An Assessment of the Future Climate Impact of Commercial Aviation Activity

"A Scenario-Based Assessment Approach"

Author: Glenn M. van Dekken

Goal of This Thesis:

In the pursuit of assessing the climate impact caused by aviation and studying the impact of both action and inaction through technological, political and operational methods

13 CLIMATE ACTION

Take urgent action to combat climate change and its impacts

TU Delft

An Assessment of the Future Climate Impact of Commercial Aviation Activity

"A Scenario-Based Assessment Approach"

by

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to obtain the degree of Master of Science
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Abstract

Aviation activity results in around 5% of global climate impact, for which both the sources and the manner to improve through technology, operations, and policy need to be better understood. Therefore, a Scenario-based assessment through AirClim is done, assessing future efforts and their support for the Paris Agreement goals. The baseline showed 39% of climate impact resulting from CO_2 emissions, with 61% from NO_x-related effects and contrail-cirrus, resulting in 212.8 millikelvins of induced temperature change. Reduction of 75% climate impact in the year 2100 was possible but only through highly optimistic assumptions. Removing optimistic assumptions climate impact of 104.9 millikelvins is achievable. Comparison to relevant studies shows results to be comparatively high, besides uncertainty in component radiative forcing. More top-down and bottom-up studies must map clear boundaries to be imposed on e.g. airliners, manufacturers, and political bodies, to allow for structural climate impact reduction. Future developments are unlikely to meet Paris Agreement demands if not accompanied by a broader scope than CO_2 emissions.

Acknowledgements; A Special Thanks

I would like to spend a minor part of this thesis relaying my thanks to the people who have allowed me to work on my topic. I am sure it has already been said by many students before me and in a more general sense, the last two years have been relatively strange with the continuously iterating situation regarding the global pandemic. It has caused my thesis duration to be dragged on beyond the time I would have wished, but luckily it all comes to an end. Sadly, this situation has caused the inability to physically meet my supervisor, to which I would like to relay my first gratitude, Dr. Volker Grewer, who has provided me with honest and clear feedback whenever required. I was able to research the climate impact of aviation, through the use of the climate evaluation tool Dr. Grewe has worked on within the DLR. Subsequently, I am thankful to all other people who worked on and with AirClim, because of which the writing of this thesis was possible. My thesis was certainly differing from the general topics I have treated throughout my track, but I am happy to have been allowed to coincide both my interest in aerospace and my great concern towards the current climate crisis. My research was globally oriented in scope and I can not take any credit for putting down most of the words, as research and tools have been greatly provided through the amazing work of so many researchers, who took it upon themselves to study all sorts of facets regarding the more general or aviation-oriented climate problem. The climate crisis is a looming and grand issue, which does not always incite optimism and it takes great courage to continuously work on this often overlooked topic.

I am eventually thankful, although there could certainly be some improvements, for the support received from inter-faculty parties. At the beginning of the COVID-19 pandemic, facilities were poor to say the least, for a university rated as highly as ours, which has caused me and undoubtedly many other students a delay in their studies besides stress. Towards the end of writing my thesis, the FPP department within the faculty was able to provide a good working space for me and my fellow students, which needed the necessary nudging before it received the proper hardware. I am happy to see that as I am leaving, my continued asking has paid off and all students working after me will be able to enjoy the modern hardware and a comfortable working space.

Furthermore, I would like to thank the career and counseling services, specifically Sietske Sibie and Janne de Kan, proving a free initiative to bring together master's students working on their thesis. This helped me to get through some difficult phases and see that sadly many fellow students have problems with their thesis, because of individual reasons but also certainly undeniably structural university-based reasons. The team of psychologists at the TU Delft is professional and way too small with respect to the student overall count. Hiring more psychologists should certainly become a much larger priority, as the competitive manner of interaction and high pace education at this university is at the root of a lot of problems.

Finally, I would like to thank the committee members Prof. A. Gangoli Rao and F. Yin in advance, for taking it upon themselves to review and questioning of my work, which will hopefully allow me to graduate as a master's student from the TU Delft faculty of Aerospace Engineering.

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List of Abbreviations

ASTM: American Society for Testing and Materials

ATAG: Air Transport Action Group

ATC: Air Traffic Control

ATJ: Alchohol-to-Jet

BTS: Bureau of Transportation Statistics

BWB: Blended Wing Body

CCO: Continuous Climb Operations

CDO: Continuous Decent Operations

CEAP: Committee of Aviation Environmental Protection

DSHC: Direct Sugars to Hydrocarbons

EU-ETS: European Emissions Trading Scheme

FT: Fischer-Tropsch

GANP: Global Air Navigation Plan

GDP: Gross Domestic Product

GHG: Green House Gas

GMF: Global Market Forecast

HEFA: Hydroprocessed Esters and Fatty Acids

HTL: Hydrothermal Liquefaction

IATA: International Air Transport Association

IMF: International Monetary Fund

ISO: Intermediate Stop Operations

ITC: Induced Temperature Change

ITCC: International Council on Clean Transportation

LCA: Life Cycle Assessment

LUC: Land Use Change

LUC: Land Use Change

PMO: Primary Mode Ozone

RF: Radiative Forcing

RPK: Revenue Passenger Kilometer

SAF: Sustainable Aviation Fuel

SDGs: Sustainable Development Goals

SIP: Synthetic Iso-paraffinic fuel

SWB: Strut-Braced-Wing

TLR: Technology Readiness Level

UN: United Nations

WtW: Well to Wake, implying from raw resource to the operational use of fuel

I

Part I: Research Questions and Existing Literature

1

Introduction on Aviation & The Global Climate Crisis

1.1. Aviation Emissions and Climate Change

Climate change is a sociopolitical issue that is making its way to the forefront of day to day activities of countries, industries, and companies even forcing itself down onto the individual level through behavioral changes. The high uncertainty ranges regarding this infinitely complex problem have allowed the continued avoidance of taking adequate action. In some spheres, the existence of a human share in climate change is rejected. To understand the problem at hand and congruently the goal of this study, this introduction has been broken down into initially outlining the relationship between climate change and aviation activity. After which it is essential to understand the actions that exist to tackle to problem of aviation-induced climate change and finally this will lead up to the research purpose and thus the question of this thesis.

Climate Change and Aviation Activity; A Difficult Conundrum

In the year 2019 around 4.4 Billion passengers were carried globally [1], which is expected to triple between 2020 and 2050 [Gössling and Humpe, 2020]. When adding the CO_2 and non-CO_2 effects, this makes the aviation sector responsible for around 5% of the anthropogenic warming. Findings from the IPCC show that the change in global surface temperature as an annual average was simulated and observed to have increased to 1.2-1.25^{o}C, displaying an uncertainty of around half a degree [IPCC, 2021]. The temperature change is thus already very close to the international goal of the Paris Agreement aimed at keeping global average temperature increase well below 2.0^{o}C compared to pre-industrial levels, with a striving for 1.5^{o}C. It is uncertain what exactly will occur if the global temperature rises too high, given uncertainty regarding the response caused by feedback loops. The integrity of the Paris Agreement is at risk, not only in terms of the goal but also regarding the context of the agreement; To achieve the goal based on equity, via the use of sustainable development and expansive efforts to eradicate poverty United Nations [2015]. Gössling and Humpe estimated that about the top 10% of emitters account for around 45% of the global CO_2-equivalent emissions, which comprises of both CO_2 as well as other greenhouse gas (GHG) emissions. Contrarily, the bottom 50% of the population only accounts for 13% [Chancel et al., 2015]. Assuming the mentioned 4.4 Billion passengers carried globally, this would represent around 55%[2] of the current population partaking in air traffic. Results from Gössling and Humpe suggest that only 11% of the world population in 2018 traveled by air, with only 4% participating in international air travel. It is important to understand the details of the consumption side of air traffic, or legislation might prove ineffective and polarizing as was seen in the yellow vest protest in 2018.

The sector as whole is estimated to account for 2%[3] of the global CO_2-emissions, constituting around 12% of the total transport sector CO_2 emissions. However, the extreme conditions at which air traffic operates require extra attention due to the emissions occurring at high altitudes (10-12 kilometers). Multiple studies have outlined that besides CO_2 emissions, there are a host of non-CO_2 emissions causing contributing to the

[1] URL: `https://data.worldbank.org/indicator/IS.AIR.PSGR`
[2] World Population; URL: `https://www.worldometers.info/world-population/`
[3] ATAG, URL:`https://www.atag.org/`

aviation climate impact. Potentially significant climate impact comes from net-NO_x-effects such as ozone production, as well as water vapor forming contrails and subsequently contrail-cirrus under the right conditions [Sausen and Schumann, 2000, Sausen et al., 2005, Lee et al., 2009, 2010, 2021]. For example, Dahlmann et al. [2011] found that NO_x-emissions emitted through air traffic caused twice as much ozone production as ground NO_x-emissions. Lack of scientific consensus and provided evidence causes there to yet remain a deficit in climate response confidence [IPCC, 2013]. Contrail-cirrus in high-humidity regions is an example where the confidence is lacking due to insufficient understanding of key processes leading to contrail formation and the interaction between these processes [Lee et al., 2021]. In addition, the complex dynamic pertaining NO_x-emissions and the reactions taking place being dependent on the local concentrations and availability of key species creates a high degree of modeling uncertainty. Therefore the effects of emissions such as NO_x are harder to quantify, causing aspects such as long-lived ozone to have a low confidence level [Dahlmann et al., 2016b]. These uncertainties have to be studied for better or worse to avoid catastrophic and unwanted consequences. The problem of aviation and climate impact meets at a multi-dimensional crossroad, one where economy, psychology, and politics meet one another.

When assessing a broad scope it is easy to forget the individual experience, which is often left outside of scientific assessment but remains relevant. Stoll-Kleemann [2020] outlines that the coping mechanism generally implored is the denial of personal responsibility generally rooted in the maintenance of comfort and learned habits. Especially the psychological and cultural beliefs labeling transport as a norm has provided passengers with a strong tendency to use forms of transportation such as air traffic. These norms are opposed through tools such as shaming, which might serve as a tool to change behavior. There is international support to reduce climate impact as a whole, as seen by agreements such as the Kyoto Protocol and the Paris Agreement and through United Nations outlined Sustainable Development Goals (SDGs) such as goal 13 of 'Climate Action'[4]. Politics, global and local, offer a host of opportunities to change the emission burden of aviation and other industry. Continuous uncertainty causes countries to be at odds with reducing climate impact and maintaining their local, short-term political interests, making large-scale climate action difficult. The general scientific uncertainty of climate change does not reflect positively, causing debate and polarization between different economical and ethical ideologies.

Aviation Emissions and Climate Impact; What can be Controlled?

The interaction between sociopolitical and economic interests is infinitely complex to model. A more simplistic model allows the subdivision under three specific umbrellas. These are the technological sphere, the operational sphere, and the political sphere. The most understandable aspect is that aircraft need fuel to perform flight movements, and this fuel can account for around 17-25% of the overall operational cost [Eurocontrol, 2019]. Not to forget that fuel cost will fluctuate, which might cause a cost increase or reduction for the airliners. Post-COVID-19 the compounded annual rate of fuel efficiency improvement was 1.5%, where the growth in demand was around 4-5% [Melo et al., 2020, Airbus, 2019, Boeing, 2019]. COVID-19 has caused a reduced global passenger flux of 64% [Air Transport Bureau, 2020]. It is uncertain how this recovery will occur, but it might yield some benefits in terms of emission reduction and early retirement[5] of less fuel-efficient aircraft such as the A380s, Boeing 747s & 757s. The Air Transport Bureau also reports a reduction in revenue of around 65% and the International Monetary Fund (IMF) a drop in Gross Domestic Product of 3.5-4.3%. This precarious situation has caused many consumer-dependent businesses to seek state support.

The total outlined anthropogenic warming caused by aviation of around 5% is to be reduced through technology, but more strategies exist. For example the swapping of conventional Jet-A fuel by Sustainable Aviation Fuels (SAFs), optimization of air-traffic management, or simply by reducing air traffic through providing of alternative modes of transport and human psychology [Larsson et al., 2019]. Strategies such as formation flight or climate-optimal routing exist, which could reduce both fuel consumption and effects from non-CO_2-emissions. All options should receive due diligence, such as SAFs for which still uncertainty exists about the availability, competitiveness, performance, and impact. Strategies such as SAFs are current primarily used for small-scale public relations tests [Pechstein et al., 2020]. The 2019 usage was only 0.05% which was short of the 2 million tons 2020 goal [O'Connell et al., 2019]. A multitude of small changes exists such as the upgrading of data structure allowing for more dynamic adjustments within air-traffic management, which is all outlined in the ICAO Global Air Navigation Plan (GANP) [ICAO, 2016b].

[4] SDG Climate Action, URL:`https://sdgs.un.org/goals/goal13`

[5] URL: `https://samchui.com/2020/05/10/covid-19-a-list-of-retired-aircraft/`

Current inconsistent global policy, incomplete understanding of emission impact has allowed the aviation industry to continue to grow unsustainably [Becken and Mackey, 2017]. An attempt at global policy to measure and mitigate aviation emissions is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which provides a temporal framework for making emissions measurable and generating a market surrounding the buying and trading of emissions certificates. Other European policies such as the EU-Emission Trading Scheme (EU-ETS) exist, which enforces the surrender of allowances following emissions and handing out fines when not all emissions are accounted for. These policies can help breach the gap by imposing economic incentives or limiting the freedom of industry. Becken and Mackey [2017], warns that all sectors will eventually have to work towards reducing their GHG emissions, given only then the act of carbon offsetting will be possible. However, carbon offsetting does not remove the emission of CO_2, but only causes the annual rate to remain constant. Through assuming changes in technology, operations, and policy, scenarios have been assembled to assess the impact of these changes.

1.2. Motivation and Filling in the Knowledge Gap

There is a need for models that make aviation-induced climate impact more comprehensible to scientists and politicians alike. Climate change is non-linear and displays inertia to change due to the long lifetime of species, creating a problem that is inherently different from most more linear life processes. Critical climate evaluation tools such as AirClim exist, through the use of which one can shed light on the future through the act of building scenarios [Grewe and Stenke, 2008, Dahlmann et al., 2016a]. The AirClim is used to look at climate performance through near-surface temperature change, providing insight into climate impact for a specific scenario. Through scenario building in AirClim, the effect of emissions such as CO_2, NO_x, H_2O & subsequent contrail-cirrus formation can be visualized. The NO_x climate impact is contracted into net-NO_x-effects caused by short-term ozone increase, long-term ozone decrease, and temperature change induced by CH_4 reduction. This thesis aims to generate scenarios in the time-frame 1940-2100, looking into the potential impact of technology, operations, and politics. Which is achieved through both qualitative and quantitive assessment. Furthermore, it serves as a critical assessment of aspects such as the implication of SAFs. Transport & Environment [2020] suggests that mandating biofuels could have adverse consequences related to underestimate impacts such as land use change (LUC). LUC is the act of changing the land use purpose, which could have adverse results for local or global carbon stock. The act of changing land can be accompanied by deforestation, biodiversity loss, reduced carbon-sequencing potential, and food competition [Wicke et al., 2012].

