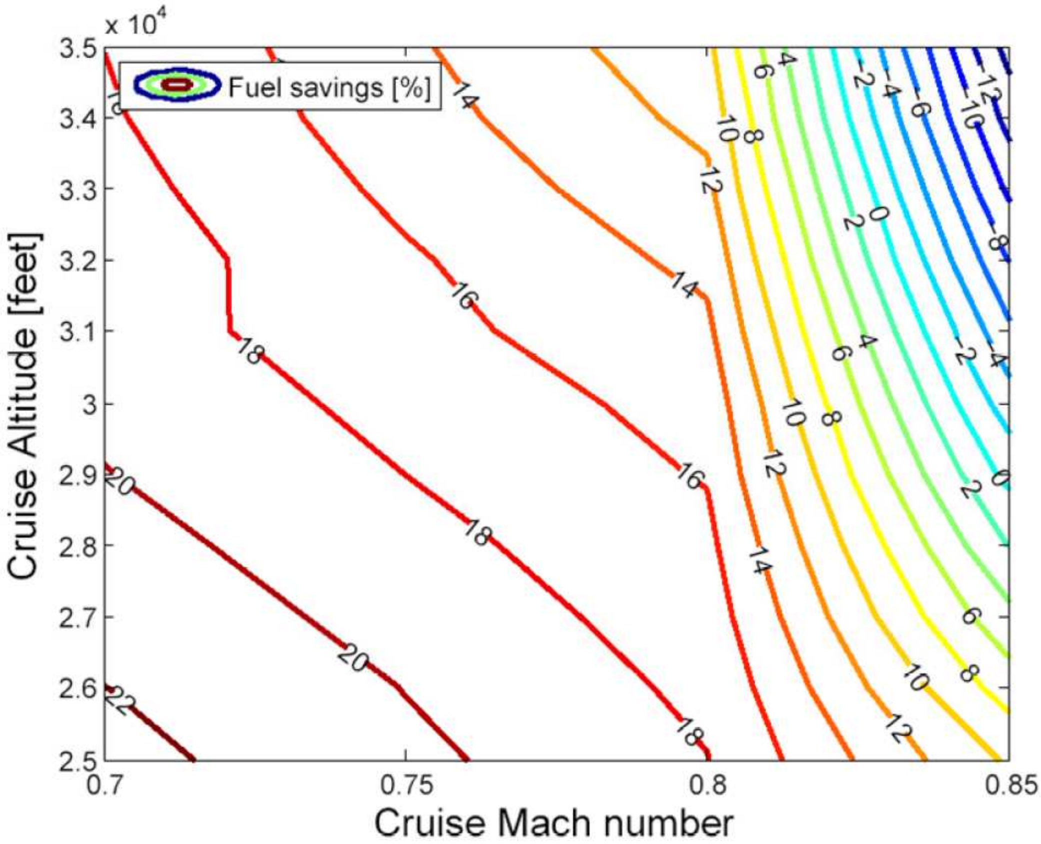


Figure 3.30: Fuel savings of unducted fan relative to turbofan configuration [adopted from Faupin, 2006].

Some novel airframe concepts often discussed in the aeronautical community are the blended wing body and the joined wing aircraft. Both concepts potentially affect the vortex pattern and strength, which might have an effect on contrail formation and persistence. In Gierens and Ström [1998], it is concluded that the formation of aerodynamic contrails is possibly more likely to occur for heavy, slow, wide-body aircraft.

Kerosene	LH2	Methane
0.029 kg/MJ	0.075 kg/MJ	0.045 kg/MJ

Table 3.3: Energy specific emission index for different fuels [adopted from Penner et al., 1999; table 7-11].

3.4 Fuels

Potentially alternative fuels for aviation are other carbon based fuels such as ethanol or methanol. Hydrogen is also often discussed in the aeronautical community as fuel for next generation aircraft. In the following, these fuels are discussed in the context of contrail avoidance.

According to equation 2.2, fuels with higher water emissions indices would increase the potential for contrail formation. However, the fuel calorific value q_{net}, appearing in the denominator in equation 2.2, is also fuel specific and contrail avoidance is affected by both parameters. The ratio EI/q_{net}, called the energy-specific emission index, combines both fuel specific parameters in equation 2.2. Lower values of EI/q_{net} imply lower values of the mixing line slope σ, and would hence reduce the potential for contrail formation. The values for hydrogen and methane are compared to kerosene in table 3.3. Both hydrogen and methane have higher values of EI/q_{net} and would hence increase the potential for contrail formation.

Hydrogen, which is generally seen as the most likely alternative to kerosene as aviation fuel, does not cause the formation of soot or aerosol particles during combustion, having an impact on the radiative properties of contrails. This additional effect has been investigated in several studies and is discussed in more detail in section 3.4.3 on page 109.

3.4.1 Fuel sulphur content

Sulphur plays an integral role in the contrail formation process, facilitating water nucleation on soot particles and providing volatile particles serving as condensation nuclei. A reduction of the fuel sulphur content would reduce the emission of SO_3 and H_2SO_4, and have an impact on the aerosol density in the plume and contrail precursor activation. It would be technically possible to reduce the fuel sulphur content. However, reducing the fuel content might have no or only a very little impact on contrail formation as mentioned in section 2.1.2. Water nucleation on soot particles is believed to be independent of the presence of sulphur species in the plume [Popovitcheva et al., 2001]. And even if sulphur free fuel led to the absence of volatile particles and avoided water nucleation on soot particles, ambient background particles would still provide sufficient condensation nuclei. Contrails formed on background particles, however, would very likely be composed of fewer but larger ice particles, which because of their radiative properties could result in a lower positive radiative forcing. The impact of contrails with fewer but larger particles on contrail cirrus formation has not been investigated up to now.

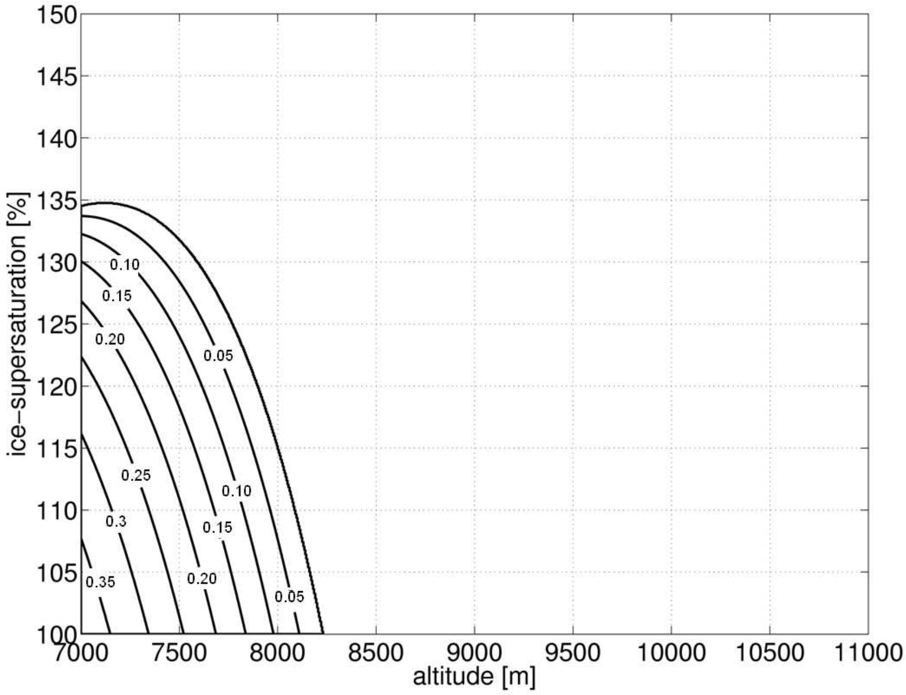
3.4.2 Fuel additives

Gierens [2007] explored the possibility of using fuel additives for contrail avoidance. It was concluded, however, that they would not be a viable contrail mitigation option. Fuel additives, if used to change hygroscopic properties of black carbon particles and hence suppress water condensation, would very likely cause the formation of contrails with fewer but larger particles, possibly having an impact on the radiative properties of contrails. Fewer but larger particles could potentially decrease the radiative forcing of contrails. The presence of volatile particles, however, would still facilitate water condensation, possibly offsetting the advantages of using fuel additives.

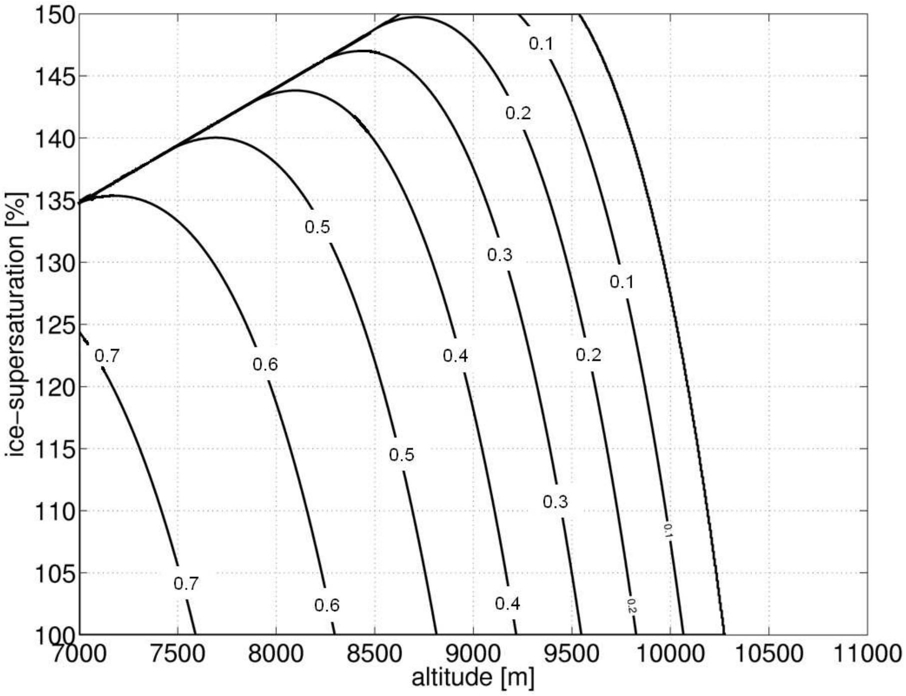
3.4.3 Hydrogen

The switch to hydrogen-fueled aircraft is being widely discussed in the aeronautical community as their emissions are restricted to water and oxides of nitrogen only [Ponater et al., 2006]. However, as discussed on page 107, the higher energy specific emission index of hydrogen powered aircraft would increase the potential for contrail formation as a higher water emission index has an increasing effect on the mixing line slope. The significance can be seen in figure 3.31, where the minimum engine efficiency required for contrail formation for a kerosene and a hydrogen powered aircraft is shown on ice-supersaturation-altitude diagrams. The diagrams are based on the ISA standard atmosphere and do not consider temperature deviations from standard values. Considering current engines, typically operating with an efficiency of about 0.35, contrail formation would thermodynamically always be facilitated at altitudes above 7250 metres if hydrogen was used as fuel. Kerosene powered aircraft of the same efficiency would facilitate contrail formation only at altitudes above about 9250 metres. At lower altitudes, the air might be too warm to facilitate the formation of contrails from kerosene-fueled aircraft but not the formation of contrails from hydrogen-fueled aircraft. At higher altitudes, the switch to hydrogen-fueled aircraft would not have a significant effect on contrail formation [Marquart et al., 2001].

Studies suggest that the global annual mean contrail cover from hydrogen fueled aircraft would increase by a factor of 1.56 compared to kerosene-fueled aircraft. However, young contrails from hydrogen-fueled aircraft would probably consist of fewer but larger particles with a very high sensitivity to variations in background



(a) hydrogen powered aircraft.



(b) kerosene powered aircraft.