Besides studying potential SAF uncertainty, the potential downsides of passivity are part of this analysis. Furthermore, the attainability of goals is questioned, besides simply understanding what actions could yield results if they were to be implemented. The COVID-19 pandemic has provided a non-regular scenario from which the impact can be studied in some more detail. The aim is to forgo an exploratory attempt to visualize the potential future scenarios and how to get there. Questioning how necessity lines up with the ambitions from industry experts and shareholders (IATA, ICAO, EU). Furthermore, the building of scenarios allows for better identification of uncertainties, and understanding of all needed components. The gap to be filled is a more general one, of how to make sense of something of such complexity and also convey this complexity in a manner that allows for understanding. Statistics based on historical trends dictate the decision space, and for a good reason. This is similarly a large limitation, especially in this field where statistics and certainty is lacking or do not exist. This is an attempt to combine and compile a more global analysis of aviation and air traffic induced climate impact.

1.3. Research Problem and Questions

Models exist which represent the contribution of aviation in the current day and what the effect is of both CO_2 and non-CO_2 emissions [Sausen and Schumann, 2000, Sausen et al., 2005, Lee et al., 2021, 2010, Intergovernmental Panel on Climate Change, 2014]. Many of these models focus more on one aspect such as implementing intermediate stop operations, formation flight or eco-friendly flying such as flying lower and/or slower [Linke et al., 2017, Linke, 2018, Dahlmann et al., 2020, Niklaß et al., 2018]. Politically and psychologically oriented studies are done on the psychological fallacies and miss-information, implementation of ticket taxes shifting demand, assigning of personal carbon allowances and general consensus and support or climate policy in aviation [Larsson et al., 2019, Scheelhaase et al., 2018, Peeters et al., 2016, Mayor and Tol, 2007, European Federation for Transport and Environment, 2019]. These are too numerous to include all-together and assess at large, yet prominent strategies and/or concepts are identified and translated into usable analysis tools. This thesis aims to provide a scenario-based assessment of the most prominent ideas and their effect, each represented in their respective scenario or a combination of concepts. Outputs from AirClim are used with the option of applying potential post-processing to the results when required. A large portion and important part will be to establish sensitivities of the primary input data as well as for the external modules which will manipulate data either in a qualitative or quantitative fashion.

Through the studying of road maps that are indicative of a supposed future, a framework was generated to understand future developmental options. The literature review, modeling methodology, and model verification will be an integral part of the prior steps to answer the primary research question:

Are the anticipated developments in the aviation sector in support of the goals agreed upon in the Paris Agreement, assessing performance through a scenario-based approach and the climate evaluation tool AirClim?

This abstract aims to return to the real world and combine the hypothetical to the actual goals set by international agreements. Initially, a baseline scenario was formulated to which other scenarios can be intercompared and then be related to the goals set in the Paris Agreement. The questions posed below should assist in answering the primary question.

- What is the current consensus of the near-surface temperature change induced by aviation activity?
- What are the direct and indirect strategies through which aviation can reduce its temperature change impact?
- What parameters need to be modeled to arrive at a holistic definition of primary modeling inputs for AirClim?
- What are the sensitivities of respectively modeled parameters and their output through the use of the climate evaluation tool AirClim?

2

Understanding Aviation Climate Impact and Potential Mitigation Strategies

The literature study serves as a knowledge base of this thesis. It is important to understand concepts and the general picture which lead to the modeling and reasoning. The review will be broken down into several sections, covering the current state of aviation emissions and knowledge, followed by the discussion of the three spheres discussed with a special short dedication to the complex topic of sustainable aviation fuels.

2.1. The Climate Impact of Aviation; Relevant Emissions & Consumers

Aviation has a disproportional impact on the warming climate, with it being a transportation service for the wealthier part of the population and the conditions of flight being very different from other modes of transport. The discussion and policies often discuss emissions too simplistically, primarily focusing on the CO_2-emissions. This does not cover the full climate impact, given that non-CO_2 emissions also contribute significantly. Non-CO_2 climate comprises of NO_x, Soot, and H_2O vapor, which through concentration-dependent microphysics evolve into their climate impact. Adding the aviation CO_2 and non-CO_2 effects together adds up to about 5% of the overall global anthropogenic warming [Lee et al., 2021]. Only 2.4% of this warming is estimated to be caused by CO_2 emissions, underlining that non-CO_2 emissions still play a large role. The radiative forcing (RF) caused by non-CO_2 emissions is still subject to a high degree of uncertainty. Figure 2.1 shows that contrails in high-humidity regions, NO_x-induced ozone, and methane display a large 9-95% confidence interval. Implying that the RF can be over or under-estimated, which then subsequently changes the induced temperature response as one can integrate the radiative forcing to arrive at the temperature change.

The impact of CO_2 emissions and the manner in which these express a climate impact do not require added explanation. However, contrail formation and the impact of NO_x emissions is less trivial and require further elaboration. Contrail formation is a process that depends on several parameters such as the humidity and temperature of the engine exhaust air, and the ambient air (at flight altitude). In the case of aviation, the exhaust plume is humid and hot and the ambient air is dry and cold. The mixing of warm exhaust gases and cold surrounding ambient air reduces the temperature and humidity of the volume of mixed air, causing the air to get saturated. Saturation occurs when there is an equilibrium between water vapor and liquid water (at a specific temperature). Contrails only form under these conditions, which is also referred to as the Schmidt-Appleman criterion [Appleman, 1953]. The number of crystals formed has been shown to be highly dependent on the concentration and size of particles. This influences the manner in which the contrail ice particles evolve into contrail-cirrus [Wong and Miake-Lye, 2010].

NO_x in and of itself has a negligible impact since it is only a small concentration but NO_x is very significant for ozone production and methane depletion. These are both greenhouse gases that are much more potent than the often discussed CO_2. The reaction in which the availability of NO_x set into motion is complex, occurs on different time scales, and is highly dependent upon local concentrations of reactive other species. In short, the depletion and production rates of methane and ozone respectively are dependent on the background concentration of NO_x (NO and NO_2), and HO_x (OH and HO_2). This is graphically represented in Figure 2.2 indicating the required and produced species within this cycle. The climate impact of the NO_x induced

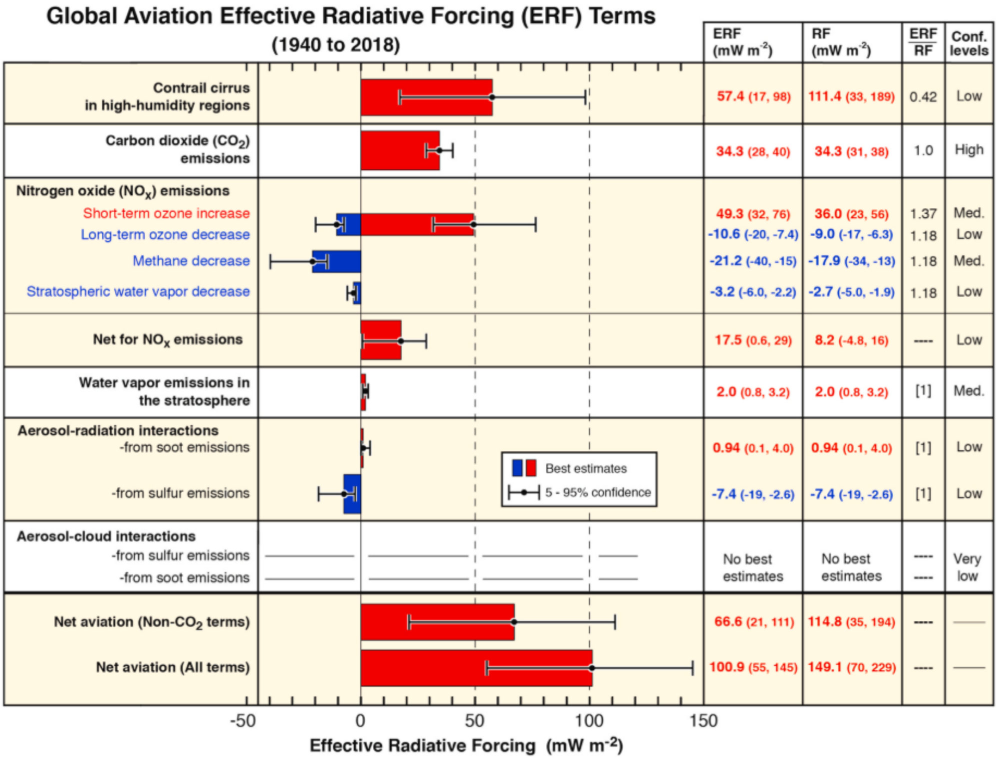

Figure 2.1: Global aviation induced Effective Radiative Forcing in units of mW/m^2 between the year 1940 up to 2018. Representing a variety of species that contributing to the net aviation radiative forcing along with the 5-95% confidence interval, confidence level, effective radiative forcing versus radiativ forcing ratio, and the confidence level of the studied mechanism Lee et al. [2021]

ozone production is then primarily dependent on the ozone lifetime, which can differ but is generally in the order of weeks. Furthermore, the figure also allows us to understand that as methane is a prerequisite for the production of ozone, depletion of methane shifts the cycle balance. This reduction of ozone production due to the linkage with methane has a long lifetime and is called the primary mode ozone (PMO) [Koch, 2015].

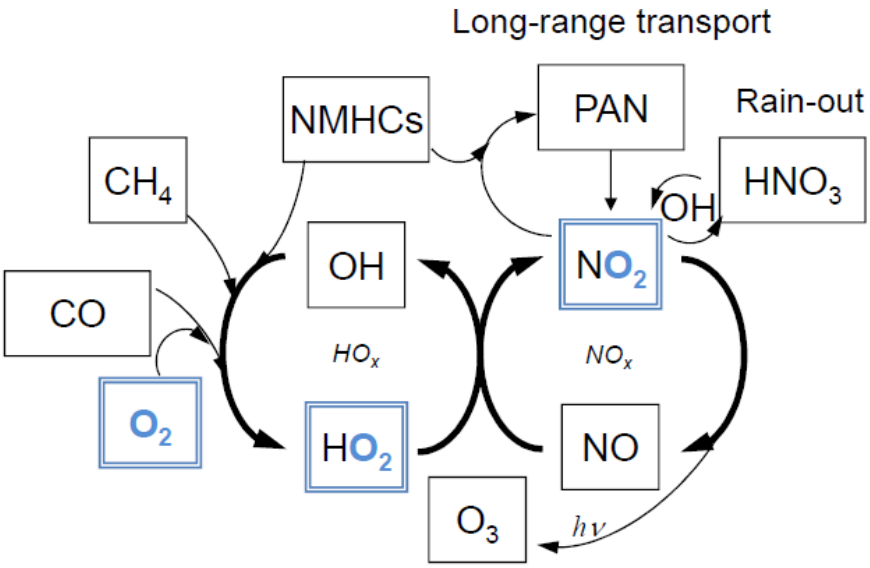

Figure 2.2: The methane (CH_4) depletion and ozone (O_3) production cycle, where throughout the cycle molecular species are indicated to be produced, depleted or to be in a form of equilibrium within the cycle. Displaying the importance of available concentrations of NO_x emissions in the form of NO_2 and NO as well as HO_x species for the production of ozone (right-bottom), which subsequently reduces the methane (left-top) which is an input to the cycle. NMHC's are non-methane hydrocarbons and PAN refers to peroxyactyl nitrate, which do not require further reference for this work [Betz et al., 2009]

Growth in demand is currently much higher than the compounded improvement rate of fuel consumption of 1.5%, this due to long aircraft lifetimes of 20-30 years [Jiang, 2013]. This will cause the fuel consumption to keep on increasing at a rapid rate [Melo et al., 2020]. Growth trends remain uncertain as COVID-19 has shown, besides the fact that human psychology might also play also shift attitude to flight in the light of the impact through emotions such as shaming [Stoll-Kleemann, 2020]. Finally, from a study by Gössling and Humpe [2020] some general statistics were outlined with respect to air travel, outlining the contribution of specific passengers and potentially justifying political measures in the future. It was estimated that in 2018 only 11% of the population had flown, out of which only 4% traveled internationally. Also, the top 10% of the world's most wealthy accounted for around 45% of the total CO_2-equivalent emissions. The bottom 50% of the population is a mere 13%. The top 10% of the frequent flyers account for 40% of all flights, causing around 55% of the estimated energy use and emissions for the commercial air transport category. This translates to the fact that the top 1% of the world population causes half the emissions from global air travel. These figures are relevant to underline potential strategies when imposing taxation schemes, that the dominant share of emissions comes from consumers repeatedly using the service.

2.1.1. Fuel Efficiency of Current Airlines; Understanding Fuel Consumption

The act of consuming fuel and the manner of emission are essential components to understand. Therefore, this section looks into several studies regarding fuel consumption. The fuel burn is a function of the flight movements and the efficiency in which these are performed. The efficiency is a result of the technology, the aircraft operation, and policies dictating flight movements. The International Council on Clean Transportation (ITCC) has performed fuel efficiency assessments for the U.S. airlines for domestic transport, as well as transatlantic operations. These studies contain and provide insight into the whole efficiency of the combined system, outlining the amount of fuel needed for the generation of an RPK [Irene Kwan and Rutherford, 2014, Kwan and Rutherford, 2015, Graver et al., 2018].

Airlines operating towards, from, or within the U.S. have to report operational data to the Bureau of Transportation Statistics (BTS). This operational data is stored and made available with the T-100 database, which was the source of the ITCC studies. The database contains information on the origin, destination, freight, distance, aircraft type, available seats, and passenger load factor. For both the domestic and transatlantic analysis 20 high capacity airlines were used to represent a large market share. Primary assumptions were that the payload includes the belly freight, which does increase the fuel burn but enhances the fuel efficiency of the aircraft due to it being closer to maximum payload capabilities. Thus the RPK is not defined within the strict sense it generally is since cargo weight is treated as a paying customer. Figure 2.3 represents a difference in fuel efficiency metric of 63% between Norwegian and British Airways for which the leading causes were both the fuel burn and seating density. British Airways uses the A380-800 and Boeing 747-400, both being quad engine heavy aircraft with a fuel efficiency of about 27-30 RPK/L. Norwegian on the other hand uses the Boeing 787-8 with a fuel efficiency of around 40 RPK/L. Airliners often have a diverse aircraft portfolio such as Turkish Airlines, KLM, and Air France. Resulting in higher performance than the industry average fuel economy of 34 RPK per liter of fuel used utilizing 2017 data. Individual performance of aircraft was underlined in the ITCC study, shown in Figure A.1 for further reference. It is shown that the Boeing 747-400 performs well below industry average and the A350-900 well above it.