Figure 3.31: Minimum engine efficiency required for contrail formation: kerosene and hydrogen.

aerosols [Ström and Gierens, 2002]. This would have an effect on the optical thickness and particle precipitation rate, and hence on the associated radiative forcing of contrails from hydrogen fueled aircraft. The radiative forcing of contrails caused by a fleet of hydrogen fueled aircraft could potentially be lower than the radiative forcing from contrails caused by a kerosene fueled fleet. This is because the microphysical properties of contrail particles from hydrogen fueled aircraft differ from the kerosene equivalents [Marquart et al., 2005].

Alexander et al. [2002] investigate the possibility of using hydrogen in fuel cells powering electric motors for aircraft propulsion. Although the concept is promising as it results in the total avoidance of contrails and other combustion products that would occur with kerosene as fuel, the use of break through technologies such as proton exchange fuel cells and super-conductive electric motors makes its application in civil aviation unlikely in the near future.

3.5 Contrail avoidance devices

Contrail avoidance strategies discussed in the previous sections have dealt with technologies directly linked to the airframe or engine. However, technology developed independently could also yield the desired effect. In the following, two distinct approaches are presented: remotely induced heat in the plume could cause contrail ice particle evaporation or prevent ice particles from nucleating, and sonication could be used to modify particles size or prevent water condensation of water on particles. Depending on the energy required for these approaches, they might be very attractive for contrail avoidance since existing aircraft could be retro-fitted with such a technology.

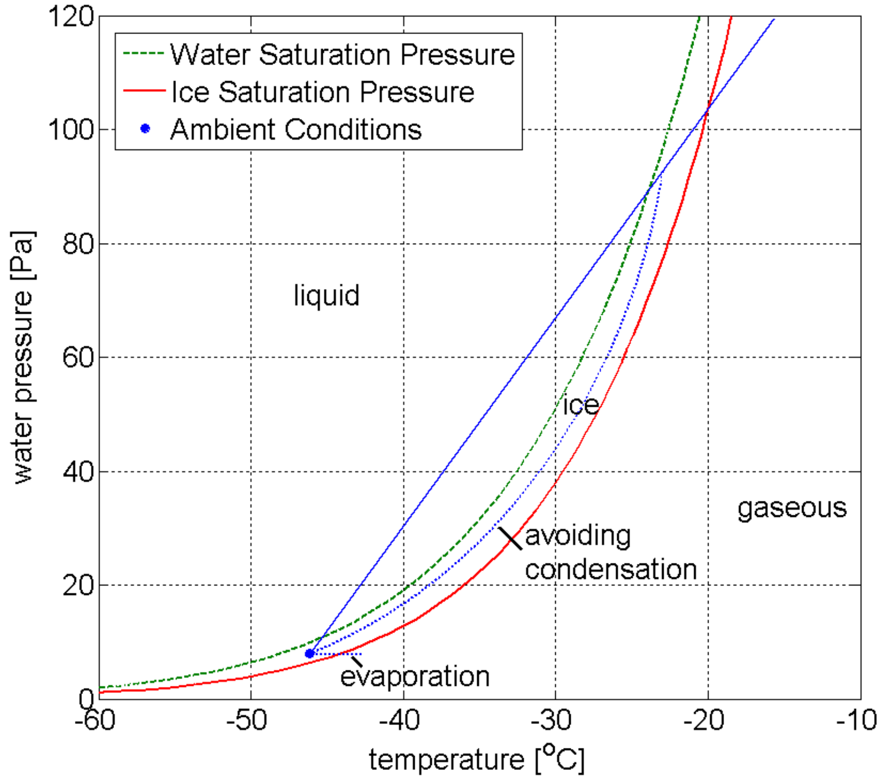


Figure 3.32: Remotely induced contrail avoidance.

Figure 3.32 shows the idea of remotely induced heat on a water phase diagram. A mixing line facilitating contrail formation is represented by the solid line. If the area in the phase diagram for which water is present in the liquid state could be avoided, condensation of water would be prevented. This is represented by the curved dotted line. Alternatively, evaporation of water droplets or ice crystals could be achieved if heat was induced post condensation, represented by the dashed line.

Both possibilities were patented during the PhD project. They are discussed in the following in sections 3.5.1 and 3.5.2.

3.5.1 Remotely induced evaporation

If the evaporation of water droplets or ice particle in the plume could be achieved, the formation of contrails could be suppressed. Heat could be remotely induced by applying electromagnetic radiation. If the frequency of the electromagnetic radiation matches the excitation frequency of water or other constituents of the exhaust, radiation would be absorbed and converted into heat energy, elevating the temperature of the contrail ice-particles and eventually causing melting followed by evaporation or sublimation of the ice particles. Subsequent condensation can be expected to not reoccur as the liquid phase is required for particle formation. Based on this hypothesis, remotely induced evaporation is investigated in the following.

Under cruise conditions, temperatures prevail where the heating of water in the solid state would result in sublimation. Assuming the heating is taking place adiabatically and isobarically, the energy required for particle sublimation is determined by the temperature difference between the saturation pressure temperature and the particle temperature, and the latent heat of ice. Figure 3.33 shows a phase diagram of water with the ice-saturation pressure line, and different levels of ice supersaturation. For given ambient conditions, heating an ice particle would result in an increase of its temperature as indicated in figure 3.33. Further absorbed heat would cause sublimation from the ice-phase into the gas-phase. Under supersaturated conditions, the temperature to achieve saturation is dependent on the level of ice-supersaturation and ambient temperature. Figure 3.34 shows the temperature difference to achieve saturation temperatures for different levels of ice-supersaturation. Relatively modest temperature differences, below 5K, would have to be overcome to achieve saturated levels.

The energy required for ice-particle sublimation is assessed in the following. Therefore, instant and adiabatic heating is assumed. Rather than calculating absolute fig-

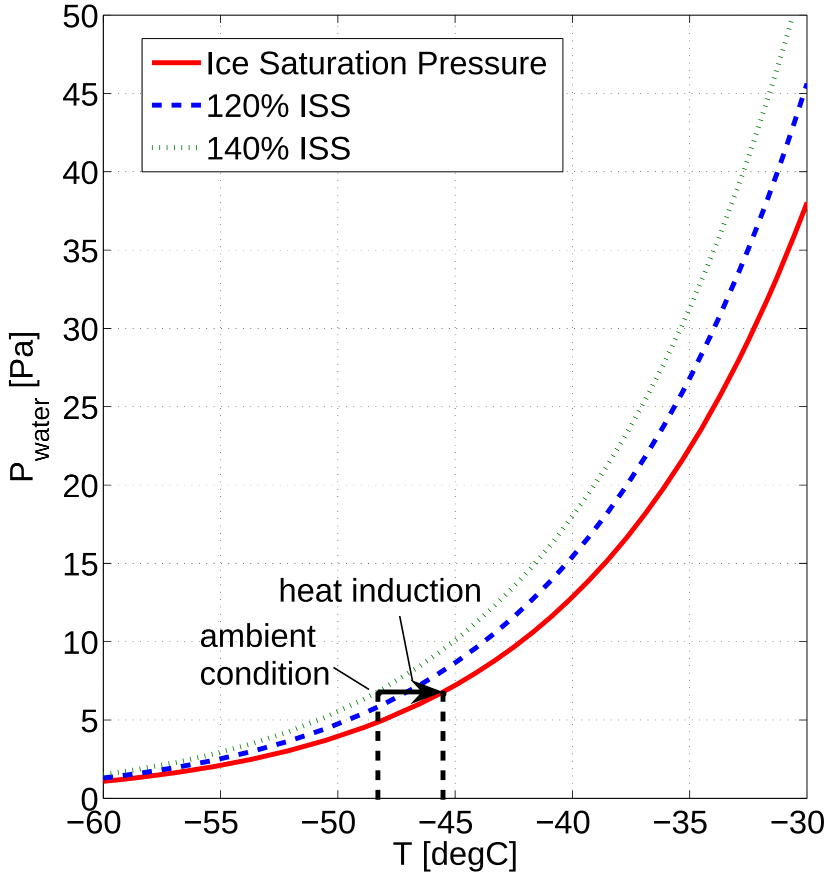


Figure 3.33: Principle for remotely induced ice particle sublimation.

ures, the power consumption for ice-particle sublimation is compared to the engine power. The net output power of a jet engine P_{engine} is the fraction of the energy contained in the fuel that is converted into useful work, given by

$$P_{engine} = \dot{m}_{fuel}\, q_{net}\, \eta_0 \tag{3.2}$$

where $\dot{m}_{fuel}$ is the fuel mass flow, q_{net} is the fuel net calorific value and η_0 is the engine overall efficiency. Assuming the ice crystals would contain water from the engine only, the power needed to evaporate these ice crystals in the engine plume

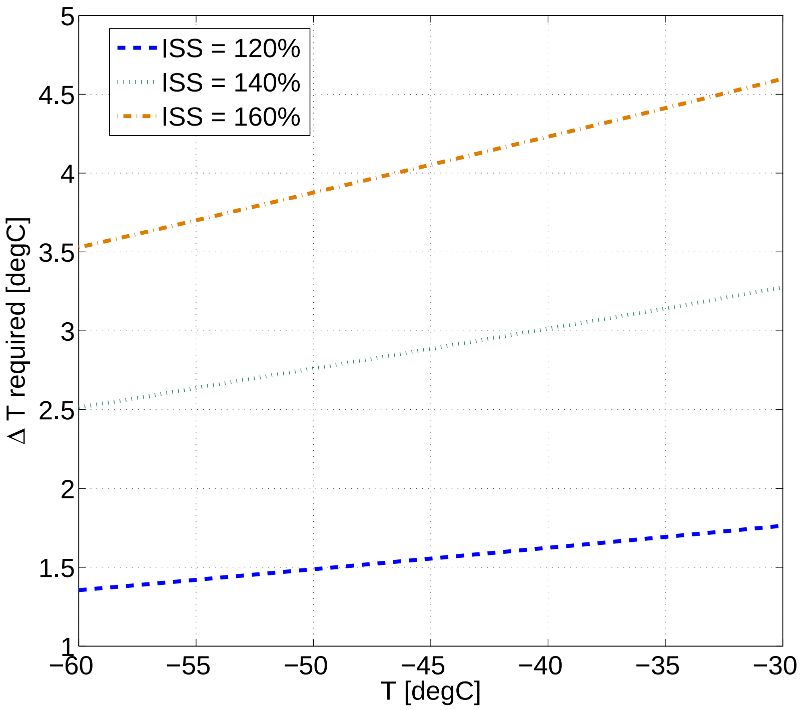


Figure 3.34: Temperature difference to saturated conditions.

is the sum of the energy required to achieve saturation plus the latent heat.

$$P_{ice} = (h_{latent} + c_{p,\ ice}\ \Delta T)\ \dot{m}_{water} \tag{3.3}$$

where h_{latent} is the latent heat of ice, $c_{p,\ ice}$ is the specific heat capacity of ice, ΔT is the required temperature difference and $\dot{m}_{water}$ is the water in the plume considering exhaust water only. With the specific emission index of water $EI_{water} = \dot{m}_{water}/\dot{m}_{fuel}$, equations 3.2 and 3.3 can be rearranged to

$$P_{ice}/P_{engine} = \frac{(h_{latent} + c_{p,\ ice}\ \Delta T)\ EI_{water}}{\eta_0\ q_{net}} \tag{3.4}$$

The term P_{ice}/P_{engine} denotes the ratio of the power required for ice particle sublimation to engine power.

The water emission index and the fuel calorific value of kerosene is about 1.25 and 43MJ/kg, respectively. The specific heat capacity of ice is about 1900J/kg/K and the latent heat of ice is 334000J/kg. Assuming a temperature difference of 5K and an engine efficiency of 35%, the theoretical fraction of engine power needed in order to evaporate contrail ice crystals becomes 2.5%. Considering a device efficiency of 80%, the power required increases to 3.1%. Since only a fraction of a journey occurs under conditions where the formation of persistent contrails is facilitated, the device would be operating only temporarily. For a modern mid-size commercial passenger aircraft, the block fuel burn penalty has been calculated to be 0.7% assuming the device operating during 10% of the flight time. The increase in block fuel is primarily dependent on how long the device is operating. For continuous operation of the device, the increase in overall fuel consumption has been calculated to be as high as 3.6%.

3.5.2 Remotely induced heat to suppress condensation

Alternative to remotely induced heat for ice particle sublimation, the condensation of water could be suppressed by artificially alevating the temperature of the condensation nuclei. Electromagnetic radiation would then be absorbed by volatile and non-volatile condensation nuclei. With carbon and sulphur both having a very high ability to absorb electromagnetic wave radiation, microwaves could be applied more effectively than in the case of remotely induced evaporation.

As the emissions index of carbon and sulphur species is much lower than for water, the energy required to prevent water condensation in terms of engine power would potentially be lower that that required for ice sublimation. With a specific heat capacity of black carbon of 8.517J/(mol kg) [Lide, 2003] and a molar mass of 12.01g/mol, the mass specific heat capacity is 710J/(kg K), which is below that of ice. The soot emission index is estimated at $0.04E^{-3}kg_{soot}/kg_{fuel}$ [Döpelheuer, 1997], well below that of water. The power required in terms of engine power to heat soot condensation nuclei by 5K can be calculated with formula A.2 setting the latent heat to zero. Substituting the variables accordingly yields $9.4E-9$. This power requirement would be negligible, equivalent to just several Watts depending on the engine size. Losses would occur at the microwave device itself and the heat transfer from the soot particles to the surrounding air. In terms of additional fuel burn, both the impact from the additional weight and the power consumption could potentially be as low as fractions of a percent.

3.5.3 Sonication

Sonication, also known as acoustic cavitation, is a process during which micro size gas bubbles are created as a consequence of pressure reduction induced through the application of ultrasound. Applying ultrasound on micrometer sized droplets can result in their vapourisation. As this technique could be used to prevent the formation of contrail ice-particles exposing liquid contrail precursors to ultrasound, it was patented during the PhD project. The energy consumption of ultrasound devices potentially being relatively low, sonication could be an attractive contrail avoidance method.

3.5.4 Chemical devices

Although the extent of the environmental implications of contrails is only known relatively recently, their avoidance has always been of military interest. The visibility of military aircraft is strongly enhanced in the presence of contrails, and military forces developed interest in their avoidance already in the very early years of aviation. In the US, a contrail forecast model called JETRAX is operated to allow the prediction of areas and altitudes that facilitate contrail formation. This enables military pilots to avoid regions in the atmosphere that would enhance their visibility through the formation of contrails. Earlier methods for contrail avoidance included a simple rear mirror installed in the cockpit to allow pilots to observe whether a contrails forms behind the aircraft or not. If so, he would simply climb/descend to an altitude where no more contrail would form in the aircraft wake.

More sophisticated military contrail avoidance strategies involve the release of chemicals into the jet exhaust to either suppress contrail formation or cause the formation of small and invisible contrail particles [Andreson et al., 1970]. With a possibly negative radiative forcing of contrails consisting of very small particles, initiating the formation of very small contrail particles could be a solution. The chemical as described in Andreson et al. [1970] is chlorosulfonic acid (HSO_3Cl), which would break down into hydrogen chloride (HCl) and sulfur trioxide (SO_3) under conditions that can be found in the engine exit and in the plume. Sulfur trioxide, a deliquescent substance, would take up the water in the plume, causing the formation of many small ice particles. According to Andreson et al. [1970], the mass flow of sulfur trioxide to be injected into the plume is about 1-3% of the fuel flow. This equates to about 15-43g chloro sulfonic acid required per kg fuel burned. The device would require a tank with chloro sulfonic acid to be carried on board the aircraft, implying a fuel burn penalty. Assuming enough substance carried along to allow operation during 75% of the journey, the additional weight on a 8000nm flight with a modern mid-size (250 passengers) civil transport aircraft would be 880-2600kg. The fuel burn penalty for carrying the additional weight was calculated to be 2.0-6.2% using the NASA flight optimisation system FLOPS. The substances released with this technology could potentially have a harming effect on the atmosphere. Hydrogen chloride dissolved in water forms hydrochloric acid, which can be an irritant or even corrosive. With an annual global fuel consumption of 155Mt kerosene in 2002 [Horton, 2006], about 0.5-1.6Mt hydrogen chloride would have been released into the atmosphere. Comparing this to the annual worldwide industrial production of 20Mt hydrogen chloride per year demonstrates the dimension, possibly being a strong argument against the application of chlorosulfonic acid for contrail avoidance in civil aviation.

Alternatively, additions to the plume could be used to alleviate the saturation pressure required for condensation of water [Singh, 1991]. This could be achieved by injecting detergents or surfactants, such as alcohols, into the plume. The substances would require to be resistant to oxidation in a relatively hot environment, and preferably biodegradable. According to Singh [1991], actual tests were performed where the detergent mass flow used to suppress contrail formation was about 12% of the engine fuel mass flow. Using FLOPS, it was calculated that the associated fuel burn penalty on a long-haul trip would be in the 17% range, assuming a modern mid-size civil transport aircraft. Laboratory test results ranging from 1% to 25% quoted in Singh [1991], resulting in a block fuel burn penalty of 1.4%, are more promising, but the range indicates that further investigation is required.

Chapter 4

Contrails vs. carbon dioxide

As it became apparent in previous chapters, contrail mitigation strategies with respect to current aircraft and engine technology imply a fuel burn penalty, inevitably causing an increase in greenhouse gas emissions. A qualitative representation of this trend is given by the bottom right arrow in figure 4.1. Current technology trends indicate that next generation aircraft will be derivatives of present technology. Improvements in fuel economy will be mainly achieved through design advances on a system level to achieve reductions in weight and improvements in aerodynamics and engine efficiency. However, engines operating at higher efficiency are more likely to cause the formation of contrails. This trend is represented by the upper left arrow in figure 4.1. Ultimately, the long term goal is to reduce the radiative forcing from all aircraft pollutants simultaneously as indicated by the bottom left arrow in figure 4.1.

Depending on the length of the transition period from contrails to no contrails, contrail avoidance, once introduced, could almost immediately result in the reduction of the radiative forcing from aviation. If contrail avoidance is accompanied with

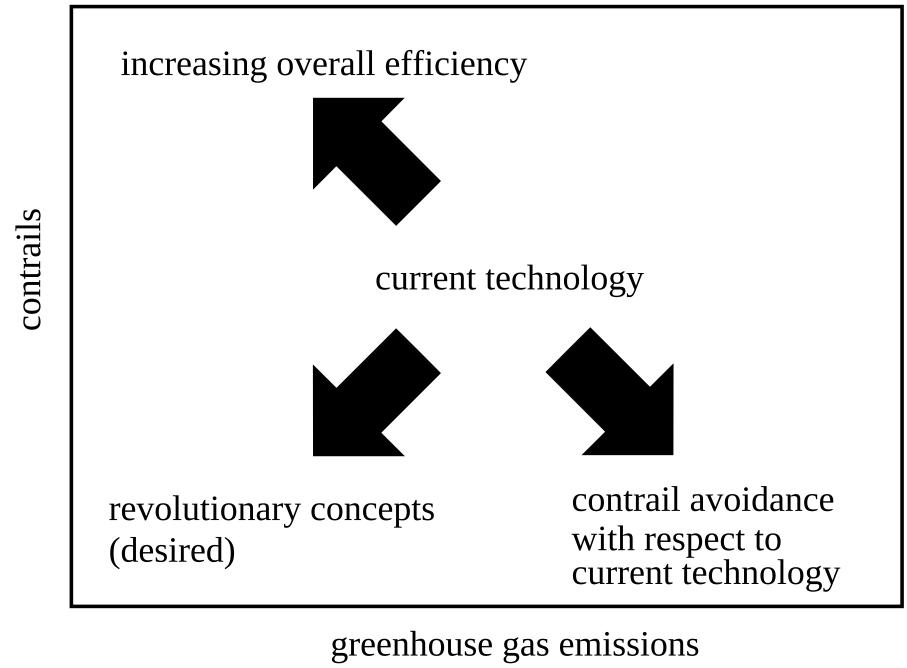


Figure 4.1: Emissions trends with respect to current aircraft and engine technology.

an increase in CO_2 which remains in the atmosphere for longer than a century, it might not be justified to enforce contrail avoidance in the near future even though contrails might exceed the radiative forcing from all other aircraft pollutants. As pollutant's life times and feedback mechanisms differ from each other, so too do their climatic long term impacts. Radiative forcing is only a metric reflecting the strength of a pollutant's perturbation in the global radiation budget of accumulated emissions that occured in the past. Radiative forcing is a metric that does not reflect the environmental impact of emissions that will take place in the future. In the light of this, there are indications that contrail mitigation should be abandoned in the short term, but favoured it in the long term:

- it has been shown that the efficacy of contrails is smaller than 1 [Ponater et al., 2005].

- simulations suggest that the transient climate response of radiative forcing is delayed compared to carbon dioxide [Ponater et al., 2005].

- carbon dioxide remains in the atmosphere over a time period in the range of 100 years which is much larger than that of radiative forcing, in the range of minutes up to some hours.

Unlike CO_2 emissions, the radiative forcing from contrails would virtually become zero the moment they are banned. The accumulated impact from contrails by the time they are avoided is potentially marginal compared to the overall impact of the long-lived carbon dioxide emissions. As a result, it might be desirable to introduce contrails avoidance only if they do not cause additional carbon dioxide emissions. As long as this is not the case, the overall long term impacts from aviation beyond radiative forcing could be far less severe if contrails avoidance was introduced in the more distant future when the associated fuel burn penalty is less significant. Hence, it might currently be more desirable to concentrate on more fuel efficient technologies, along with further reductions in NO_x and noise. The long term goal should be the development of technologies which exhibit the potential to reduce carbon dioxide emissions along with contrail mitigation.

This issue is investigated in this section by assessing the long-term increase in temperature due to aviation emissions by means of a linear climate response model. The resulting temperature change due to CO_2 concentrations and contrail cover was calculated for a set of scenarios. Anthropogenic background emissions were adopted from the emission scenario database of the intergovernmental panel on climate change [IPCC, 2000]: the A1B and the B1 scenario. The A1B scenario assumes an integrated world that facilitates rapid economic growth, the population reaching 9 billion in 2050 followed by a gradual decline, quick spread of novel and efficient technologies, converging income between regions, extensive social and cultural interactions, and a balanced emphasis on all energy sources. The B1 scenario represents a more integrated world and is more ecologically friendly. It is characterized by rapid economic growth as in A1B, but with rapid changes towards a service and information economy, reductions in material intensity, the introduction of clean and resource efficient technologies, and an emphasis on global solutions to economic, social and environmental stability. Figure 4.2 shows the differences in the global average CO_2 concentration for both scenarios.