Results from the transatlantic nonstop operations resulted in a fuel economy of 34 RPK/L (43 RPK/kg assuming Jet A1 conversion through the density that 1 liter represents 0.79 kilograms of fuel). The conversion to RPK/kg is relevant for later purposes, as this metric will be used. Furthermore, results for domestic flights within the U.S. show growth of fuel economy to around 57 RPMs per gallon (30.6 RPK/kg), which is significantly lower than the transatlantic fuel economy already indicating a difference between domestic and international flight routes Zheng et al. [2019]. Also, a study on airliners operating between the U.S. and Latin America found results similar to the transatlantic performance, with an industry average of 37 RPK/L (47 RPK/kg) Xinyi Sola Zheng and and Rutherford [2019]. Finally, transpacific routes had an average fuel efficiency of 31 RPK/L (39.2 RPK/kg) [Graver and Rutherford, 2016]. Cultural and geographical differences are at the root of these differences through aspects such as premium seat density, transported cargo volume, and fleet age to only name a few. The concept of fuel economy is one which shall be returned to later during the modeling setup and has therefore been shortly summarized in this section. It is also important that the reader understands the differentiation which can already exist between airliners and what lies at the locus of such differences. The total performance then becomes a function of aspects such as seating density, load factor, on-board freight, and the fuel needed, which is a better measure than solely the fuel consumption.

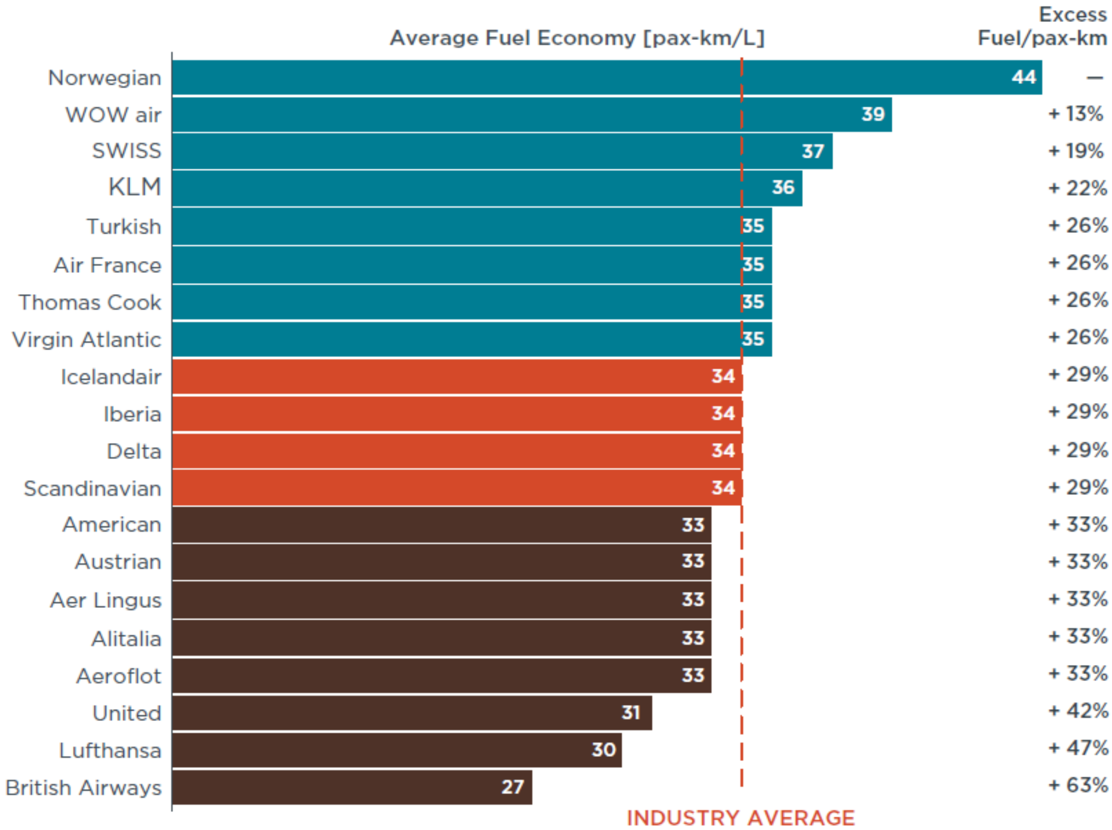

Figure 2.3: Average Fuel Economy in RPK/L generated from studying 20 airliners for transatlantic operations for the year 2017, representing an industry average of 34 RPK/L and inter comparison between the top performer Norwegian and other airliners. Division is shown between airliner performing above industry average (blue), at industry average (orange), and below industry average (brown) Graver et al. [2018]

2.2. The Operational Sphere and Climate Impact

Fuel consumption is besides being a function of the technology, dependent on the interaction between the technology and the world in terms of legislation and how airliners use their vehicles. For the studies of aircraft operations and developments, the ICAO Global Air Navigator Plan (GANP) was used as a framework [ICAO, 2016a]. Conceptualization of improving aircraft operations is available, but the question remains as to what these will amount to in terms of fuel consumption. The GANP generates an industry-oriented summary and guideline for improvements but does not mention novel strategies, which will also be part of the discussion. Brain and Bastin [2019] estimated that several options from the GANP would amount to around 60% of to be achieved savings, under which: Continuous Descent and Climb Operations (CCO & CDO), Space-based ADS-B surveillance, and Trajectory-Based Operations. Other things like Air Traffic Flow Management, Performance Based Navigation, and Runway Sequencing are assumed to have less impact. For aspects such as CCO & CDO, a tangible fuel saving can be estimated, but for ADS-B, Trajectory-Based Operations, and Performance-Based Navigation this is not easily done. Being aware of the implications of these technologies is still essential as they could justify qualitative assumptions and allow for the implementation of operational practices such as formation flight, climate-optimal routing, and intermediate stop operations (ISO).

2.2.1. Current Knowledge on Wake Energy Retrieval; Formation Flight

Wake energy retrieval (formation flight), is a concept where the wake from a leading object can be retrieved by a trailing object. Formation flight is often seen in birds when traveling over long distances, where they group themselves in a V-shape of varying sizes. In an aircraft context, the vortices leaving the wing can be used and with the correct position, the up-wash can lower energy requirements for the trailing object. The concept was already tested in 1984 on the Do 228 aircraft using the Prandtl lifting line theory [Hummel and Beukenberg, 1990]. Figure 2.4 provides a graphical representation of formation flight, in which also the two important aspects can already be seen regarding the formation efficiency: trailing distance and lateral distance of the formation.

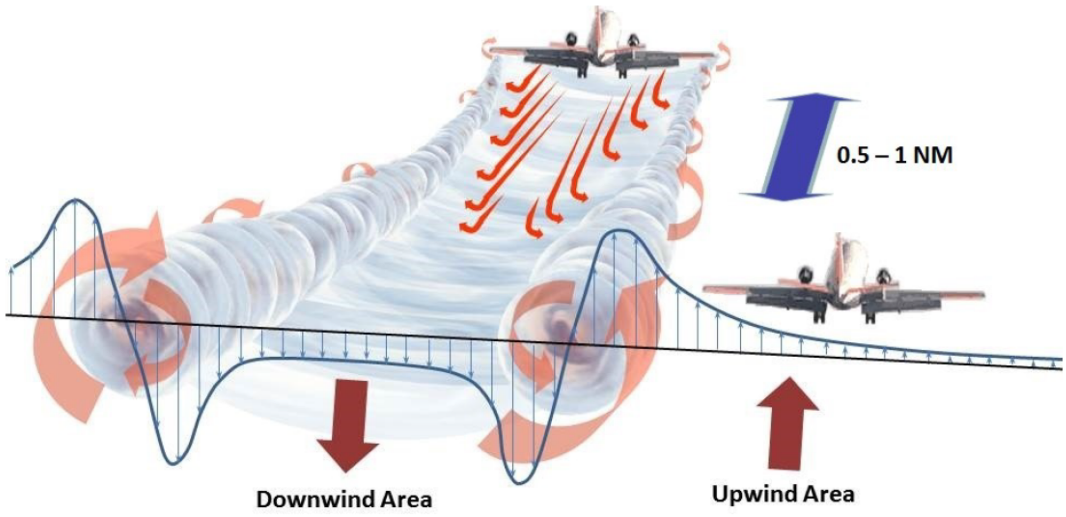

Figure 2.4: Schematic of the underlying concepts of formation flight, indicating an upwind and downwind region with their respective force-fields, as well as a horizontal spacing between the leading and trailing aircraft. Displaying the importance of a longitudinal and lateral position of the participating aircraft [Koloschin and Fezans, 2020].

The efficiency of formation flight is also dependent on aircraft size, which was apparent from studies where the formation existed out of a F/A-18 jet and a DC-8 military transport. Around 29% fuel burn reduction was measured, where commercial savings are estimated to be more in the order of 5-10% fuel savings [Nangia et al., 2020]. Appendix A Table A.1 contains relevant data on formation flight tests. It was found that fighter jets or combined formations with fighter jets allow for much higher fuel savings. This could be related to less stringent rules regarding object proximity. Besides the question of the amount of fuel savings, the question of passenger comfort being affected by noise and vibrations remains. Simulations of fuel savings of formation flight were done by Unterstrasser and Stephan [2020], which found estimates of 10% fuel saving for all participating aircraft. Several studies are in agreement on the large induced drag reductions ranging from 25-39%, causing a reduced fuel flow ranging from 8-18% Kent and Richards [2020]. If formation flights will be performed is still questionable though Airbus UpNext's Chief Executive Officer Sandra Bour Schaeffer anticipates formation flights could be used routinely from 2025 for commercial oceanic flights [Aviation Week Intelligence Network, 2019]. Unterstrasser [2020] states that despite obvious challenges, formation flight still yields positive output and would require less technological complexities to be realized as compared to hardware or aircraft concept changes. Likewise, it is stressed that there are serious re-routing penalties which will have to be out-weighted by formation flight fuel savings. Problems may present themselves if the network of participatory parties is not large enough, making it hard to form optimal formations with minimal rerouting cost.

The Impact of Formation Flight Induced Contrail-Mixing

Formation flight does not only yield a potential positive outlook regarding the fuel consumption but also regarding other atmospheric processes as a result of wake-mixing [Unterstrasser and Stephan, 2020, Dahlmann et al., 2020, Unterstrasser, 2020]. Unterstrasser [2020] found through performing high-resolution simulations with the LES model EULAG-LCM, that both the time-integrated ice mass and the total extinction are reduced in formation flight. The total extinction is a function of the optical thickness across the formed contrail. Through formation flight, the time-integrated total extinction and ice mass were reduced by 20-50% and 30-60% respectively. This implies that when contrails form they have less of an impact, which is thus caused by the mixing of contrails during formation flight. The baseline was the total ice mass and total extinction of two aircraft generating two separate contrails forming at different times. This reduction can be explained by the fact that emissions are mixed, which leads to saturation effects. These saturation effects impact both the formation of contrails and the impact of NO_x emissions. It was already mentioned in section 2.1 that NO_x emissions participate in the cycle for ozone production and subsequent methane depletion. It was found that a doubling of local NO_x emissions as done with formation flight, leads to a net-ozone production which is relatively lower compared to regular operations [Dahlmann et al., 2020]. Thus, NO_x saturation effects caused by contrail mixing reduced the ozone production compared to observing two separate flights. Overall on average 5% fuel could be saved, and the NO_x-emissions induced impact could be reduced by 11%. The average near-surface temperature change could be reduced by 24% for the total formation. In later work, Dahlmann et al. [2020] prescribed a reduction of 48% of the RF of contrail-cirrus resulting from contrail-mixing. Formation flight could thus besides generally reducing the fuel consumption, also have relevant other impacts.

2.2.2. Climate Impact Reduction Potential Following Altitude Changes

Currently, aviation is optimized for time and fuel consumption, with aircraft operation at higher altitudes resulting in lower fuel consumption and lower flight times. Grewe et al. [2017] states that only optimizing for fuel consumption might yield a higher climate impact given the non-CO_2-effects out-weight the CO_2 savings. Avoiding climate-sensitive regions could be achieved through flying climate-optimal routes. The climate impact of NO_x is not uniform and non-singular, many aspects such as the altitude, geospatial location, background concentration of relevant species, and time of the day play a role in the total climate impact. Contrail-induced cloudiness may cause warming and cooling depending on location and time of day. Implementing climate-optimal routing through AirClim is beyond the scope of this thesis, therefore values from literature are presented, which can be used later on. It is expected that climate-optimal routing could reduce the climate impact by 10% and up to around 15%. This would be at a 1% cost increase and a little more when reducing the climate impact by 15%. A market-based mechanism (MBM) should be established including relevant emissions, changing the sole optimization of fuel consumption. Generating incentives for airliners and manufacturers to re-design aircraft to accommodate climate-optimal flights, comes primarily down to the penalties and rewards awarded for behavior. If policy focus remains primarily on CO_2, adverse design choices might cause a reduction in fuel consumption but an increase NO_x emissions. For example, increasing the overall pressure ratio and allowing for an increasing high-pressure turbine entry temperature [Kyprianidis and Dahlquist, 2017].

Dahlmann et al. [2016b] studied how climate impact could be reduced with keeping both the price of sustainability and the environment in mind. Changes in cruise altitude and cruise velocity were of primary interest. This assessment focussed on the A330-200 fleet in 2006 and a hypothetical redesigned fleet that could operate better within the new altitude and velocity regime. A reduction of the temperature response by 42% could be accomplished, which would increase the cost by 10%. A redesigned fleet could reduce the fuel burn by 11%, the temperature response by 32%, with a cost increase of 4-5%. The redesigned fleet could have an 11% reduced fuel burn and a 32% reduced temperature response at a 4-5% increase in the operating cost. Matthes et al. [2021] also studied flying both lower and higher by 2000 feet (600 meters) from standard flight level. They found that for flying lower, the CO_2 emissions increased due to increased drag. However, the overall RF reduces due to changes in the RF of the non-CO_2 emissions and indirect net-NO_x-effects. The aviation-induced temperature change could be reduced by 20% through lower flight. Flying higher results in an increased total temperature change by around 10%, regardless of the fuel consumption reduction. The results are outlined in Table 2.1, which are to be used later on. Flying lower will be a component of climate-optimal routing but is only to be considered an integral part of it.