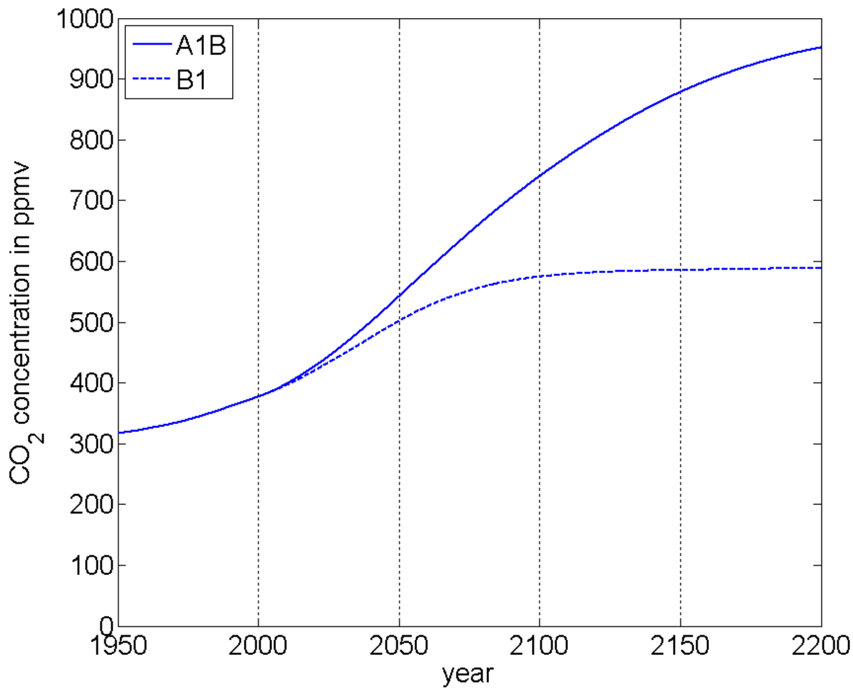


Figure 4.2: Global CO_2 concentration for the IPCC scenarios A1B and B1.

Aviation emissions were calculated online from the background scenarios. As the world grows richer, air transport becomes affordable to a larger proportion of the population, and passenger numbers rise until reaching saturation. In this study, it was assumed that the annual growth in passenger numbers can be related to the difference in the global average real GDP per capita and the air fare in the form

$$\frac{\partial}{\partial t}AP(t) = \alpha(GDP_{PC}(t) - \beta AF(t)) \tag{4.1}$$

where AP is air-traffic passengers per year, GDP_{PC} is the average worldwide real gross domestic product per capita, and AF is the adjusted air fare. The adjusted air fare is an artificial metric representing global spendings on air-transport. The parameters α and β in equation 4.1 were calibrated in order to match historical passenger numbers.

In this study, it is assumed that the market is not saturated by 2200, and model results show that passenger numbers will continuously grow until 2200. This is partly because air travel is becoming less expensive in absolute terms due to more efficient aircraft technology, but also because at the same time the world is growing richer as emerging economies reach similar standards of living as today's western world. This trend is already indicated by the rapid growth rates of emerging economies. However, uncertainty factors such as a negative perception of aviation, policies and regulations, the depletion of resources, wars, natural events with devastating consequences, or disruptive technologies could potentially offset the demand for air transport and cause negative passenger growth rates. Flights per person per annum are calculated to reach about 20 by the year 2200 in the A1B scenario simulations, and 10 in the B1 scenario simulations. In comparison, an individual is taking about 0.3 flights in 2007. However, this number is heavily determined by the developed economies with annual flights per person already exceeding 20 in some places. If emerging economies were picking up and wealth was becoming more evenly distributed, it can be imagined that emerging economies reach standards similar to that of developed economies. The advent of very light jets and air taxi services is already indicative of aviation becoming the principal transport mode in future.

In this model, the air fare is calculated from the average fuel consumption per passenger per journey, and the cost of kerosene. The oil price was based on historical data; estimates regarding the future oil price were made assuming an oil price increasing by 6% per annum between 2005 and 2200. Block fuel, and hence CO_2 emissions, are calculated from the Breguet range equation considering advances in structures, the propulsion system, and aerodynamics, and the average journey length,

$$BF = RS\left(e^{\frac{S\,g}{L/D\;\eta\;FCV}} - 1\right) \tag{4.2}$$

where BF is the block fuel, L/D is the lift to drag ratio, RS is the ratio passenger weight to empty aircraft weight, η is the overall efficiency of the propulsion system, and S is the journey length. FCV denotes the fuel calorific value, and g is the gravitational acceleration. In the model, the technology parameters (L/D, RS, η) evolve over time. Initial values are based on historical data, and the progress is assumed to take place asymptotically, chosen respectively to match historical improvements and create reasonable forecasts. Table 4.1 shows the initial, current, and saturation values of the technology parameters as assumed in the model.

	initial	2007	saturation
η	.2	.23	.6
L/D	12	18	30
R	.1	.2	.3
S [nm]	200	1000	2000

Table 4.1: Aircraft technology parameters.

In all scenarios, aviation fuel was assumed to be kerosene. As the upper limit in overall engine efficiency considering current designs is about 0.56 [Green, 2005], further improvements are assumed to be achieved with the application of novel thermodynamic cycles such as intercooling or exhaust recuperation. An increase in L/D up to 30 by 2200 can be attributed to reductions in induced, parasitic and wave drag, facilitated by the introduction of laminar flow control and novel designs of the lifting bodies. Structural improvements are due to advances in stronger and lighter materials, such as carbon nano tubes, and more integrated designs such as the blended wing body. Including operational measures that enhance the fuel efficiency would be beyond the scope of this study. The possibility of alternative fuels such as hydrogen or bio-fuel is also not addressed. The radiative forcing of atmospheric CO_2 is calculated from the normalised radiative forcing [Houghton et al., 1990], which reads

$$RF'(t) = \frac{\ln(CO_2(t)/CO_2')}{\ln(2)} \tag{4.3}$$

where RF' is the normalised radiative forcing, CO_2 is the atmospheric CO_2 concentration, whereas CO_2' denotes the pre-industrial CO_2 concentration. The actual radiative forcing can be obtained from

$$RF(t) = \frac{RF'(t)}{RF'(t_0)}\, RF(t_0) \tag{4.4}$$

where RF is the actual radiative forcing and t_0 denotes an arbitrary time at which the radiative forcing relative to pre-industrual times is known. The CO_2 induced radiative forcing was then combined with the background radiative forcing, taken from the IPCC scenarios. The background forcing was adjusted to CO_2 equivalents considering the efficacy of the various pollutants. The temperature response was calculated from solving

$$RF(t) = \alpha \Delta T(t) + \beta \frac{\partial}{\partial t} \Delta T(t) \tag{4.5}$$

where ΔT denotes the temperature change relative to pre-industrialization times [Hartman, 1996]. The parameters α and β denote the climate feedback parameter of a certain pollutant, and the global heat capacity, respectively.

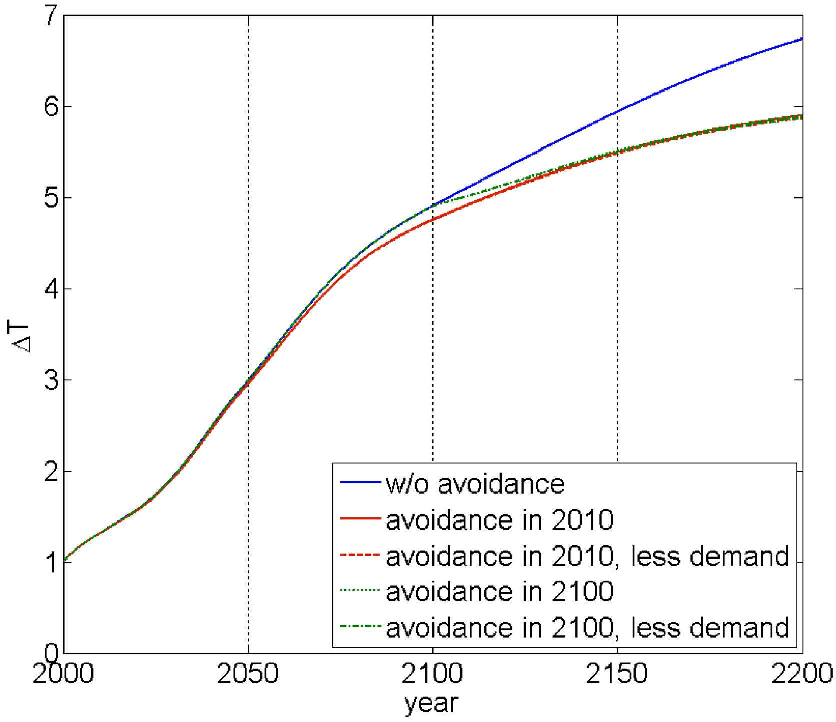
The radiative forcing due to contrails can be linearly related to global fuel burn

[Marquart et al., 2003]. In this study, the radiative forcing due to contrails was assumed to be linearly related to annual passenger numbers. It was calibrated against the estimated radiative forcing of 10mW/m^2 in 2002 for line-shaped contrails [Sausen et al., 2005]. By 2200, depending on the scenario, the contrail radiative forcing was calculated to reach values several 10 times higher than the value for 2002. The climate feedback parameter of contrails was assumed to be 0.47 [Ponater et al., 2005], and the lifetime of aviation CO_2 was assumed to be 140 years. No other air-traffic pollutants were addressed in this study.

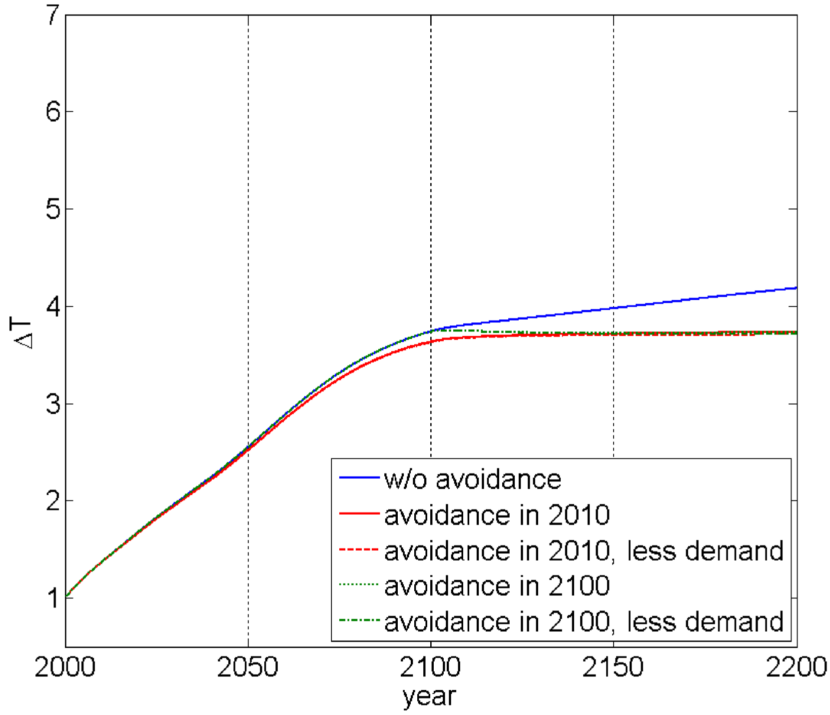
The model was used to investigate the relative increase in global average temperature between 1950, the time when aviation became the medium for mass transport, and 2200. The fuel burn penalty associated with contrail avoidance was assumed to be 10% relative to the prevailing technology. The scenario simulations assume two different times for the introduction of contrail avoidance: the year 2010, and 2100. The introduction of contrail avoiding measures was assumed to take place immediately. As the fuel burn penalty also imposes an additional cost to the passenger, contrail avoidance may reduce the volume of air traffic, caused by increased air fares. An extra set of simulations was performed to take this effect into account.

Results of the model runs in terms of global temperature change are shown in figures 4.3(a) and 4.3(b). The global temperature change from aviation alone is given in figures 4.4(a) and 4.4(b). Results suggest that the temperature change in the case contrails were avoided would be lower than in the presence of contrails. The temperature change just from contrails ranges from about 1 degC by the year 2200 for the A1B scenario simulations to about 0.5 degC for the B1 scenario simulations. Contrail avoidance would decelerate the increase in earth's temperature. According to the results, the transient temperature response pattern exhibits temperature peaks in the B1 scenarios that could be avoided if contrails were avoided in 2010 instead of 2100. As positive feedback loops are not considered in this study, temporarily higher temperatures could potentially trigger other climatic feedback mechanisms. These have the potential to accelerate, and ultimately lead to a larger overall temperature rise in the B1 scenario simulations where contrail avoidance is introduced in 2100.