	NO_x **Ozone**	NO_x **PMO**	NO_x **Methane**	**Direct** H_2O	**Contrail Cirrus**	**Aerosol Indirect Warm Cloud**
				ΔRF [W/m^2]		
LOW	-6.7%	-3.6%	-1.4%	-26.7%	-11.1%	-47.9%
HIGH	8.2%	0.0%	14.3%	33.3%	6.7%	2.7%

Table 2.1: Percentage difference caused by cruise altitude changes of the radiative forcing in units W/m^2, caused by NO_x, H_2O, contrail cirrus and aerosol indirect warm cloud compared to the baseline cruise altitude. Simulation results show a reduced radiative forcing for the 600 meters lower flight (LOW) and an increased radiative forcing for the 600 meters higher flight (HIGH) [Matthes et al., 2021]

2.2.3. Fueling Strategy: Intermediate Stop Operations & Fuel Tankering

Fuel is a large part of airline operations and can run up 17-25% of operating expenses. Therefore, fuel consumption is an important parameter to optimize both in terms of technology and but also the economy. Sometimes the economy of chosen climate impact, in cases where the action of fuel tankering is performed by airliners. Where airliners take more than required fuel along, since tanking on the destination airport would be more expensive, thus decreasing the flight fuel efficiency due to heavier flight. In the ECAC area, 16.5% of flights perform full fuel tankering and 4.5% perform partial tankering. This results in an estimated

286,000 tonnes of extra fuel burnt per year, which amounts to 0.54% of the total ECAC jet fuel used and 901,000 tonnes CO_2 [Tabernier et al., 2021, Eurocontrol, 2019]. Proper political measures have to be implemented to reduce the likeliness of such behavior.

A more positive manner that involves tanking strategy would be intermediate stop operations (ISO), which is a strategy that would reduce the amount of needed fuel since the aircraft will stop more often. Implementing ISO generates questions such as the number of overlays possible, static or dynamic determination of overlay airports, suitable aircraft types, and passenger comfort due to time loss. The general concept is that ISO allows the aircraft to fly lighter, thus lowering the required thrust [Swaid et al., 2018]. Performing ISO would increase the amount of take-off and landings, causing more near-surface emissions in the form of Hydrocarbons (HC) and Carbon-monoxide (CO). Estimated from Linke et al. [2017] point to the fact that doubling the landings and take-offs could increase the CO and HC emissions by 33-34%. Fuel consumption could be up to 15% lower depending on the mission but due to relocation of non-CO_2 emissions an increase in average temperature response (ATR) over 100 years of 2.3% was found. Resulting primarily from increased radiative forcing through ozone production and contrail-formation. This increase was caused by the optimization method, which optimized flight altitude for aircraft weight, ultimately causing a higher flight level. Other studies such asGreen [2005] estimate up to 10% system-wide fuel savings for optimized short-range aircraft, whereas Langhans et al. [2013] estimated up to 9% fuel savings with a focus on real locations serviced by the Boeing 777 and the A330. Poll [2011] estimates a lower range from 1% up to 7% fuel savings, based on a simplified model which does not assume route optimizations. ISO will require proper assessment of the retrofitting and/or redesign of aircraft and their possibility to allow for optimal fuel savings and potentially utilizing lower flight as outlined in the previous section. Further in-depth assessment of this strategy is outside the scope of this work, thus primary implementation will be through assuming general reductions caused by the strategy.

2.3. The Technological Sphere and Climate Impact

Improvement in technology is the primary manner to reduce fuel consumption, furthermore, technological decisions could e.g. focus on lowering the NO_x-emissions to change the proportionality of the emission spectrum. Technology could be subdivided into two categories: revolutionary and evolutionary improvements as they are called in the IATA road-map to 2050 document [International Air Transport Association (IATA), 2019]. The roadmap provides a summary of all prominent and known technologies and also provides future scenarios which could occur. AerSale [2019] expects that from 2019 onwards around 45% of in-service aircraft will be replaced, which might be increased now with the additional early retirement of older or fuel in-efficient aircraft. New aircraft models such as the Boeing 787 and the A350 can yield fuel savings in the range of 20-25% compared to their predecessors [Kaltschmitt, 2018], so possibly there will be a higher annual increase soon resulting from these developments. Instead of completely new aircraft one can also apply retrofits, allowing for improvements during the aircraft's lifetime. Retrofits can differ from minor savings such as electric taxiing causing around 3% fuel savings, or a new engine which can go up to 25% savings relative to predecessors. Although individual percentages are too precise for the later models, it is important to understand what categories yield what savings. Different retrofits and their Technology Readiness Level (TLR), along with the expected fuel savings, can be found in Appendix A Table A.2.

Besides retrofitting and sticking with known aircraft concepts, more novel concepts exist. Such as the Blended-Wing-Body (BWB) and the Strut-Braced-Wing (SBW). The SBW concept is essentially a high wing configuration with a strut supporting the high wing, something often seen on single-piston recreational aircraft such as the Cessna models. These struts provide load alleviation, therefore reducing the required material for the wing. This then allows for a reduced wing circumference which reduces the parasitic drag, allowing for lower speed angles and thus more natural flow even allowing potentially natural laminar flow. Due to reduced weight, the engine can be lighter beside the high wing configuration allowing for ultra-high-bypass engines. Combining the reduced drag, weight, better aerodynamics, and potential for a high-bypass engine, can result in substantial fuel savings [Gundlach IV et al., 2000]. Bradley and Droney [2012], Bradley et al. [2015], Bradley [2017] have identified several promising concepts under the Boeing and NASA partnership project called SUGAR, of which some could enter into service around 2030-2040. A breakdown of these concepts is shown in Appendix A Table A.3. A host of SUGAR configurations exist, ranging from using next-generation gas turbine engines to concepts including electric and hybrid-electric propulsion. Estimates range from 40-90% of fuel savings, with the latter being for hybrid electric configurations. The SBW might allow for smooth implementation into the current infrastructure compared to BWB, the infrastructural difficulty of the implementation is not something at the forefront of the studies but should be in the awareness of the reader.

The BWB utilizes the fact that the current tube-and-wing design does not utilize the whole body efficiently to generate lift. Using a more integrated architecture of body and wings the aerodynamics could be significantly improved. It is estimated that over 2015 aircraft models a 27% fuel burn reduction could be possible [Road, 2015]. Other simulations by NASA estimate a range of 45-50% compared to the Boeing 777-200 with GE90 engines [Nickol and Haller, 2016]. A breakdown of the currently more known studies/projects is given in Appendix A Table A.4. Both the SBW and BWB which are currently only assessed for their benefits and the potential of their existence, besides technology many other dimensions such as maintenance, crew, passenger comfort, and flight speed will be part of the feasibility discussion of these concepts.

2.3.1. The IATA Road-Map to 2050 Scenarios

In the previous section, a general overview was provided of the technologies and/or concepts that could improve upon the current increase in fuel consumption. Since these were specific measures and the approach of this thesis is more global and top-down, the primary interest in the IATA report lies in the synthesized scenarios displayed in it. The IATA presents on the basis of their analysis 5 scenarios including a baseline, minor technological changes, major changes through new concepts, and a scenario including electrification. These will be summarized below for later use.

Technology Scenario 1 (T1): Fixed Aircraft Programs
This scenario is taken as a baseline or reference scenario, where only imminent aircraft are taken into account. For example introduction of the Boeing 777X-8/9 wide-body aircraft, which is supposed to yield around 20% improved fuel usage compared to the 777-200LR/777-200ER. With an EIS of 2023 and 2020 respectively, however the EIS of 2020 has already been pushed to 2023[1] which can already put some of these assumptions for the reference into question. So T1 will only allow N+1 (2020-2025) imminent aircraft EIS for analysis and is a hypothetical reference.

Technology Scenario 2 (T2): Conservative Assessment
The T2 scenario does not assume only N+1 roll-out of aircraft projects, yet it assumes limited developments as it only allows for the tube and wing design with e.g. turbofan engines. Therefore no radically new concepts or new forms of propulsion are assumed for this assessment, nevertheless, continuous fuel efficiency improvements will still be achieved at a similar pace as current improvements.

Technology Scenario 3 (T3): Introduction of New Configurations
T3 will allow the introduction of new configurations, such as the BWB and SBW. The newer configurations are expected to arrive during the N+2 and N+3 period (2025-2035 & 2035+). During the N+2 period smaller BWB are assumed and/or SBW aircraft for the smaller seat capacity around 101-150 and 151-210. Seat capacity of 500+ will be taken up by a large BWB introduction into the fleet.

Technology Scenario 4 (T4): Electrification of Aircraft
T4 is similar to T3, however more substantial savings are obtained in T4 due to the assumption of introducing hybrid-electric and fully-electric propulsion. Refer to Table A.4 and Table A.3 for some of these concepts. Electric options are only considered for the seat ranges up to 150 passengers, above which similar savings as T2 and T3 are assumed. The T4 scenario is described to be in analogy with the current state of the automotive industry. This scenario has a sub-division into T4a and T4b:

- **T4a:** is a medium optimistic description inspired by the Zunum Aero forecast, which allows the assumption that hybrid-electric propulsion is available for the N+2 generation in the 51-100 seat range.
- **T4b:** is a very optimistic pathway, where the Wright Electric's forecast is followed of 100% CO_2 reduction for the 51-100 and 101-150 seat range. This is achieved through fully electric propulsion from renewable sources.

2.4. The Political Sphere and Climate Impact

This section aims to summarize both imminent, already implemented as well as novel ideas of political interference which have been considered or could potentially be considered for application in the aviation sector. First, a summary will be presented providing a revision of the relevant policies. Then a general discussion is provided concerning novel policy concepts.

[1] Fourth-Quarter Results; URL:https://boeing.mediaroom.com/news-releases-statements?item=130819

2.4.1. The Current Political Landscape Regarding Aviation

Global policies which are followed by everyone and cover every required basis are impossible. Within this thesis and thus the building of scenarios, it is important to understand the current goals and aims are from political debate. Within the scope of climate change two directives, the Kyoto Protocol [United Nations, 1998] and the more recent Paris Agreement were essential milestones United Nations [2015]. It was pledged to keep the global average temperature increase compared to pre-industrial levels well below 2.0^{o}C, striving for 1.5^{o}C with the recognition that this would reduce the risk of climate change impact to a significant degree. This framework allows for only 200-350 GtCO_2 to be emitted by all of the activity measured from 2016 CAN & ICSA [2018].

In the light of the Paris Agreement, the ICAO was tasked with devising methodologies to measure and control the emissions from aviation. This resulted in the Carbon Offsetting Scheme for International Aviation (CORSIA), which will cover international flight movements and include a Market Based Measure (MBM). The MBM will allow the continued growth of the sector in the spirit of carbon neutrality. CORSIA started in 2020-2021 and consists of three respective phases: the pilot phase (2021-2023), Phase 1 (2024-2026), and phase 2 (2027-2035). As the phases progress voluntary participation will turn into mandatory participation, excluding small emitters, new airliners, and humanitarian aid. As the scheme progresses, the required offsetting will be computed on the basis of airliner size and aviation sector growth, where the individual contribution will become a more prominent component over time.

In the European Union (EU), a scheme already exists which is called the EU-Emission Trading Scheme (EU-ETS) [European Parliament, 2008, European Parliament and the Council of the European Union, 2009], which was meant to cover intra- and extra-EU flights, but was limited to intra-EU under international pressure. Where CORSIA is an MBM and can accommodate a growing sector, the EU-ETS is a cap-and-trade mechanism. This implies that certificates for emissions are limited, have to be traded, and are handed out under conditions by the respective organizations. The inclusion of non-CO_2-impacts from aviation have not yet been included [Scheelhaase, 2019]. Both the EU-ETS and CORSIA have as a primary focus the CO_2 emissions, with CORSIA not applying to domestic flights and only covering so-called CORSIA routes of international participatory countries. Fahey and Lee [2016] approximate that the impact resulting from non-CO_2 emissions of the 2005 global fleet was 3.2% and only 1.7% was derived from CO_2 emissions. It is important to note that offsetting schemes are not a final solution, notes Becken and Mackey [2017]. It does not stop CO_2 and other emissions from entering the atmosphere but reduces the annual increase of the emission through the purchase of certificates which then redirect funding to net-negative producers of CO_2. Offsetting is not sustainable, as the CO_2 in the atmosphere still grows. Besides the risk existing that not enough industries will be incentives to move to net-negative CO_2 emissions themselves.

2.4.2. Novel and Mainstream Ideas on Aviation Taxation

Ticket prices can increase through several pathways, such as more expensive fuel due to economic fluctuations, but also due to the attempt to tax products/services to account for the externalities. In a general sense, a tax is lifted on a product to re-circulate capital to upkeep the infrastructure which allowed the production, transport, and delivery of a product or service. Of course, the tax is lifted on the use of infrastructure which is not owned or built by the company in question. The primary component for aviation here is aviation fuel, which has remained exempt under Article 24 of the Chicago Convention and has been left in place because fuel costs are a large part of the cost.

All sorts of strategies have been studied either academically or in practice. Faber and Huigen [2018] studied the exemptions from Value-Added-Tax for aviation, which was found to be varying in manner and success. Ticket taxes could also yield adverse results if implemented in a way where far destinations might become more appealing since the price is already high, causing the undertaking of highly polluting travels [Mayor and Tol, 2007]. A study commissioned by the European Commission (EC) performed on 24 Member States estimated that an increase in ticket price by 10%, could yield a demand reduction of around 9-11% in most countries [European Federation for Transport and Environment, 2019]. Falk and Hagsten [2019] found that introduction of flight tax in Austria and Germany, which are wealthy countries with dense road and highway infrastructure, the initial reduction of demand is high which quickly reduces the next year from 9% reduced flights to 5% reduced flights. Hubs that did not serve predominantly low-cost airliners did not see any change, supporting that a small tax only hits the low-earners and not the group constituting the majority of flights.

Furthermore, more radical measures exist which might not have the preference when observing the aviation sector as a growing body. In a report for the Committee on Climate Change by Carmichael [2019], examples such as frequent flyer- and air miles levies are named. Highlighting that 15% of the UK population is responsible for 70% of the flights. One could signal the undesired behavior of frequent flights without taking away the option of an annual holiday. Also, Carmichael states that there should be a ban on frequent flyer reward schemes which stimulate demand. Another measure could be the implementation of the personal carbon allowance, or the right to fly. This is likely to be seen as a highly undesirable scheme, which is predominantly discussed in academic circles and was assessed in 2006-2008 UK government studies. The personal carbon allowance is an egalitarian concept, where people would obtain tradable CO_2-permits, much like the EU-ETS concept of cap and trade. Allowing the less wealthy people who do not fly, to gain a surplus by selling permits [Paterson and Stripple, 2010]. Personal carbon allowances are hypothesized to be an encapsulating approach as it combines economic, psychological, and social aspects. Combining these could allow for behavioral changes more easily than taxation. [Parag and Fawcett, 2014]. Interactive studies have shown that working with allowances prompts another manner of decision-making, causing carbon budgeting [Capstick and Lewis, 2010]. Jagers et al. [2010] found that the Swedish public responded favorably when observing personal attitudes to personal carbon allowances and carbon taxes, looking at the attitude, trust in politicians, fairness, and ideology. Carbon taxation was found to be more favored, as the personal carbon allowance would require habit changes. Of course, questionnaires and interactive programs can only lead to implications and human behavior is different in those tests than in reality. There are still many concerns regarding exemptions, the number of certificates, thus making it not a concept that can be implemented in a short time-span [Bertoldi, 2019]. Knowledge of some more novel concepts allows for a compilation of several options besides the more general schemes of CORSIA and the EU-ETS. Qualitative testing can be done on the demand-cost relation through some more general assumptions.

2.5. Sustainable Aviation Fuels & Their Potential Impact

The question of Sustainable Aviation Fuel (SAF) has two very prominent dimensions. The need for obtaining a new source of fuel given the pollution and depletion of conventional fuel, and the SAF performance in terms of emission compared to conventional fuels. However, incentivizing the usage of SAFs will increase demand, when not done properly this could lead to undesirable market effects. For example, the EU New Green Deal will likely aim for 2% SAF in 2025, 5% in 2030, and 63% in 2050[2]; Up-scaling of land use for different biomass production, might cause displacement and cause deforestation of lands rich in carbon stock. Furthermore, the feedstock growth and supply might shift to non-signatory countries, causing carbon leakage [Lambin and Meyfroidt, 2011]. Assume a farmer changing grown crop due to higher pay-out, a shift from feedstock 'A' to feedstock 'B'. This does not imply that the demand for feedstock 'A' has suddenly reduced, although due to lower availability the price may increase and this may indirectly reduce the demand for a product. This implies that generally, the consequence would be that feedstock 'A' will be grown elsewhere and import/export balances change. Thus displacing feedstock cultivation and thereby causing indirect land use change (LUC). Carbon leakage can be minimized through directives such as the RED II, which disallows SAFs to count if obtained from primary lands such as tropical forests. Regardless, obtaining an exact quantification of the footprint of specific fuels is complex. Subsequently making it harder for politicians, countries, and international bodies to fully legally shield the process. De Jong et al. [2017], states that previous studies display a large variety in results, which is primarily due to methodological choices, such as accounting of co-products. Also, more elementary unknown factors such as total yield, yield improvement, world population, and consumption are similarly uncertain.

Conventional and renewable fuel pathways differ slightly as indicated by Figure 2.5. Besides the similarities, renewable fuels require the cultivation of feedstock, and this feedstock has to be converted into RJF, which stands for rocket jet fuel. There are various processing methods and since the requirements for aviation fuels are high, as they have to deal with large temperature variations and with extreme height, there are several approved SAF processing technologies by the American Society for Testing and Materials (ASTM). The ASTM is the authority in this field and has as of now approved five different pathways: Hydroprocessed Esters and Fatty Acids (HEFA) , Fischer-Tropsch (FT) , Hydrothermal Liquefaction (HTL) , Alcohol-to-Jet (ATJ) and Direct Sugars to Hydrocarbons or Synthetic Iso-paraffinic fuel (DSHC & SIP) .

These are the pathways that are also assumed to be viable for consideration in the supplementary CORSIA

[2] Reuters, URL: `https://www.reuters.com/business/aerospace-defense/eu-climate-blueprint-pressures-airlines-cut-emissions-20`

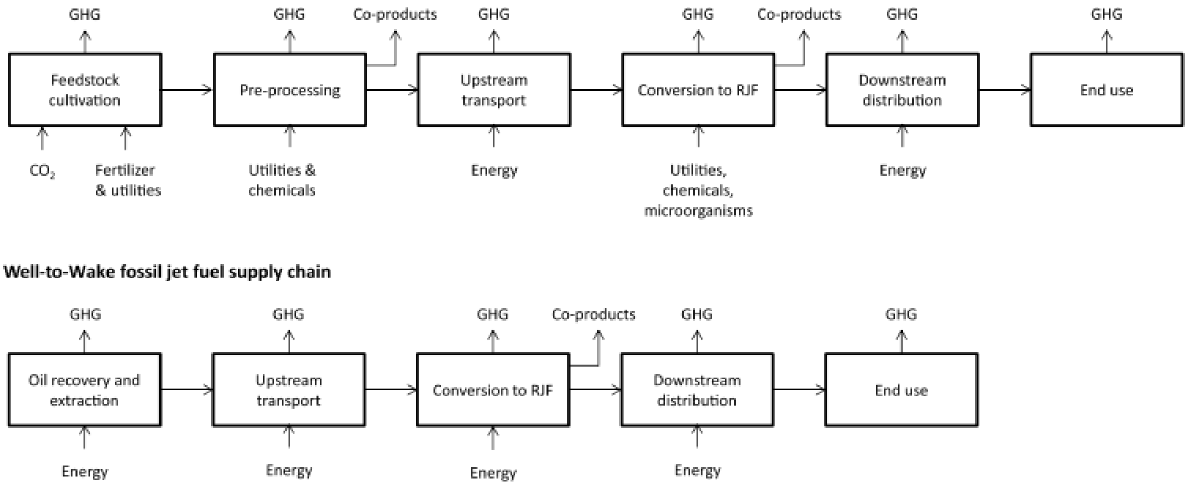

Figure 2.5: Life cycle analysis from a well to wake perspective for both conventional (bottom) and any type of sustainable feedstock (top), showing the inputs flowing into each processes, and the products flowing out of each process from acquiring the resource to final usage [De Jong et al., 2017]

document, which will be treated shortly [United Nations, 2021]. Lange [2011], makes an attempt at quantifying the LUC induced on specific types of land through inventories of carbon stock and finds working the majority of land would be counterproductive. Assuming a fossil fuel baseline of 83.8 gCO_{2e}/MJ, only several combinations of land, feedstock, and spatial location would yield a low enough LUC to make SAF production sustainable. The option of feedstock on degraded land seems desirable and positive, however, degraded land will likely present lower yields and the investment for making the land productive might be more substantial. This outlines both the production volume and accounting problem of SAFs evidently, which will require further investigations in the future.

2.5.1. CORSIA Supporting Document LUC LCA Methodology

The CORSIA supplementary document describes the eligible fuels and the life cycle assessment (LCA) methodology [United Nations, 2021]. Part I of this document provides a methodology for the computation of core life cycle GHG emissions for several established SAFs. Where part III looks a the ILUC which has been included following the obligation to understand the extent to which SAFs can reduce the GHG emissions under the proposed MBM. The Committee of Aviation Environmental Protection (CEAP) agreed to include ILUC as an addition to the core-LUC, which can then be compared to the baselines of 89 gCO_2e/MJ for conventional jet fuel. As the CEAP acknowledges large uncertainty, two established models were used in parallel: GTAP-BIO and GLOBIOM.

The study covers 17 pathways for land-based feedstock over specific regions such as the USA, Brazil, the EU, and Malaysia & Indonesia, which are primary production points for SAF feedstock. Only pathways which would yield iLUC were included in this analysis, excluding pathways such as forestry residues, used cooking oil, etc. The LUC spans the cultivation, production region, conversion technology, and SAF production region. The findings from this study are summarized in Table **??**, which is the forecasted figures for the year 2035.

As can be seen, the 'other SAF' and 'other region' contributions amount to two-thirds of the total projected market share in 2035. Here for the 'other SAF' segment WtW value, the average of the other 16 pathways was used. The document states that the other SAF should consist of low iLUC risk pathways which were not included in the analysis. There could be a future scenario where the fuel required can not be provided or is provided from pathways that are not sustainable. The GTAP-BIO and GLOBIOM models are not perfect and can have under or overestimated LUC impacts. The last two columns are included for comparison, including results from De Jong et al. [2017] of some similar feedstock pathways assuming two manners of co-product accounting. They are included to show that the accounting method of co-products can yield substantial differences and that the LUC estimations for specific feedstock and pathways vary widely. Outlining the importance of global studies on the topic regarding the 'what if' either SAF performs well, or poorly compared to the estimations.

Feedstock and Processing Method	Core LCA	Estimated iLUC	Well to Wake	Market Share 2035	De Jong et al. Energy	De Jong et al. Displ.
	gCO2e/MJ	gCO2e/MJ	gCO2e/MJ	%	gCO2e/MJ	gCO2e/MJ
Corn (ATJ)	55.8	23.60	79.40	4.00%	54	71
SugarCane (ATJ)	24	8.00	32.00	4.00%	31	31
Sugarcane (SIP)	32.8	11.30	44.10	4.00%	76	79
Sugar Beet (SIP)	20.2	32.40	52.60	3.00%	-	-
Soy Oil (HEFA)	40.4	25.59	65.99	3.90%	-	-
Rapeseed (HEFA)	47.4	24.10	71.50	2.50%	-	-
Palm Oil Closed pond (HEFA)	37.4	39.10	76.500	1.00%	-	-
Palm Oil Open pond (HEFA)	60	39.10	99.100	1.00%	-	-
Miscanthus (FT)	9.35	-28.26	-18.91	2.35%	-	-
Miscanthus (ATJ)	9.35	-44.27	-34.92	2.35%	-	-
Switchgrass (FT)	10.4	-3.80	6.60	1.35%	-	-
Switchgrass (ATJ)	10.4	-14.50	-4.10	1.35%	-	-
Poplar (FT)	8.3	-5.20	3.10	2.70%	10	-6
Other SAF	-	-	38.11	33.20%	-	-
Other Regions	-	-	-	33.30%	-	-
Total				100%		

Table 2.2: CORSIA supporting document averaged GTAP-BIO and GLOBIUM values for core life cycle analysis, indirect land use change estimations and total land use change estimations; Where applicable results from full LCAs from De Jong et al. [2017] are presented to outline the agreement or large variation observed in results.

3

AirClim: An Efficiency Tool for Climate Evaluation

AirClim is an efficiency tool for climate evaluation, which allows the testing of scenarios by assessing the near-surface temperature change [Grewe and Stenke, 2008, Dahlmann et al., 2016b]. It is an extension to the earlier linear response model by Sausen and Schumann [2000]. This extension includes the linearization of the relation between emissions of CO_2, NO_x and H_2O. Furthermore, the impact of atmospheric composition for CO_2, O_3, CH_4, water vapor, and contrails is included. AirClim accounts for spatial emissions by using three-dimensional emission data, allowing assessment of the temporal evolution of air traffic and the conversion of temporal data into near-surface temperature change. More detail on AirClim is provided in section 3.1 and further discussion on the three-dimensional emission inventory in section 3.2.

3.1. The General Outline of AirClim; Inputs and Outputs

The general outline of the climate evaluation tool AirClim will be discussed, for further reference on the model Grewe and Stenke [2008], Dahlmann et al. [2016b] can be consulted. It is essential to understand the boundary conditions for modeling a scenario in AirClim, besides the underlying scientific background and the model verification done in the past.

Figure 3.1 shows the general overview of the modeled approach implemented. The modeling approach can thus be divided into three segments: pre-calculated processes, emission data, and the model AirClim which to get the mean near-surface temperature change. The pre-calculated processes are the rose-colored boxes, which deal with the idealized assumptions regarding emission regions based on aircraft activity and respective emissions strength. Here the strength signifies the mixing ratio per unit of time, which influences the potency of atmospheric chemistry. These boundary conditions are inputs for the climate chemistry model E39/C and E39 respectively, to compute the stratospheric adjusted radiative forcing for ozone and water vapor changes. Climate sensitivities are taken into account for CO_2, CH_4, O_3, contrails, and H_2O through the application of an uncertainty range. Then the yellow boxes outline the purpose of the eventual use of AirClim; The application of perturbations to input data, and the assessment of the climate impact of these perturbations on the defined baseline case. The emission perturbation data consists of the spatial emissions in terms of a 3-D emission distribution, besides a definition of the temporal emissions for an amount of 'N' differing scenarios. Further aspects of the temporal evolution can be defined, such as the normalization year of the 3-D emission inventory and characteristics of the NO_x emissions. Then, the blue processes indicate calculations performed while running AirClim with respective inputs, using both the input data and the pre-calculated idealizations regarding emissions regimes, strength, and radiative forcing. Then the change in emissions and the change in atmospheric composition are combined to evaluate the temporal evolution of the composition perturbation. Combining this with radiative forcing idealization for the assessed species to find an evolution of the overall radiative forcing, which can then be integrated to arrive at a near-surface temperature change.

AirClim has been compared to other climate models and shows a good agreement, e.g. with the results from the complex model E39/CA for the TRADEOFF scenarios. In these scenarios, flight altitudes were shifted up and down with the global mean RF difference compared to AirClim being less than 3%. Compared to

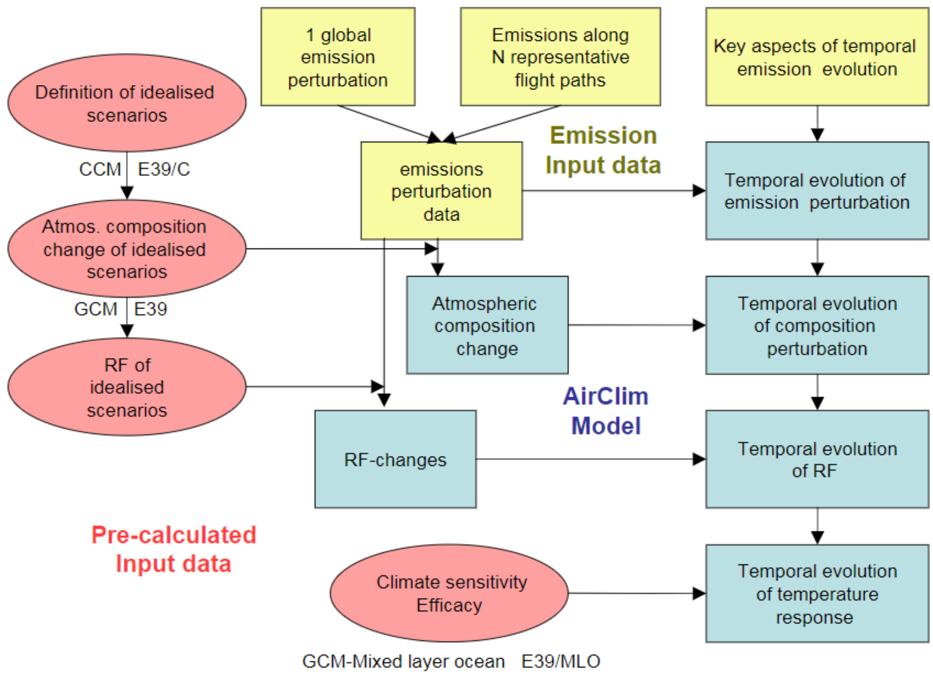

Figure 3.1: General overview of the multi-step approach towards the computation of near-surface temperature change and ozone depletion caused by the emissions from input scenarios. Yellow processes represent the functional chain, rose the pre-calculated atmospheric data and blue processes indicate the stepts towards mean near-surface temperature change Grewe and Stenke [2008]

the E39/CA model, the RF of both ozone and methane were 33% and 31% higher, which could be caused by lower spatial resolution or non-linearities. Also, dissimilarities existed between contrail-cirrus RF compared to studies by Burkhardt and Kärcher [2011], where the coverage was similar though the RF was 9% lower. AirClim accounts for latitude dependencies related to contrail coverage, but not for the latitude dependencies related to the RF of contrail coverage. The model thus does not show a departure from other available models but is still subject to earlier uncertainties regarding the complexity of atmospheric chemistry, the lack of knowledge, and the lack of adequate data to describe the exact atmospheric concentration distribution at a high resolution. The uncertainty is also a function of the used three-dimensional emission inventories, which is turned to next.