The simulations carried out in this study indicate that the temperature rise due to the additional CO_2 emissions associated with contrail avoidance would not exceed the temperature rise that would occur if contrails were not avoided. The temperature drop caused by the absence of contrails would set in immediately (given that contrail avoidance would be introduced abruptly), and the time span until temperatures adjust according to prevailing greenhouse gas concentrations would be relatively short. Contrail avoidance therefore seems to be inevitable to achieve environmental compatibility of aviation, but it is less important when it will be introduced. Although the fuel burn penalty associated with contrail avoidance of 10% was chosen to be relatively high in this study, the difference in global temperature rise from aviation CO_2 between the scenarios with and without contrail avoidance were not significant. The overall fuel burn penalty would be less severe if it was assumed that it would affect the air fare and slow down passenger growth rates. Since the fuel burn penalty is relative to a prevailing technology, and the fuel economy of aircraft can be expected to increase considerably in future, the impact on the air fare in absolute terms would be less severe if contrail avoidance was only introduced in the long term. As technological evolution is primarily demand driven, it could be expected that postponing the introduction of contrail avoidance would allow higher growth rate, and aircraft technology reaching higher efficiencies faster.

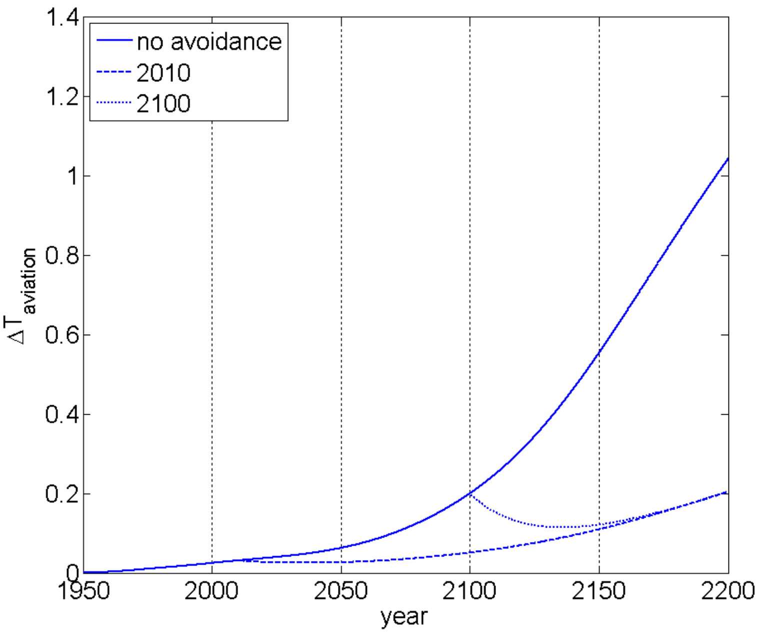


(a) A1B scenario

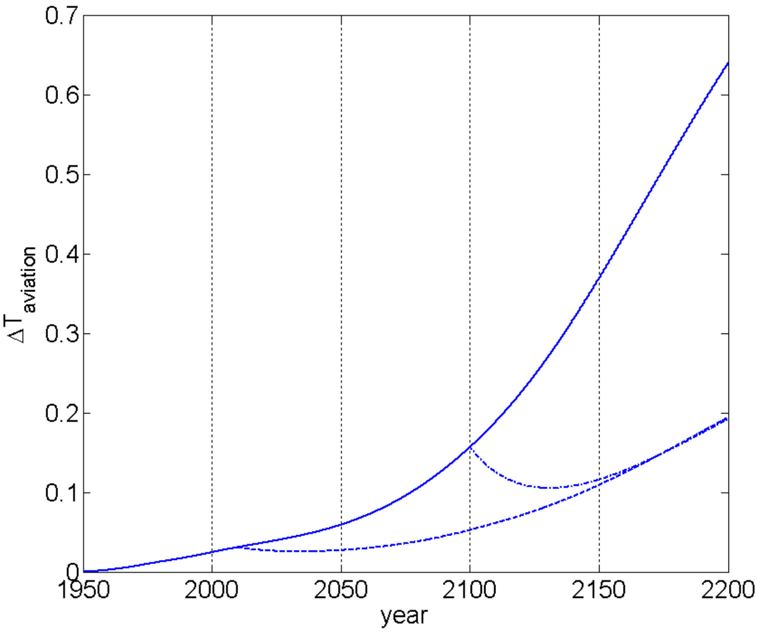


(b) B1 scenario

Figure 4.3: Global temperature change.



(a) A1B scenario



(b) B1 scenario

Figure 4.4: Global temperature change from aviation only.

Chapter 5

Conclusions

Global warming and its consequences, as discussed in chapter 1, is regarded to be a serious threat to mankind and creates the demand for new, cleaner technologies. Air traffic, having experienced continuous growth since the advent of commercial aviation, is projected to contribute increasingly to the annual CO_2 emissions. Apart from CO_2, aircraft place emissions in the atmosphere where their environmental impact is altered compared to ground level. Water contained in the exhaust gases of a jet engine enables the formation of contrails, and the resulting increase in cloud cover potentially contributes more to the overall aviation radiative forcing than all other air-traffic emissions combined. As a result, contrail avoidance is an emerging discipline of increasing interest. This thesis is the first comprehensive study on contrail avoidance, making a general contribution to the understanding of the problem.

Contrail avoidance strategies were developed as part of the PhD project, and existing approaches could be found in literature available in the public domain. The various identified contrail avoidance strategies exhibit fundamental differences in their physical and technical nature. Short, mid and long term solutions are distinguished. Short term solutions offer the option of current aircraft to be retrofitted with contrail avoidance technology. Of the identified technologies, that applies to flight path adjustment as discussed in section 3.1 or contrail avoidance devices such as remotely induced heat induction to suppress contrail formation, as described in section 3.5. In the mid term, contrail avoidance could become part of the aircraft design process. That could either happen through the optimisation of an aircraft incorporating a short term solution, or the optimisation of the aircraft for flight altitudes where contrail occurrences are reduced, as described in section 3.3.1. These approaches would allow the design of more environmentally compatible next generation aircraft being based on existing technology without having to apply changes of disruptive character. In the long term, the introduction of contrail avoidance would allow a more integrated approach. A novel engine concept was developed during the PhD project, as described in section 3.2.2, which exhibits the possibility of avoiding contrails and reducing all aircraft emissions simultaneously. The engine concept combines the advantages of already existing technologies in a synergistic way, resulting in superior performance compared to conventional technology with lower emissions. Its feasibility is primarily dependent on advances in heat exchanger technology regarding weight, pressure loss and size.

A common feature of the identified short and long term contrail avoidance strategies is the associated fuel burn penalty, and hence increase in CO_2 emissions. Figure 5.1 shows best estimates of fuel burn penalty estimates for several avoidance strategies as calculated during the PhD project and available in literature in the public domain. It has to be taken into account, however, that the numbers are first estimates and not the results of accurate assessments, having the purpose to support the identification of priorities for further research activities. According to the estimates, changing aircraft cruise altitude during flight (free flight) exhibits an effective and viable method for contrail avoidance. It is accompanied by a fuel burn penalty of below 1% and can be applied to current aircraft technology. The fuel burn penalty could be further reduced applying new technologies such as variable geometry airfoils, which allow the adaptation of the wing depending on the altitude to maximise the lift to drag ratio. This could have the overall effect of reducing thrust requirements during flight, and hence reducing the fuel burn penalty associated with this contrail avoidance technique. However, free flight is currently impeded by air-traffic management restrictions and safety issues, a problem that could be overcome by introducing more sophisticated traffic collision avoidance systems. Another short term solution developed during this PhD project is the application of devices which remotely induce heat to suppress condensation, as discussed in section 3.5. Although the technical feasibility of this technology is subject to further research, it would theoretically result in the total avoidance of contrails with a negligible fuel burn penalty. In the mid term, aircraft optimised for different cruise altitudes have the potential to reduce contrail occurrences. The calculated fuel burn penalty is 5%, which is relatively large compared to other contrail avoidance technologies. However, the study was carried out for one particular aircraft configuration only and did not allow compromises in terms of cruise velocity. Unducted fan configurations cruising at lower altitude and speed could have the potential to cut back in both CO_2 and contrail occurrences.

As contrail avoidance provokes the emission of additional CO_2, which remains in the atmosphere for longer than a century, it might not be justified to introduce their avoidance in the near future even though contrails might exceed the radiative forcing from all other aircraft pollutants combined. Since pollutant's life times and feedback mechanisms differ from each other, so too do their climatic long term impacts. Radiative forcing is a metric reflecting past emissions, but the development for a case supporting contrail avoidance requires a relevant comparison of

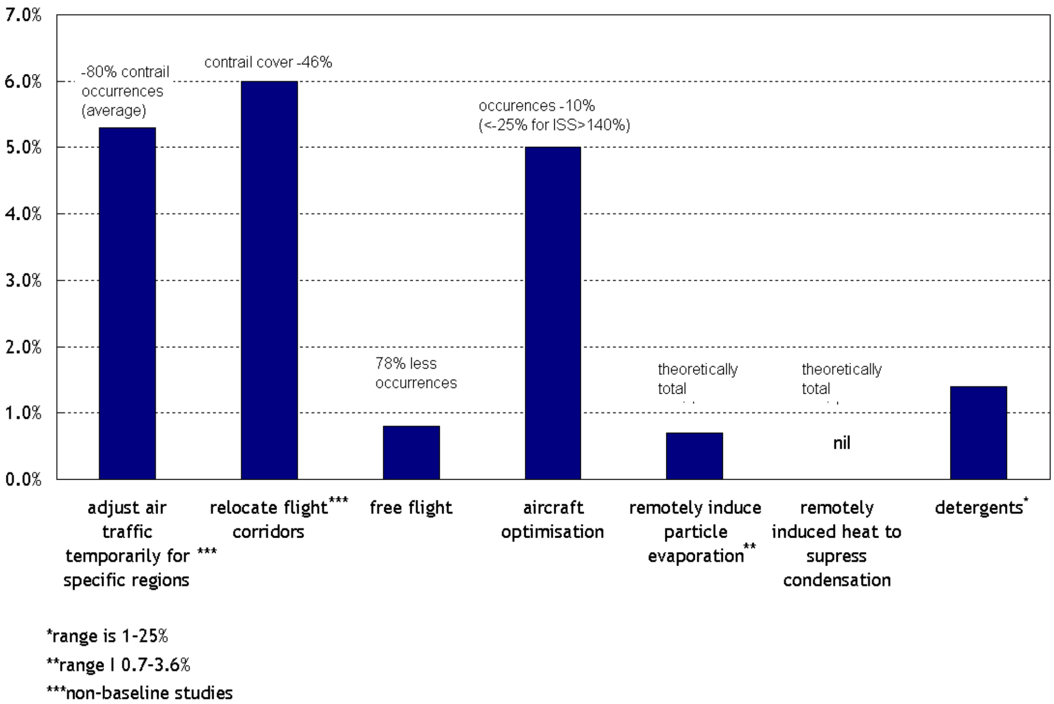


Figure 5.1: Fuel burn penalty associated with contrail avoidance.

aviation pollutants in terms of their future environmental impact. Therefore, the introduction of a metric other than radiative forcing enabling the comparison between the future impact of contrails and other aviation pollutants is a prerequisite. This issue was addressed during the PhD project and is discussed in section 4. A one-dimensional climate response model was used to calculate the long term global temperature change from both aviation CO_2 and contrails. Results suggest that although the short term contribution to the global temperature change from contrails might be insignificant, it would exceed that of CO_2 in the long term. Since the radiative forcing from contrails becomes zero at the time they are banned, their avoidance in the long term would be sufficient, allowing more time to develop a contrail avoidance technology that does not come with a fuel burn penalty.