3.2. Thee Dimensional Emission Inventories

There are several projects/studies which have synthesized three-dimensional emission inventories. Some are based upon somewhat older studies and thus data, such as the TRADEOFF/QUANITFY (2000) and the NASA (1992) data-set. More recent emission data sets are the AERO2K with data from 2002 and REACT4C. REACT4C[1] is based on the CAEP/8 data for the base year of 2006. These two inventories are of explicit interest given they will be used and compared as inputs for running AirClim. The AERO2K data were collected over six weeks, measured in sets of a single week each to account better for daily, weekly and seasonal differences in North America and Europe. Data for the rest of the world was extracted from another database (Back Aviation) and might therefore not have the same accuracy and averaging of different effects [Michot et al.]. The Back Aviation did not include trajectory data, whereas the REACT4C inventory was focused specifically on route changes and has a higher resolution in this respect. Likewise, the REACT4C approach is not based on only data from a specific year and uses data from five winters and three summers between 1989 and 2010 to assess the long term. Thus, where AERO2K has analyzed six different weeks, the data is still limited to the measurement year. The REACT4C inventory attempts to pattern long periods and uses this on the 2006 CAEP/8 data. Therefore, the AERO2K inventory might be highly sensitive to the year of data collection and thus yield more year-biased results compared to REACT4C. Besides this, the CAEP movement data likely spans multiple continents given it is a subsidiary of the ICAO, which covers all international flight movements of signatory

[1] REACT4C, URL: `https://cordis.europa.eu/project/id/233772/reporting`

countries.

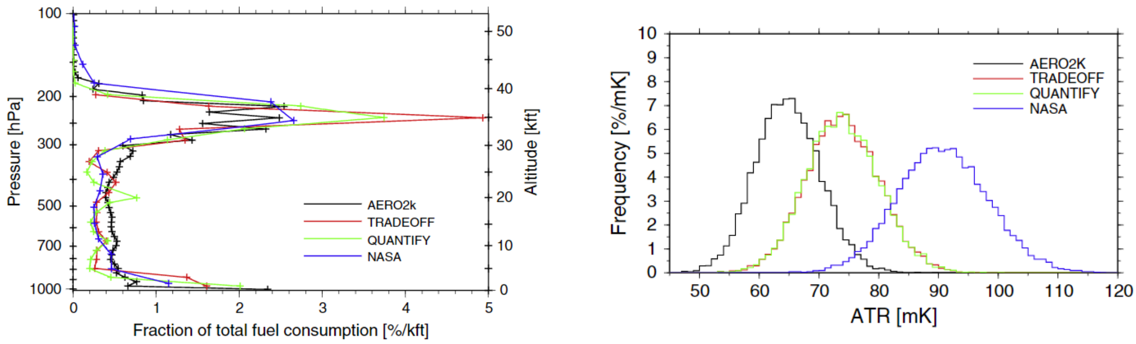

Figure 3.2: The fraction of total fuel consumption in %/kft versus the altitude/pressure in hPa per defined 3-D emissions inventory (left) and the ATR_{100} frequency density function in mK versus the frequency of the ATR_{100} per mK vertically (right). Showing the AERO2K, TRADEOFF, QUANTIFY and NASA three-dimensional emission inventories and differences induced due to differences in emission inventory structure when modeling the same scenario [Dahlmann et al., 2016b]

The REACT4C inventory is like the Quantify & TRADEOFF inventories in comparing fuel consumption fraction per altitude. The AERO2K, TRADEOFF, QUANTIFY and NASA emissions inventories are plotted in Figure 3.2 displaying the fuel consumption fractions versus altitude, and the ATR_{100} frequency density function calculated in Dahlmann et al. [2016b]. The AERO2K inventory has an overall larger proportion of fuel consumption in the lower segment of the atmosphere below the 300 hPa. Above the 300 hPa, the AERO2K inventory fuel consumption concentration behaves in a zig-zag manner, similar to the QUANTIFY and TRADEOFF inventories. Both display a sharp spike in fuel consumption around the pressure of 240 hPa (35 kft). It can also be observed that the integrated quantity of fuel consumption at higher altitudes is higher for the TRADEOFF and QUANTIFY inventories, between the 300-200 hPa. When running a specific scenario using the different inventories, the frequency density function of that ATR_{100} shows a significantly higher ATR for the NASA inventory, and a mean difference of around 10-20 mK between the TRADEOFF/QUANTIFY compared to the AERO2K. The observed difference can be used to perform a consistency check when comparing the AERO2K to the REACT4C inventory. There must be efforts to generate higher resolution emission inventories, which allow comparison to the performance of lower resolution inventories to observe the potential differences. Also, the emission data should become of a higher resolution as the measurement equipment continuously improves with improvements such as space-based ADS-B.

II

Part II: Climate Impact Modeling Approach & Model Response Assessment

4

Aviation Climate Impact Modeling Methodology & Baseline Establishment

This chapter covers the methodology for building the baseline scenario for the scenario-based assessment, which is done through initially understanding the scientific consensus is surrounding scenario building. Then this chapter aims to outline the modules used to manipulate the baseline scenario with the respective synthesis method and implications. chapter 5 will cover a numeric assessment through the application of AirClim using the methodology outlined below.

4.1. The Scenario Based Assessment Concept

It is essential to understand the meaning of a scenario, and how it helps answer the questions at hand. A scenario-based assessment is a tool to understand the future through what is known, used to prove a point or to change general thinking. Wright et al. [2013] breaks these three primary objectives down into enhancing understanding, challenging conventional thinking, and improving decision making.

Scenarios combined or derived with adequate mathematical tools allow a researcher to search for casual relations. Depending on the subject matter and the framework, there could always be a distinction between what is likely and what is unlikely, but one should always consider the relation to the current reality. An especially relevant theme for climate science-related studies is to explain the hypothetical future in the short- and long-term. Scenario assessments allow for a re-framing and can shift perspective by asking the 'what if' questions. There can be several manners in which to perform a scenario-based assessment, under which exploratory versus normative, and quantitative versus qualitative. Exploratory scenarios are scenarios that allow adventurous forecasting, which might be based on ambitious goals or qualitatively assesses a concept. Normative scenarios are inverted, where parameters are determined to fit the desired scenario outcome. Another important distinction is the model being derived from trends, a model derived from computational data or based upon a narrative that does not have sufficient or any measurable content. This is quantitative versus a qualitative scenario respectively [Peeters, 2017].

This thesis and the scenarios presented serve a multitude of purposes. Through the help of AirClim and the concept of scenario building, the climate impact of aviation activity can be better understood. Synthesized scenarios will relate to existing literature and political pledges, and where possible results can be related to previously done studies. The choice has been made to create a data tool that can accommodate a wide range of scenarios, both qualitative and quantitative options. The variety of assessed scenarios could allow more insight into seldom studied ideas or highlight specific topics for further research.

Through the generation of several scenarios with each distinctive focus, patterns can be identified to reduce the climate impact most effectively. Based on that which was previously outlined in chapter 2, a non-exhaustive list of to-be-tested scenarios can be found in Figure 4.1, where all the yellow-colored scenarios are aspects that are covered, to what extent will be outlined later. The grey boxes indicate specific topics which are known topics but will not be subject to further studies.

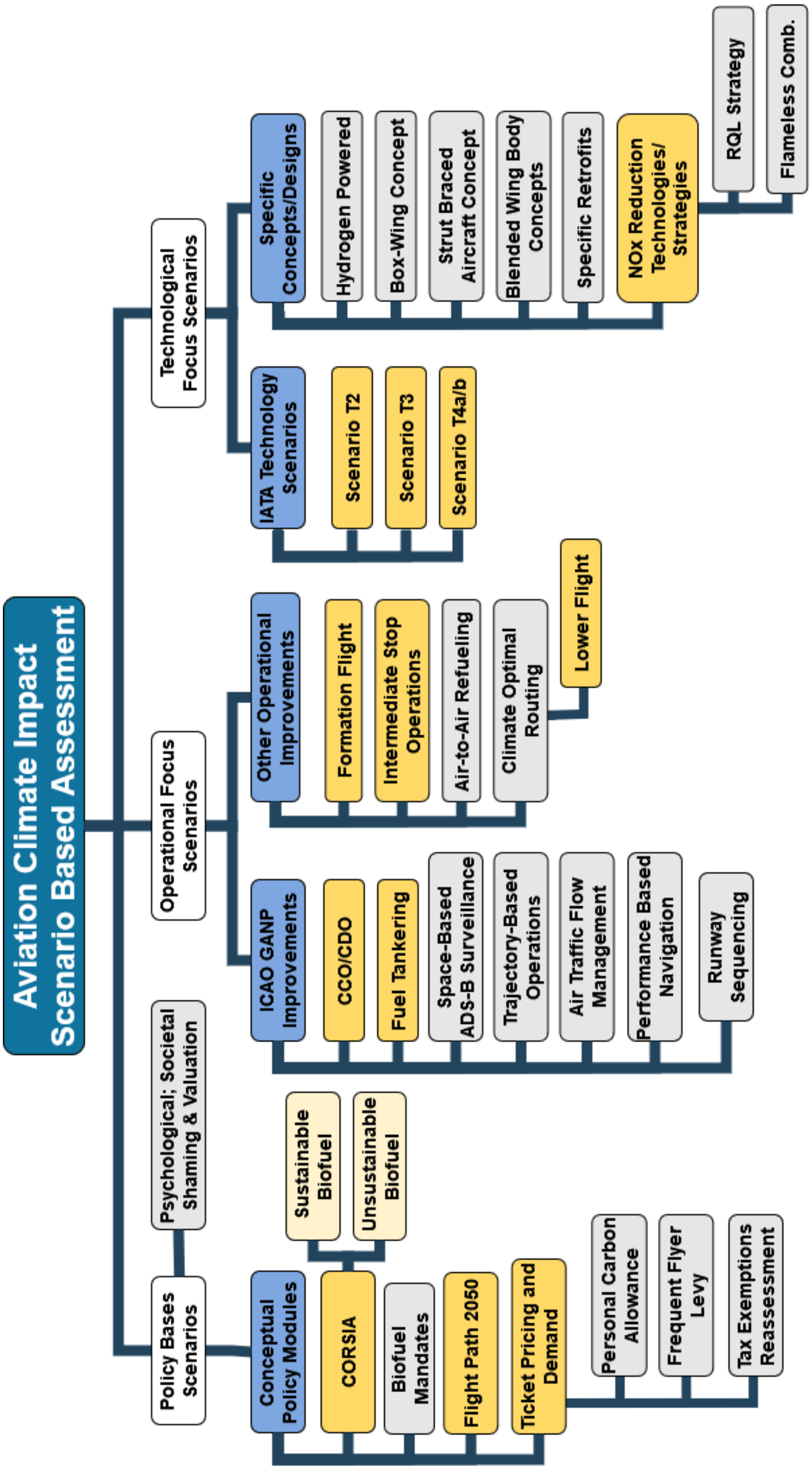

Figure 4.1: Breakdown representing a breakdown of relevant concepts to look at for later scenario based assessment, not representing an exhaustive list of the theme. The breakdown is subdivided in several categories (white), which are subsequently subdivided in deemed relevant sub-categories (blue). Finally, these sub-categories contain concepts which will be studied through the scenario based assessment (yellow) and those which are not treated further (grey)

4.1.1. A Top-Down Approach to Generating Input Data

The baseline scenario will be synthesized through a top-down approach, thus assuming that the evolution of one variable is indicative and linked through assumptions to other variables. A general understanding of the aviation sector's temporal evolution in terms of relevant parameters had to be generated. The best available and indicative parameter is the revenue passenger kilometers (RPKs), which are recorded by both the ICAO and IATA. Furthermore, RPK forecasts exist from relevant companies such as Boeing and Airbus on the temporal evolution. The RPK indicates the number of revenue-paying passengers multiplied by the flown distances, which can then be linked to efficiency parameters to calculate other relevant parameters. The general top-down structure synthesized for this thesis is outlined in Figure 4.2. The process is broken down into three groups, the primary input data, the pre-processing, and the post-processing steps. This chapter will deal with all the required knowledge for the primary input data, where the 'Process' boxes indicate the data synthesize path, the model setup input is indicated on the left, and the model variables, which can be user-selected, flow into the process from the right. The model variables which can be iterated to generate scenarios and their impact will be assessed in chapter 5.

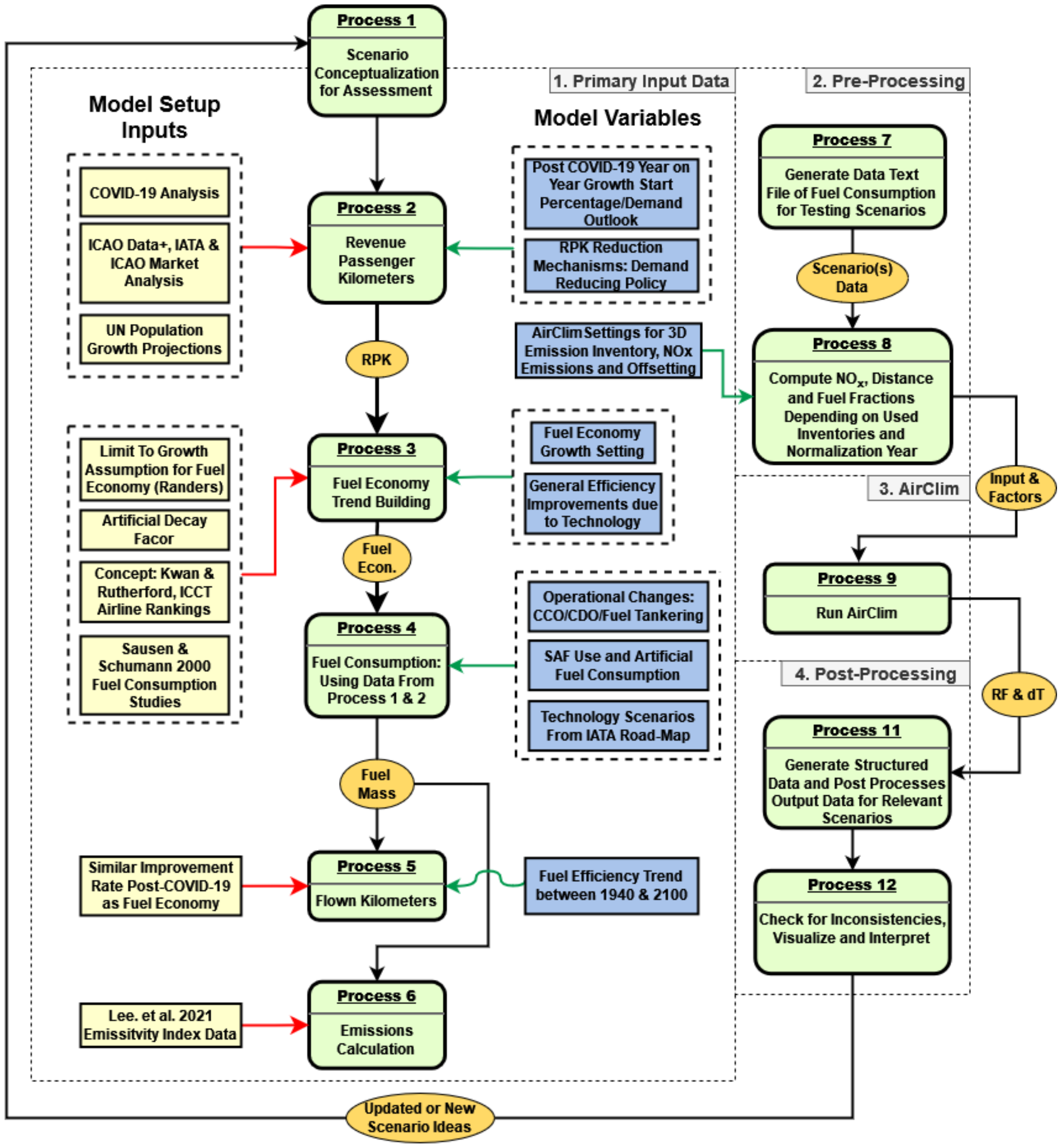

Figure 4.2: The process flow overview of the complete procedure of the scenario based assessment including the four steps: primary input data generation, pre-processing for use in AirClim, the running of AirClim and the final post-processing steps to allow for the final output data. The data flow is indicated by the green process boxes with relevant parameters named along the flow. The primary input data contains both description of parameters needed to build the model (model setup inputs) and parameters which could be changed (model variables)

Initially, the RPK baseline is established through the ICAO data, adding data from additional sources where needed. For modeling the RPK temporal growth, the UN population growth projections were the template.

The data set generations for the RPKs do not contain any special events besides the COVID-19 pandemic and its recovery. Thus no political intervention, abrupt changes in technology, or anything deviating from the current business as usual. The RPK trend is then used to find the total fuel consumption through using the fuel economy parameter. The fuel consumption can be converted to flown kilometers through the fuel efficiency and the nominal global emissions through the emissivity index of respective species from Lee et al. [2021]. Eventually, the essential inputs for AirClim are the fuel consumption, the flown kilometers in the normalization year, the NO_x emissions in the normalization year, and variables such as carbon offsetting and the EI_{NO_x} trend. This process is then used to generate the baseline, which can be iterated upon to arrive at different scenarios. All these variables named will be treated in chronological order below.

4.2. Primary Input Data & The Baseline Scenario

The baseline scenario is the reference point for the climate impact of aviation and model adjustment. Model adjustment implies that whenever there is a change to represent an alternate scenario, a comparison can be made to the baseline scenario. The baseline scenario can be seen as a business as usual scenario, meaning a world with air traffic from available data until the end of the time frame at 2100, which will not be subject to much change. Nonetheless, efficiency improvements through retrofitting and newer aircraft types do still occur. The baseline represents a future where there is no extensive effort or failed effort to change the impact of aviation on the climate. Given the increased strive for political climate action, this is unlikely, but it is always good to keep in mind what the worse case could be. This method thus allows for the inter-comparison between baseline and baseline iterations.

4.2.1. Story-Line for the Baseline Scenario Formation

For the baseline, it has been decided that even though global climate policy will be implemented to some degree, the baseline will assume no policy measures driving down the demand or emissions being offset. There is still improvement in the efficiency though this will stagnate over time. The COVID-19 recovery pattern could have a significant influence on the future climate impact of aviation. Since the recovery was still happening when this was written, an assumption had to fill in the recovery gap. The baseline takes a U-shape/Nike-woosh recovery shape of around five years, and this will remain unchanged for all following scenarios, only allowing change post-pandemic recovery. The baseline scenario is essentially assuming a failure of policy and the creation of incentives to reduce aviation climate impact. Demand for aviation is also continued to grow, either due to consumers participating in air traffic or individuals performing more flight movements. A relation however is drawn between the reducing population growth and aviation demand, this is done for the reason that there is no agreed method on this front. To interpret the baseline, findings from Grewe and Stenke [2008] should be kept in mind, which shows that for a mixed subsonic fleet the difference between peak CO_2 emissions and the peak in temperature change deviate by some 30 years. There is thus a delay of 30 years between emissions and expression in terms of temperature change, making changes near the year 2100 less significant. With this general idea in mind, the standard data flow can be explained, outlining the baseline conditions along the way.

4.2.2. Revenue Passenger Kilometer

The Revenue Passenger Kilometer (RPK) is a metric that outlines the demand for air transport by revenue-paying passengers. The ICAO defines RPK as: 'one revenue passenger-kilometer means that one passenger is carried on one kilometer' [1]. The ICAO and IATA present monthly and annual updates on the RPK, which allowed the generation of most of the historic RPK trends. For the time-frame 1971 to 2017, data from the ICAO Data+[2] project was used as shown in Figure 4.3. The gaps between 2017 and 2020 were filled up primarily with IATA reports which are released monthly [IATA, 2020a, 2021b, 2020b, 2019a,b, 2021a]. Data before 1971 as estimated by assuming exponential growth, and using the average growth percentage for the 1971-2017 period of 6%. Also, the CO_2 emissions in 1971 were over five times less than 2019 levels allowing for simplification, as post-1971 fuel will not have a great impact.

The ICAO and IATA state differing growth rates for the year 2018 [ICAO, 2018a,b, IATA, 2019a]. However, this only generates an uncertain range of around 46 billion, representing only 0.6% of the total RPKs. Data for the onset of the pandemic in 2019 reported an Asia Pacific 2017 to 2018 year-on-year growth reduction of 8.5%

[1] RPK, URL:https://www.icao.int/MID/Documents/2017/AviationDataandAnalysisSeminar/PPT11-India-IntroductiontoAirTransportSt
pdf
[2] ICAO Data+, URL:https://data.icao.int/newdataplus/

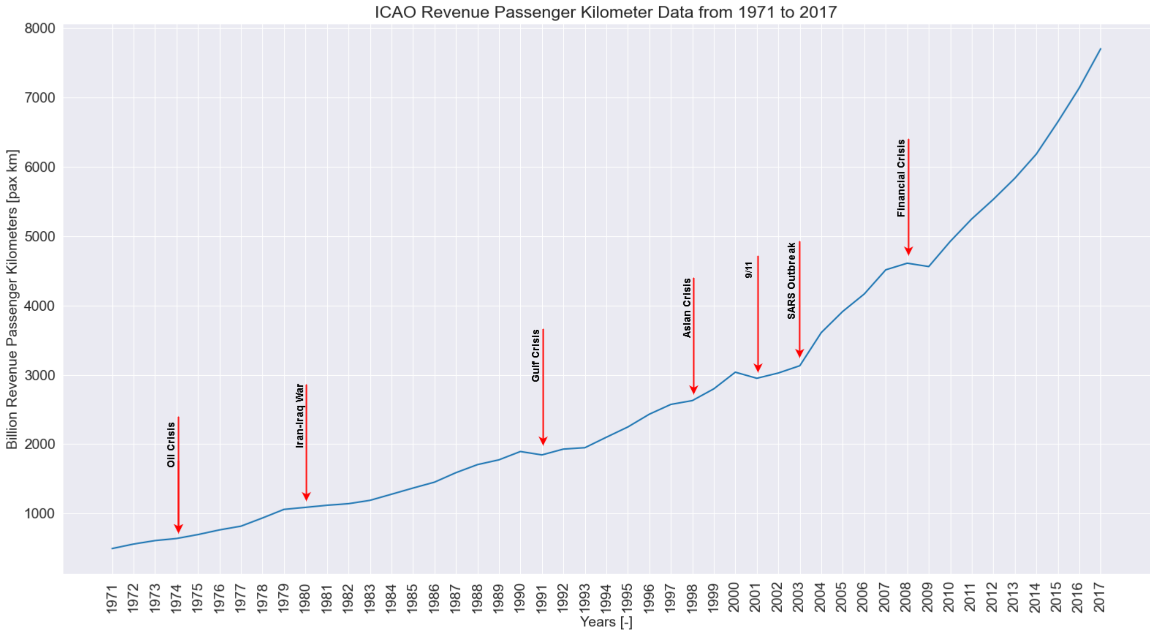

Figure 4.3: ICAO available data on the revenue passenger kilometers for the years 1971 to 2017 including information on relevant events

to 4.5% in 2019. The Asia Pacific area makes up close to half of the overall annual RPKs growth[IATA, 2019b]. The ICAO estimated a year-on-year increase of 4.9% of 8,686 billion RPKs [ICAO, 2019]. The 2019 RPK growth rate was the first year since the Global Financial Crisis of 2008 that the demand growth was below about 5.5%.

For this study, it is important to have a basic understanding of the possibilities of recovery modes. When generating the model the 2019 and 2020 was available [ICAO, 2020, IATA, 2020b,a, 2021b]. Some data was not directly available, but through publishes images a data-set could be built as seen in Figure 4.4. To check the consistency of the IATA and ICAO data, the IATA statement was checked which stated that from 2019 to 2020 the RPK dropped by 66%. The ICAO reported a 68% drop in RPK, showing that the data from both instances show similarities. The used COVID-19 recovery model will be outlined next.

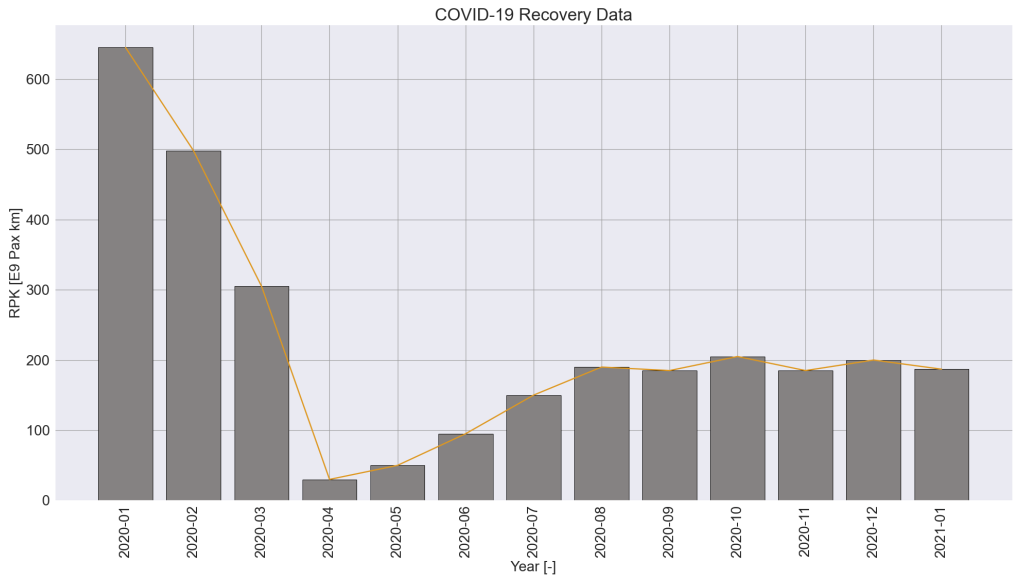

Figure 4.4: The Revenue Passenger Kilometer in passenger kilometer between the years 1971 and 2017 including events left to right: the oil crisis, Iran-Iraq war, Gulf-crisis, Asian crisis, 9-11, SARS and the 2008 financial crisis. Source: ICAO, IATA, OAG

COVID-19 RPK Recovery Model

To receive an estimate for the COVID-19 RPK recovery, industry and consultancy forecasts were used as guiding input for the model. An understanding was obtained through comparison to previous viral or bacterial outbreaks and other events which depressed the RPK baseline growth, shown in Figure 4.5. Both U-shaped and V-shaped recoveries are seen for SARS outbreaks in the Asia Pacific and the China Domestic markets, which are general recovery modes representing a linear or more gradually accelerating recovery. It remains questionable how the COVID-19 pandemic will recover. Cultural behavior and international response are dynamic resulting demand recovery from COVID to be non-homogenous globally. Studies and publications from various instances are presented in Table 4.1.

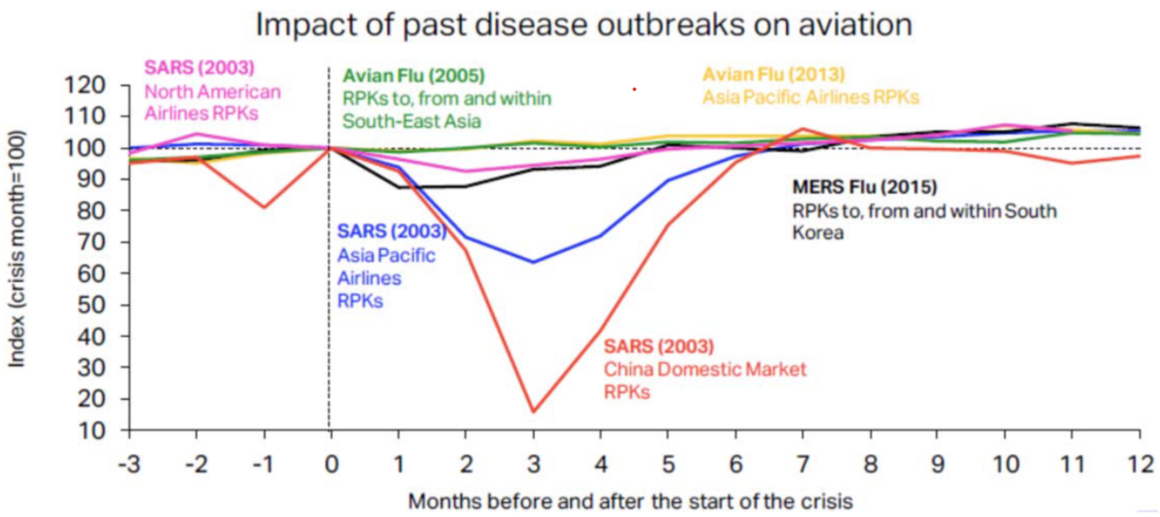

Figure 4.5: Representation of impact of outbreaks on the aviation sector demand where the vertical axis present an index with 100 representing the baseline scenario, and the horizontal axis representing the months before and after the crisis. The SARS outbreak and recovery months are shown for North America, Asia Pacific, and China (pink, blue & red). Also the Avian Flu in South-East Asia and Asia Pacific (green and yellow). Finally, the MERS Flu within South Korea is shown (black). Both U-shape and V-shaped recovery patterns can be observed [International Air Transport Association (IATA), 2020].