Although contrails are believed to have a larger radiative forcing than other aviation pollutants, the scientific evidence for the impact of contrail cirrus clouds is not strong enough yet to support arguments in favour for the introduction of contrail avoidance. As long as more accurate forecasts of the environmental impact from contrail cirrus will become available and do not undercut already existing figures, they would strengthen the argument for contrail avoidance. Furthermore, contrail avoidance technologies are not readily available, and contrail avoidance could only be introduced once a technology is sufficiently developed. Although several avoidance strategies were identified in this thesis, their feasibility and techno-economical consequences are far from being fully understood.

If contrail avoidance turns out to be inevitable for sustainable aviation, its introduction would probably only be possible through regulations or tax incentives because it would impose a cost on aircraft operators. Alternatively, a paradigm shift towards cleaner products might result in the environmentally aware passengers being willing to pay a supplement for reducing their individual footprint. A similar approach exists already by allowing passengers to offset their carbon footprint by paying an extra fee on top of their airfare. If contrail avoidance was available at a reasonable price, people might want to fly with an airline that operates with cleaner technology. Most of the journeys by aircraft are undertaken by middle and upper class, who have more disposable income to spend, and the new environmental awareness might lead to more spendings on greener products. Companies already make use of the new green way of thinking and claim cleaner technologies than competitors [The Times article by Webster, 2007; 15 June]. As opposed to greenhouse gases, contrails are a visible pollutant, observable in the sky during daylight, and apart from being seen as an environmental problem, people could start to regard contrails as harming the aesthetics of their environment. Depending on how the issue of contrail avoidance will be perceived by the public, airlines that adopted a contrail avoidance technology might eventually have a competitive advantage over other airlines. New market opportunities could be created within a competitive environment where the results are profit driven.

Often, the opinion of governments is a precursor to the public opinion, and the speed of diffusion of the topic amongst the public is then a matter of how severely the topic is debated and how quickly it is distributed by the media. An extract from the aviation White Paper by the UK Department for Transport [2003] sends first signals on how aviation pollutants other than CO_2 are already perceived:

> "The impact of aviation on climate change is increased over that of direct CO_2 emissions alone by some of the other emissions released and their specific effects at altitude. These effects include increased tropospheric ozone, contrail formation and a small amount of methane destruction. The environmental impacts of aircraft have been assessed by the Intergovernmental Panel on Climate Change (1999) and more recently by the Royal Commission on Environmental Pollution (2002), and they are thought to be 2-4 times greater than that from CO_2 alone. While further research is needed on these issues, the broad conclusion that emissions are significantly more damaging at altitude is clear."

Depending on the outcome of future research, contrail avoidance is likely to either appear on top of agendas or give airlines a competitive advantage if it is demanded by their customers. The market for contrail avoidance technology is potentially large. With an estimated 22,700 new passenger and freight aircraft going into service between 2006 and 2025 [Airbus, 2006], the number of aircraft worldwide would be more than doubled. If each aircraft had to be equipped with a contrail avoidance device, companies that could offer a viable solution and possess intellectual property rights might be able to find the contrail problem lucrative.

5.1 Recommendations

5.1.1 Assessing the environmental impact of contrails

A more accurate assessment of the environmental impact from aviation-induced ice clouds other than that of line shaped contrails should be a priority. Scientific evidence is required to make adequate decisions regarding the contrail problem.

Aerodynamic contrails could potentially occur independently from engine-provoked contrails. If that was the case, than there would be situations where only engine provoked contrails emerge, where both emerge at the same time, and where only aerodynamically induced contrails emerge. In the case that both aerodynamic contrails and engine-provoked contrails form simultaneously, the avoidance of engine-provoked contrails would not necessarily imply the avoidance of aerodynamic contrails. Additionally, the actual contrail cover, and hence environmentally related implications, would be larger than calculated in studies up to now. Further work should address the development of a model for forecasting aerodynamic contrails and their impact on the environment.

A more relevant metric than radiative forcing representing an impact further down the impact chain, as described on page 6, is required to compare air-traffic pollutants regarding their future impact. An alternative approach is given in chapter 4, where scenarios with and without contrail avoidance are compared to each other regarding their long term global temperature change.

A design tool allowing the calculation of the environmental impact from contrails is desirable for the development of contrail avoidance strategies and during the design process of next generation aircraft. A prototype allowing the calculation of contrail occurrences was used in the study addressed in section 3.3.1. However, further work is recommended to increase its fidelity and also consider other pollutants than CO_2 and contrails.

5.1.2 Recommendations on avoidance technologies

As most of the contrail avoidance strategies presented in this thesis are currently not explored in great detail, the recommendations on further work on the individual strategies would be vast. Therefore, recommendations regarding further research on technologies are given in a broader sense in the following.

An engine concept repeatedly discussed in the aeronautical community is unducted fans. In particular, cruise altitude and aircraft wake dynamics of unducted fans designs offer the potential for reducing contrail occurrences and modify their radiative properties. Hence, considering contrail formation already in the design process of unducted fan aircraft, they could be the first generation of aircraft designed with an aim to reduce the impact of contrails. Therefore, further work would be necessary to understand environmental implications of unducted fans apart from CO_2.

The same is true for blended wing body aircraft. Their effect on contrail formation and radiative properties due to different aircraft wake patterns and engine integration methods has not been addressed in any studies.

The practical feasibility of contrail avoidance devices as introduced in section 3.5 is subject to further investigation. As contrail avoidance devices exhibit an opportunity for contrail avoidance without a significant fuel burn penalty and the possibility of being able to retrofit existing aircraft, further work is strongly recommended.

References

Creating employment and prosperity in Europe, a study by ACI Europe of the social and economic impacts of airports. PPS Publications, 1998.

Advisor Council for Aeronautics Research in Europe. Strategic research agenda vol 1. ACARE, October 2002.

Airbus. *Global Market Forecast 2004-2023*. Airbus, 2003.

Airbus. *Global Market Forecast 2006-2025*. Airbus, 2006.

D. Alexander, Y.-M. Lee, M. Guynn, and D. Bushnell. Emissionless aircraft study. AIAA 2002-4056, July 2002.

G. Ameyugo, M. Taylor, and R. Singh. Distributed propulsion feasibility studies. In I. Grant, editor, *CD Proceedings of the 25th International Congress of the Aeronautical Sciences*, Hamburg, September 2006. Optimage Ltd on behalf of the International Council of the Aeronautical Sciences (ICAS).

C. E. Andreson, S. J. Birstein, and B. A. Silverman. Method and apparatus for supressing contrails. USP 3,517,505, June 1970.

N. E. Antoine and I. M. Kroo. Aircraft optimization for minimal environmental impact. *Journal of Aircraft*, 41(4):790 – 797, 2004.

H. Appelman. The formation of exhaust condensation trails by jet aircraft. *Bulletin American Meteorological Society*, 34(1):14–20, January 1953.

H. S. Appleman. Effect of supersonic aircraft on cirrus formation and climate. In *Conference on aerospace meteorology*, Los Angeles, March 1966. American Meteorological Society and American Institute of Aeronautics and Astronautics.

S. Arrhenius. On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine*, 41:237–275, 1896.

S. Boggia and K. Rüd. Intercooled recuperated gas turbine engine concept. In *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA 2005-4192, Tucson, Arizona, July 2005.

S. Brunet, F. Garnier, and L. Jacquin. Numerical/experimental simulation of exhaust jet mixing in wake vortex. AIAA-99-3418, 1999.

D. J. Campbell. Revolutionary propulsion and power for 21st century aviation. AIAA 2003-2561, July 2003.

S. A. Changnon. Midwestern cloud, sunshine and temperature trends since 1901: Possible evidence of jet contrail effects. *Journal of Applied Meteorology*, 20:496–508, January 1980.

A. Chlond. Large-eddy simulation of contrails. *Journal of Atmospheric Sciences*, 55:796–819, March 1998.

S. C. Crow. Stability theory for a pair of trailing vortices. D1-82-0918, September 1969.

D. Daggett, L. Fucke, R. C. Hendricks, and D. J.H. Eames. Water injection on commercial aircraft to reduce airport nox. AIAA-2004-4198, 2004.

M. Y. Danilin, D. W. Fahey, U. Schumann, M. J. Prather, J. E. Penner, W. K. W. Ko, D. K. Weisenstein, C. H. Jackmann, G. Pitari, I. Kohler, R. Sausen, C. J. Weaver, A. R. Douglass, P. S. Connell, D. E. Kinnison, F. J. Dentener, E. L. Fleming, T. K. Bernsten, I. S. A. Isaksen, J. M. Haywood, and B. Kärcher. Aviation fuel tracer simulation: Model intercomparison and implications. *Geophysical Research Letters*, pages 3947–3950, 1998. only in database.

J. M. W. Dings and P. M. Peeters. Economic screening of aircraft preventing emissions. Main Report, Dutch Transport Research Centre, 2000.

A. Döpelheuer. *Berechnung der Produkte unvollständiger Verbrennung aus Luftfahrttriebwerken*, volume IB-325-09-97. DLR, Oberpfaffenhofen, 1997.

D. M. Etheridge, L. P. Steele, R. L. Langenfelds, R. J. Francey, J.-M. Barnola, and V. I. Morgan. Natural and anthrogogenic changes in atmospheric co_2 over the last 1000 years from air in antarctic ice and firn. *Journal of Geophysical Research*, 101(D2):4115–4128, February 1996.

C. J. Eyers, P. Norman, J. Middel, M. Plohr, S. Michot, K. Atkinson, and R. A. Christou. Aero2k global aviation emission inventories for 2002 and 2025. EC, G4RD-CT-2000-00382, April 2004.

F. Faupin. Performance assessment of an open rotor propfan. Master's thesis, School of Mechanical Engineering, Cranfield University, August 2006.

Richard C. Feagin and William D. Morrison. Delta method, an empirical drag buildup technique. *NASA CR-151971*, December 1978.

C. Fichter, S. Marquart, and R. Sausen. Impact of cruise altitude on contrails. In *Proceedings of the AAC-Conference*, pages 322–327, Friedrichshafen, June 2003.

C. Fichter, S. Marquart, R. Sausen, and D. S. Lee. The impact of cruise altitude on contrails and related radiative forcing. *Meteorologische Zeitschrift*, 14(4):563–572, August 2005.

P. J. Flatau, R. L. Walko, and W. R. Cotton. Polynomial fits to saturation pressure. *Journal of Applied Meteorology*, 31(12):1507–1513, December 1992.

K. A. Geiselhart. A technique for integrating engine cycle and aircraft configuration optimization. NASA Contractor Report 191602, February 1994.

K. Gierens. On the transition between heterogeneous and homogeneous freezing. *Atmospheric Chemistry Physics*, 3(2):437–446, April 2003.

K. Gierens. Are fuel additives a viable contrail mitigation option? *Atmospheric Environment*, 41(doi:10.1016/j.atmosenv.2007.03.014):4548–4552, 2007.

K. Gierens and E. Jensen. A numerical study of the contrail-to-cirrus transition. *Geophysical Research Letters*, 25(23):4341–4344, December 1998.

K. Gierens, U. Schumann, M. Helten, H. Schmit, and A. Marenco. A distribution law for relative humidity in the upper troposphere and lower stratosphere derived from three years of mozaic measurements. *Ann. Geophysicae*, 17(9):1218–1226, 1999.

K. M. Gierens and J. Ström. A numerical study of aircraft wake induced ice cloud formation. *Journal of Atmospheric Sciences*, 55(21):3253–3263, November 1998.

J. E. Green. The technology challenge. Presentation to the Royal Aeronautical Society, April 2003.

J. E. Green. Future aircraft - greener by design? *Meteorologische Zeitschrift*, 14(4):583–590, August 2005.

J. Hansen, M. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G. A. Schmidt, G. Russell, I. Aleinov, M. Bauer, S. Bauer, N. Bell, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, M. Kelley, N. Kiang, D. Koch, J. Lean, J. Lerner, K. Lo, S. Menon, R. Miller, P. Minnis, T. Novakov, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, D. Shindell, P. Stone, S. Sun, N. Tausnev, D. Thresher, B. Wielicki, T. Wong, M. Yao, and S. Zhang, S.Zhang. Efficacy of climate forcings. *Journal of Geophysical Research*, 110(D18): D18104, September 2005.

D. L. Hartman. *Global Physical Climatology*. Academic Press, New York, 1996.

J. Hendricks, B. Kärcher, U. Lohmann, and M. Ponater. Do aircraft black carbon emissions affect cirrus clouds on the global scale? *Geophysical Research Letters*, 32, June 2005.

A. J. Heymsfield, L. M. Miloshevich, and C. Twohy. Upper-tropospheric relative humidity observations and implications for cirrus ice nucleation. *Geophysical Research Letters*, 25(9):1343–1346, May 1998.

O. Höffe. *Gerechtigkeit - Eine Philosophische Einführung*, volume 2. Verlag C.H. Beck, München, 2004.

F. Holzäpfel, T. Hofbauer, D. Darracq, H. Moet, F. Garnier, and C. F. Gago. Analysis of wake vortex decay mechanisms in the atmosphere. *Aerospace Science and Technology*, 7:263–275, 2003.

G. Horton. Forecasts of co2 emissions from civil aircraft for ipcc. QINETIQ/06/02392, November 2006.

J. T. Houghton. *Global Warming - The Complete Briefing*. Cambridge University Press, 3 edition, 2004.

J.T. Houghton, G.J. Jenkins, and J.J. Ephraums. *The IPCC Scientific Assessment*. Cambridge University Press, 1990.

W. W. Huebsch and D. C. Lewellen. Sensitivity study on contrail evolution. In *36th AIAA Fluid Dynamics Conference and Exhibit*, San Francisco, June 2006.

IPCC. Climate change 2007: The physical science basis. Summary for Policymakers, Geneva, Switzerland, February 2007.

IPCC. IPCC special report emission scenarios, 2000.

IPCC Working Group 1. *Summary for Policy Makers*. IPCC, 2001.

L. Jacquin and F. Garnier. On the dynamics of engine jets behind a transport aircraft. AGARD FDP Symposium, CP-584, May 1996.

E. Jensen and O. B. Toon. The potential impact of soot particles from aircraft exhaust on cirrus clouds. *Geophysical Reserach Letters*, 24(3):249–252, 1997.

E. J. Jensen, A. S. Ackerman, D. E. Stevens, O. B. Toon, and P. Minnis. Spreading and growth of contrails in a sheared environment. *Journal of Geophysical Research*, 103(D24):31557–31567, December 1998a.

E. J. Jensen, O. B. Toon, S. K. Kinne, G. W. Sachse, B. E. Anderson, K. R. Chan, C. H. Twohy, B. Gandrud, A. Heymsfield, and C. Miake-Lye. Environmental conditions required for contrail formation and persistence. *Journal of geophysical research*, 103(D4):3929–3936, February 1998b.

B. Kärcher and T. Koop. The role of organic aerosols in homogeneous ice formation. *Atmos. Chem. Phys. Discuss.*, 4:6719–6745, 2004.

B. Kärcher and U. Lohmann. A parameterization of cirrus cloud formation: Heterogeneous freezing. *Journal of Geophysical Research*, 108(D14):2–1, July 2003.

B. Kärcher, Th. Peter, U. N. Biermann, and U. Schumann. The initial composition of jet condensation trails. *Journal of the atmosphere sciences*, 53 (21):3066–3083, 1996.

B. Kärcher, R. Busen, A. Petzold, F. P. Schröder, U. Schumann, and E. J. Jensen. Physicochemistry of aircraft-generated liquid aerosols, soot, and ice particles 2. comparison with observations and sensitivity studies. *Journal of geophysical research*, 103(D14):17129–17147, July 1998.

Bernd Kärcher. Contrails: Observations, formation mechanism, atmospheric impacts, uncertainties. DLR Mitteilung 2001-01, Institut für Physik der Atmosphäre, Oberpfaffenhofen, 2000.

Bernd Kärcher. Aviation-produced aerosols and contrails. *Surveys in Geophysics*, 20(2):113–167, 1999.

A. Kristensson, J.-F. Gayet, J. Ström, and F. Auriol. In situ observations of reduction in effective crystal diameter in cirrus clouds near flight corridors. *Geophysical Reserach Letters*, 27(5):681–684, March 2000.

D. S. Lee. The impacts of aviation on climate. *Issues in Environmental Science and Technology*, (20), 2004.

J. J. Lee, S. P. Lukachko, I. A. Waitz, and A. Schafer. Historical and future trends in aircraft performance, cost and emissions. *Annu. Rev. Energy Environ.*, 26:167200, 2001.

A. H. Lefebvre. *Gas turbine combustion*. Hemisphere Publishing, 1983.

D. C. Lewellen and W. S. Lewellen. The effects of aircraft wake dynamics on contrail development. *Journal of the atmospheric sciences*, 58:390–406, February 2001.

D. R. Lide. *CRC Handbook of Chemistry and Physics*. CRC Press. Boca Raton, Florida, 84 edition, 2003.

R. Lindzen, M.-D. Chou, and A. Y. Hou. Does the earth have and adaptive infrared iris? *Bulletin of the American Meteorological Society*, 82(3):417–432, March 2001.

D. Lucisano. Analysis and optimisation of a novel aero engine concept. Master's thesis, School of Engineering, Cranfield University, 2007.

H. Maclin and C. Haubert. Fifty years down - fifty years to go. AIAA 2003-2788, AIAA/ICAS International Air and Space Symposium and Exposition, 2003.

H. Mannstein and U. Schumann. Aircraft induced cirrus clouds over europe. *Meteorologische Zeitschrift*, 14(4):549–554, August 2005.

H. Mannstein, P. Spichtinger, and K. Gierens. A note on how to avoid contrail cirrus. *Transportation Research Part D: Transport and Environment*, 5 (10):421–426, September 2005.

S. Marquart, R. Sausen, M. Ponater, and V. Grewe. Estimate of the climate impact of cryoplanes. *Aerosp. Sci. Technol.*, 5(1):73–84, 2001.

S. Marquart, M. Ponater, F. Mager, and R. Sausen. Future development of contrail cover, optical depth, and radiative forcing: Impacts of increasing air traffic and climate change. *Journal of Climate*, 16:2890–2904, September 2003.

S. Marquart, M. Ponater, L. Ström, and K. Gierens. An upgrade estimate of the radiative forcing of cryoplane contrails. *Meteorologische Zeitschrift*, 14 (4):573–582, August 2005.

John H. McMasters and Russell M. Cummings. From farther, faster, higher to leaner, meaner, greener - future directions in airplane design in the new century. AIAA 2003-553, January 2003.

R. Meerkötter, U. Schumann, R. D. Doelling, O. Minnis, T. Takajima, and Y. Tsushima. Radiative forcing by contrails. *Annales Geophysicae*, 17(8): 1080–1094, August 1999.

P. Minnis, D. F. Young, D. P. Garber, L. Nguyen, W. L. Smith, and R. Palikonda. Transformation of contrails into cirrus during success. *Geophysical Research Letters*, 25(8):1157–1160, 1998.

P. Minnis, J. K. Ayers, R. Palikonda, D. R. Doelling, U. Schumann, and K. Gierens. Changes in cloudiness and their relationship to contrails. In *Proceedings of the 12th Symposium on Global Change Studies and Climate Variations*, pages 239–242, 2001.

P. Minnis, L. Nguyen, D. P. Gaerber, D. P. Duda, R. Palikonda, and D. R. Doelling. Simulation of contrail coverage over the usa missed during the aircraft shutdown. In *Conference Proceedings: Aviation, Atmosphere and Climate*, pages 224–231. European Comission, 2003.

G. Myhre and F. Stordal. On the tradeoff of the solar and thermal infrared radiative impact of contrails. *Geophysical Research Letters*, 28(16):3119–3122, August 2001.

H. A. Niedzballa and D. Schmitt. Comparison of the specific energy demand of aeroplanes and other vehicle systems. *Pergamon Aircraft Design*, pages 163 – 178, 2001.

Stefan K. Nielsen. *Air travel, life style, energy use and environmental impact*. Byg dtu r-021, Denmark Tekniske Universitet, 2001.

R. B. Noland and V. Williams. Policies for mitigating contrail formation from aircraft. In *Proceedings of the AAC-Conference*, pages 328–333, Friedrichshafen, June 2003.

F. Noppel, R. Singh, and M. Taylor. A gas turbine engine. EP1852590, November 2007.

R. Paoli and F. Garnier. Interaction of exhaust jets and aircraft wake vortices: small-scale dynamics and potential microphysical-chemical transformations. *C. R. Physique*, 6(4-5):525–547, 2005.

R. Paoli, J. Helie, and T. Poinsot. Contrail formation in aircraft wakes. *Journal of Fluid Mechanics*, 502:361–373, March 2004.

J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken, and M. McFarland, editors. *Aviation and the Global Atmosphere*, 1999. A Special Report of IPCC Working Groups I and III, Cambridge University Press.

A. Petzold, R. Busen, F. P. Schröder, R. Baumann, M. Kuhn, J. Ström, D. E. Hagen, P. D. Whitefield, D. Baumgardner, F. Arnold, S. Borrmann, and U. Schumann. Near-field measurements on contrail properties from fuels with different sulfur content. *Journal of Geophysical Research*, 102(D25): 29867–29880, December 1997.

A. Petzold, M. Gysel, X. Vancassel, R. Hitzenberger, H. Puxbaum, S. Vrochticky, E. Weingartner, U. Baltensperger, and P. Mirabel. On the effects of hydrocarbon and sulphur-containing compounds on the ccn activation of combustion particles. *Atmos. Chem. Phys. Discuss.*, 5:2599–2642, 2005.

M. Ponater, S. Marquart, and R. Sausen. Contrails in a comprehensive global climate model: Parameterization and radiative forcing results. *Journal of Geophysical Research*, 107(D13), 2002.

M. Ponater, S. Marquart, R. Sausen, and U. Schumann. On contrail climate sensitivity. *Geophysical Research Letters*, 32:10706, May 2005.

M. Ponater, S. Pechtl, R. Sausen, U. Schumann, and G. Hüttig. Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment. *Atmospheric Environment*, in press, 2006.

O. B. Popovitcheva, M. E. Trukhin, N. M. Persiantseva, and N. K. Shonija. Water adsorption on aircraft-combustor soot under young plume conditions. *Atmospheric Environment*, 35(9):1673–1676, 2001.

F. H. Proctor, D. A. Hinton, J. Han, D. G. Schowalter, and Y.-L. Lin. Two dimensional wake vortex simulations in the atmosphere: Preliminary sensitivity studies. Technical Report NASA-AIAA-97-0056, 1997.

H. R. Pruppacher and J. D. Klett. *Microphysics of Clouds and Precipitation*. Kluwer Academic Publishers, 2000.

Y. Qu. Superconducting heat transfer medium. U.S.P. 6,132,823, October 2000.

R. Revelle and H. Suess. Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO2 during the past decades. *Tellus*, 9:18–27, 1957.

H. L. Roger, D. S. Lee, D. W. Raper, P. M. de F. Foster, C. W. Wilson, and P. J. Newton. The impacts of aviation on the atmosphere. *The Aeronautical Journal*, 106(1064):522–546, October 2002.

H. L. Rogers and K. P. Shine. Critique of the use of relative greenhouse effect / global warming potential methodologies in aviation. personal communication, February 2005.

R. Sausen, K. Gierens, M. Ponater, and U. Schumann. A diagnostic study of the global distribution of contrails part i: Present day climate. *Theor. Appl. Climatol.*, 61:127–141, 1998.

R. Sausen, I. Isaksen, V. Grewe, D. Hauglustaine, D. Lee, M. Gunnar, M. O. Köhler, G. Pitari, U. Schumann, F. Stordal, and C. Zerefos. Aviation radiative forcing in 2000: An update on ipcc (1999). *Meteorologische Zeitschrift*, 14(4):555–561, August 2005.

F. Schröder, B. Kärcher, C. Duroure, J. Ström, A. Petzold, J.-F. Gayet, B. Strauss, P. Wendling, and S. Borrmann. On the transition of contrails into cirrus clouds. *Journal of the atmospheric sciences*, 57(4):464–480, 2000.

U. Schumann. Aircraft emissions. *Encyclopedia of Global Environmental Change*, 3:178–186, 2002.

U. Schumann. On conditions for contrail formation from aircraft exhausts. *Meteorol. Zeitschrift*, 5:4–23, February 1996.

U. Schumann and P. Wendling. Determination of contrails from satellite data and observational results. In U. Schumann, editor, *Air traffic and the* *environment-background, tendencies, and potential global atmospheric effects*, pages 138–153, Heidelberg, 1990. Springer Verlag. only in database.

U. Schumann, J. Ström, R. Busen, R. Baumann, K. Gierens, M. Krautstrunk, and J. Schröder, F. P. Stingl. In situ observations of particles in jet aircraft exhausts and contrail for different sulfur-containing fuels. *Journal of Geophysical Research*, 101(D3):6853–6869, March 1996.

U. Schumann, R. Busen, and M. Plohr. Experimental test of the influence of propulsion efficiency on contrail formation. *Journal of Aircraft*, 37(6): 1083–1087, 2000.

U. Schumann, J. Srom, F. Arnold, T. K. Bernstein, P. M. Forster, J.-F. Gayet, and D. Hauglustaine. Aviation impact on atmospheric composition and climate. *Second European Assessment of Stratospehric Research*, 2001. only in database.

U. Schumann, F. Arnold, R. Busen, J. Curtius, B. Kärcher, A. Kiendler, A. Petzold, H. Schlager, F. Schröder, and K.-H. Wohlfrom. Influence of fuel sulfur on the composition of aircraft exhaust plumes: The experiments sulfur 1-7. *Journal of Geophysical Research*, 107(D15), 2002.

K. A. Sehra and W. Whitlow. Propulsion and power for 21st century aviation. *Progress in Aerospace Sciences*, 40:199–235, 2004.

J. A. Seidel, A. K. Sehra, and R. O. Colantonio. Nasa propulsion research: Looking forward. NASA/TM-2001-211087, September 2001.

K. P. Shine and P. M. de Forsters. The effect of human activity on radiative forcing of climate change: a review of recent developments. *Global and Planetary Change*, 20:205–225, 1999.

K. P. Shine, J. S. Fuglestvedt, K. Hailemariam, and N. Stuber. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*, 68(3):281–302, 2005.

S. Singh. Method of suppressing formation of contrails and solution therefor. USP 5,005,355, April 1991.

A. M. Starik, A. M. Savelév, N. S. Titova, and U. Schumann. Modeling of sulfur gases and chemiions in aircraft engines. *Aerospace, Science and Technology*, 6(1):63–81, 2002.

F. Stordal, G. Myhre, W. Arlander, T. Svendby, E. J. G. Stordal, W. B. Rossow, and D. S. Lee. Is there a trend in cirrus cloud cover due to aircraft traffic? *Atmospheric Chemistry and Physics Discussion*, 4:6473–6501, October 2004.

L. Ström and K. Gierens. First simulations of cryoplane contrails. *Journal of geophysical research*, 107(D18):2–1, 2002.

N. Stuber, O. Forster, G. Rädel, and K. Shine. The importance of the diurnal and annual cycle of air traffic for contrail radiative forcing. *nature*, 441(15): 864–867, 2006.

The Economist print edition. Cleaning up. Special Report, May 2007.

C. Thomas and D. Raper. The role of aero engineering in the sustainable development of the aviation industry. *The Aeronautical Journal*, 104(1037): 331–333, 2000.

D. Travis, A. Carleton, and R. Lauritsen. Contrails reduce daily temperature range. *Nature*, 418:601, 2002.

UK Department for Transport. The future of air transport. White Paper, London, December 2003.

B. Webster. New aircraft takes off for a greener but noisier future. *The Times*, 15 June 2007.

V. Williams and R. B. Noland. Reducing the climate change impacts of aviation by restricting cruise altitudes. *Transportation Research D*, 7(6): 451–464, 2002.

V. Williams and R. B. Noland. Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation. *Transportation Research D*, 10(4):169–280, 2005.

B. E. Wyslouzil, K. L. Carleton, D. M. Sonnenfroh, W. T. Rawlins, and S. Arnold. Observation of hydration of single, modified carbon aerosols. *Geophysical Research Letters*, 21(19):2107–2110, September 1994.

C. S. Zerefos, K. Eleftheratos, D. S. Balis, P. Zanis, G. Tselioudis, and C. Meleti. Evidence of impact of aviation on cirrus cloud formation. *Atmospheric Chemistry and Physics*, 3:1633–1644, October 2003a.

C. S. Zerefos, K. Eleftheratos, D. S. Balis, P. Zanis, G. Tselioudis, and C. Meleti. Evidence of impact of aviation on cirrus cloud formation. *Atmospheric Chemistry and Physics Discussions*, 3:3335–3359, June 2003b.

Appendix A

Appendix

A.1 Derivation of the mixing line slope

The slope of the mixing line connecting the states of the engine exhaust and ambient air on a phase diagram for water as shown in figure 2.1 on page 30 is the quotient of the differences in temperature and water partial pressure between the jet efflux and ambient air. With A denoting conditions for the exhaust and B for ambient air, it is

$$\sigma_{A,B} = \frac{p_A - p_B}{T_A - T_B} \tag{A.1}$$

Assuming the heat capacity of the air being constant and neglecting the combustion products, the temperature difference between the air entering the engine T_B and the engine exhaust T_A can be calculated from

$$q_{net}\ m_{fuel}\ (1 - \eta_0) = c_p\ m_{air}\ (T_A - T_B) \tag{A.2}$$

Combining equation A.2 and A.1 yields

$$\sigma_{A,B} = \frac{c_p \; m_{air} \; (p_A - p_B)}{q_{net} \; m_{fuel} \; (1 - \eta_0)} \tag{A.3}$$

The partial pressure of water as part of a gas mixture such as air is defined as

$$p_{water} = (m_{water} \; p_{total})/(m_{air} \; M) \tag{A.4}$$

Combining equation A.3 and A.4 yields

$$\sigma_{A,B} = \frac{c_p \; (m_{water \; A} - m_{water \; B}) \; p_{ambient}}{q_{net} \; m_{fuel} \; (1 - \eta_0) \; M} \tag{A.5}$$

The emissions index for water is defined as the amount of water added to the exhaust gases due to combustion of fossil fuel $EI_{water} = (m_{water,A} - m_{water,B})/m_{fuel}$, resulting in the final form of the mixing line slope

$$\sigma_{A,B} = \frac{c_p \; EI_{water} \; p_{ambient}}{q_{net} \; (1 - \eta_0) \; M} \tag{A.6}$$

A.2 Tools

A description of the tools used during the work programme is provided in the following.

A.2.1 FLOPS

The Flight Optimization System (FLOPS) is a multidisciplinary system consisting of computer programs. It can be used for the conceptual and preliminary design and evaluation of advanced aircraft concepts. The program suite consists of nine primary modules: 1) weights, 2) aerodynamics, 3) engine cycle analysis, 4) propulsion data scaling and interpolation, 5) mission performance, 6) takeoff and landing, 7) noise footprint, 8) cost analysis, and 9) program control.

The weights module uses statistical/empirical equations to predict the weight of each item in a group weight statement. An empirical drag estimation technique [Feagin and Morrison, 1978] is applied to calculate drag polars. The engine cycle analysis module has the capability to internally generate an engine deck consisting of thrust and fuel flow data at a variety of Mach-altitude conditions [Geiselhart, 1994]. The mission performance module uses internally generated weight, aerodynamic, and propulsion system data to calculate block fuel consumption.

A.2.2 ESDU flight performance program

The ESDU Aircraft Performance Program is a suite of programs to predict the performance of an aircraft design for which appropriate aerodynamic and engine data are available. This suite consists of three programs: the Performance program pre-processor, the flight performance program and the interpolation program. Thee suite can be used to predict point and path performance, take-off and landing performance and mission performance. The suite does not include any capability to estimate installed engine data or aerodynamic coefficients. The user can specify input data either as a constant value, a range or list of values, or as tabular data varying with a range of possible variables.

A.2.3 TURBOMATCH

TURBOMATCH, developed by Cranfield University, is a non-linear steady state gas turbine performance simulation software. It has the capability to perform design-point and off-design performance calculations.

A.3 Operational weather analysis data

Global temperature (stash code 16203) and relative humidity with respect to liquid water (stash code 15256) analysis data from the MetOffice unified model of the year 2005 was used throughout the workprogramme. The data was converted from IEEE binary files in MetOffice PP format to MATLAB format, whereas an intermediate step, the conversion from binary PP to NetCDF, was necessary. The data files cover 6 hour intervals and have a horizontal resolution of 432x325 and a vertical resolution of 19 pressure levels.

A.4 Baseline aircraft

Calculations performed during the work programme were all based on a common aircraft specification as given in table A.1. The selected aircraft class represents a modern long haul, mid-size commercial transport aircraft.

true air speed	maximum range	maximum payload
255m/s (= Mach 0.86 at 34,000feet)	8,000nm	250 passengers

Table A.1: Aircraft parameters.

Publications

Journal articles

- F. Noppel and R. Singh. Overview on Contrail and Cirrus Cloud Avoidance Technology. Journal of Aircraft, 44(5):1721-1726, October 2007.

Conference papers

- F. Noppel and R. Singh. Contrail Avoidance Project Summary. SAE Technical Papers 2007-01-3808. AeroTech Congress & Exhibition, Los Angeles, September 2007
- F. Noppel and R. Singh. The avoidance of contrails by advanced technical means. CD proceedings 18th International Symposium on Airbreathing Engines (ISABE), Beijing, September 2007.
- F. Noppel and R. Singh. On the tradeoff between CO_2 and contrails. CD proceedings 18th International Symposium on Airbreathing Engines (ISABE), Beijing, September 2007.
- F. Noppel, R. Singh, and M. Taylor. Contrail and cirrus cloud avoidance. CD Proceedings of the 25th International Congress of the Aeronautical Sciences (ICAS), Hamburg, September 2006.
- F. Noppel, R. Singh, and M. Taylor. Novel engine concept to suppress contrail and cirrus cloud formation. In Proceedings of the International Conference on Transport, Climate and Atmosphere, Oxford, June 2006.

Patents

- F. Noppel, R. Singh, and M. Taylor. Method and apparatus to suppres contrail formation (I). GBP, in press, 2007.
- F. Noppel, R. Singh, and M. Taylor. Method and apparatus to suppres contrail formation (II). GBP, in press, 2007.
- F. Noppel, R. Singh, and M. Taylor. A gas turbine engine. EP1852590, September 2007.

Other related publications

- Invited paper to Whittle 2007 commemorative event

Awards

- Runner-up prize, IMechE Whittle reactionaries prize 2007, Bristol, November 2007.
- Young scientist presentation award, International Conference on Transport, Climate and Atmosphere, Oxford, June 2006.