Reasonable consensus exists where all recovery expectations are around 2023-2024 or later, depending on near-future developments. There is a perceivable shift between estimates from Moody's and the Inmarsat polls, which were from the Spring/Summer of 2020. Bain & Company provided a more extensive long-term analysis, providing different recovery patterns depending on specified parameters. The recovery for this analysis is estimated at around 2024-2025, to which the IATA recovery models agree.

The model used for this thesis starts in January 2021. The recovery is modeled using a growth function split up into domains. Each domain is responsible for recovering a segment of 'lost' RPK, thus the three domains add up to 100% 2019 post-pandemic RPK. Data for the year 2020 already exist and will be used for that part of the recovery. The choice is made to recover to the 2019 RPKs, rather than the hypothetical RPKs if the sector would have continued to grow normally. This implies that the sector is essentially not growing during the recovery period compared to 2019. The ICAO underlined concerns about the oligopolistic nature of the aviation sector, and the fact that overcapacity could cause serious economical effects [3]. The IATA seems to display similar modeling assumptions in the fact that the growth does not return to the pre-COVID-19 trends[4], which is shown in Figure 4.6. Here it can be noted that the Apri forecast already shifted down compared to the January forecast, and either trend does not return to the pre-COVID-forecast.
Each of the three assumed recovery domains has two parameters, which are the RPK it has to recover and the recovery rate, this implies that one domain can allow recovery of some percentage of the total RPK loss at a monthly recovery rate. Each domain is programmed with values and computes the time required to recover in that setting. The recovery is modeled using a U-shaped/Nike-Woosh recovery shape. The model parameters were matched to a feasible recovery pattern regarding shape and estimates from Table 4.1, implying a

[3]ICAO, URL: `https://www.icao.int/sustainability/Documents/Covid-19/ICAO_coronavirus_Econ_Impact.pdf`
[4]IATA, URL: `https://www.iata.org/en/iata-repository/publications/economic-reports/an-almost-full-recovery-of-air-travel-i`

Organization/ Source	Company Function	General Outline of Analysis
Moody's Investors Service	Investment/bond credit rating business	Estimation make in July 2020 that a rebounce of the aviation sector would not occur any time before 2023. Expect a recovery of passengers around the end of 2023, as health and safety concern start to wind down. It is expected that further disruptions and legal enforcing of social distancing (which did eventually happen), will cause the recovery to be slower.
Bain & Company	Consultancy	Estimates from January and March 2021 including a host of recovery scenarios: baseline, coordinated recovery, accelerated vaccines and drifting. In case of good coordination and rapid vaccination of the population a recovery may be achieved around the end of 2023 to 2024. The baseline and drifting, currently being the most likely to occur, extend the recovery towards the end of 2024-2026 range. Furthermore, in their modeling the recovery does not return to the pre-crisis growth curve, but rather traces it in a parallel fashion.
ICAO	UN aviation agency	The analysis looks at passenger revenue, passenger numbers and seat capacity. No long term estimate is made, however the assumptions are of primary interest. Several recovery options are assumed, such as the nike-woosh, the U-,L- and W-shaped recovery. To support such trends, arguments such as over-capacity and respite are used.
IATA	Trade Association	50.4% improvement compared to 2020 demand, allowing 50.6% of the 2019 demand levels to be met. If the positive scenario is not to be met, only 13% could be recovered compared to 2018, totaling at 38% of 2019 levels. Recovery is still expected around 2024 on the basis of the assumptions that vaccines will be rapidly available at the end of 2021 and beginning 2022. If this were not to be the case, or the vaccines prove to be ineffective, the recovery is likely to extend to a later date.
Inmarsat Aviation	Satellite Telecommunications Provider	Results from June 2020 of over 500 polls of profesionals within the aviation sector, 60 % expects a recovery period ranging between 18 months to 3 years. Domestic travels is expected to recovery faster than international travel due to non-streamlined COVID-19 response
S&P Global Platts	Energy & Commodity Information Supplier	Unlikely that recovery will happen until 3-5 years since the crisis start end of 2019 and start of 2020. Supply side is being reduced by the airliners, meaning they are not the same size as 2019. Retirement have increased fleet efficiency. It is still expected that aviation demand will continue to grow at around 3.5% up to 2040. The recovery is expected to take up o 5 years to reach 2019 levels.

Table 4.1: Summary on the position of instances and consultancy firms about the COVID-19 recovery for the aviation sector

recovery of around four years in 2025. Initially, recovery starts slow, recovering 15% of the RPK at 14% a year as taken from an IATA forecast. The rest is recovered at a pace of 60% per year. The recovery pattern can be interpreted as countries vaccinating their populations, allowing more movement freedom. Mobility constraints will likely still exist within and between countries and continents, disallowing reaching equivalent growth to the post-COVID scenario. Due to the harsh economic situation, airliners might also not be able to cover market needs, due to the reduced available seats following aircraft retirement. The recovery pattern is plotted in Figure 4.7, combining the entire time frame. The recovery takes up to the end of 2024 thus resulting in regular continuation of growth from 2025 onwards.

Post-COVID RPK Modeling

The final segment of RPK is the time frame after the recovery up to 2100. For this segment, population growth is used as a precursor. The United Nations (UN) presented a document in 2019 with forecasts up to 2100 for the population growth United Nations [2019]. The population growth in 2020 was estimated to be slightly higher than 1% and is estimated to move towards stagnation in 2100. The growth rate is estimated to reduce in 2030 by 18%, in 2045 by 44%, in 2070 by 60%, and in 2095 the growth stagnates. The post-COVID RPK growth can thus be selected for a specific case, after which it is reduced in line with the population growth rate change.

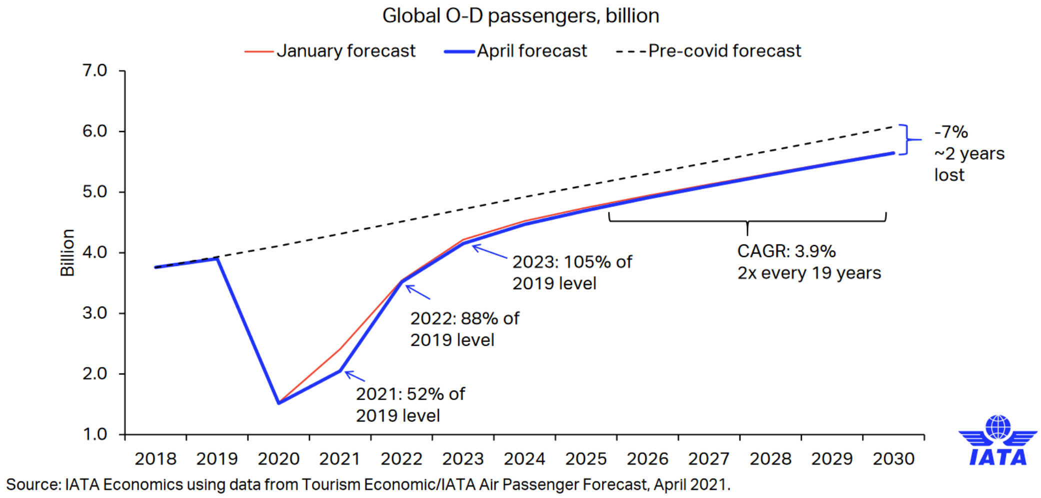

Figure 4.6: IATA Air Passenger recovery model as of May 2021, including estimates from January and pre-COVID RPK growth. Representing RPK in Billion(s) and annual timestamps on the horizontal axis. A slightly slower recovery pattern is observed for the April forecast, compared to the January forecast, and represent a post-recovery growth of doubling of RPK in every 19 years

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Full RPK Trend

Adding together the Pre-ICAO Data+ period with the average reduction rate of 6%, the 1971-2017 period, the 2017-COVID-19 period, the recovery period, and the post-COVID period. Some global market forecasts (GMFs) exist pre-dating the COVID-19 pandemic, where some include the potential influences of the pandemic. Such the Airbus 2019-2038 GMF[5], the Boeing 2021-2040 GMF[6], reportings from the Japan Aircraft Development Corporation [7] and an analysis by the Air Transport Action Group (ATAG) named Waypoint 2050[8] (W2050) were included for comparison. Furthermore, modeling projections from Planès et al. [2021] and Grewe et al. [2021] is added as a reference to the RPK baseline for this thesis. The forecasts are shown in Figure 4.7 and the differences for specific years are further elaborated in Table **??**.

Year	Grewe et al. 2021	ATAG Waypoint 2050 Central	Planes et al. 2021	Airbus 2019 GMF	Boeing 2021 GMF	JADC 2021 GMF
			RPK Difference with Modeled Baseline			
2038	12.29%	-3.68%	5.60%	34.02%	31.05%	16.58%
2050	3.84%	7.53%	15.39%	-	-	-
2100	16.13%	-	-	-	-	-

Table 4.2: Inter-comparison of revenue passenger kilometers model estimations, where the percentage indicates the difference between the baseline scenario and respectively named scenario in the table column.

It is found that estimates before COVID-19 or the ones not account much for it such as the Airbus and Boeing GMF generate a large RPK difference, whereas other estimations lie near the 10% difference. Also, the GMFs seem to still assume continued logarithmic growth, which the baseline model also does display within that time frame. It would be interesting to see what GMFs will look like subject to upcoming changes such as CORSIA, which will change the overall monetary picture for airliners and likely thus passengers.

4.2.3. Fuel Economy; The System Fuel Efficiency

The fuel economy is an umbrella term that describes all processes relating to efficient fuel use to generate RPKs. In this manner, the fuel economy describes the efficiency of the system as a whole, adding technology, aircraft operations, and things such as the aircraft seat density or load factor. Figure 4.8 provides an elementary breakdown of what could be assumed as the fuel economy, including several aspects which ultimately

[5] Airbus GMF, URL: `https://www.airbus.com/aircraft/market/global-market-forecast.html`
[6] Boeing GMF, URL: `https://www.boeing.com/resources/boeingdotcom/market/assets/downloads/07.08.21_9_057_BMO_2021_Commercial_HR_091521a.pdf`
[7] JADC, URL: `http://www.jadc.jp/files/topics/169_ext_01_en_0.pdf`
[8] W2050, URL: `https://aviationbenefits.org/media/167187/w2050_full.pdf`

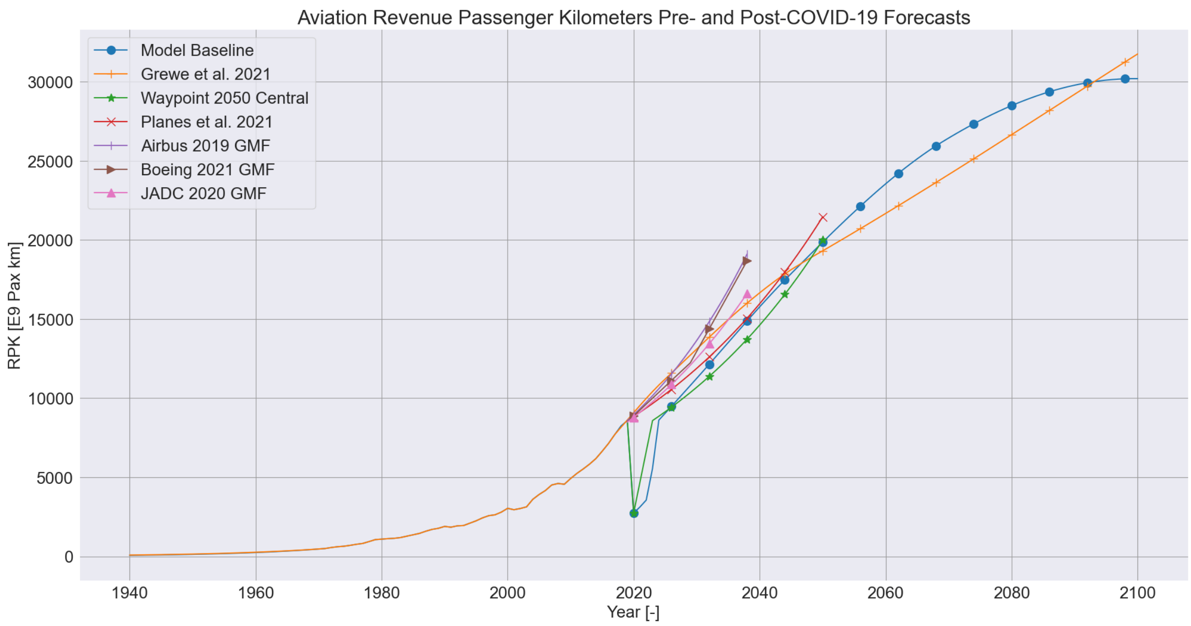

Figure 4.7: Trends of future revenue passenger kilometers from both pre-COVID and post-COVID Global Market Forecasts and literature based studied, including the baseline model in Billions of RPKs.

dictate the parameter. The fuel economy is a useful parameter, as it looks at a global description of the system, however, it lacks the ability for integrating small efficiency changes done to aircraft. The fuel economy is thus a ratio describing the relation between annual RPKs and fuel consumption, where a higher fuel economy indicates a better overall fuel performance. The fuel economy was mentioned in the ITCC studies referred to in subsection 2.1.1. One should keep in mind that the definitions slightly differ, as the payload is not assumed part of the RPKs. Comparatively, this will cause the fuel economies from the ITCC to be much higher than what will be found in this study. When performing a direct comparison, this statement is supported; Where the ITCC found a fuel economy of 47 RPK/kg in 2017, the thesis model shows a fuel economy of 20 RPK/kg.

For the computation of the fuel economy both the RPK and fuel consumption estimations are needed. The fuel economy follows the RPK computation, but the fuel economy is required to find the fuel consumption. Therefore, historical data from Sausen and Schumann [2000] could be used, which provides an accumulation of other studies and respective estimations. This data was used to set up the trend for the fuel economy from seven different input years, resulting in a tight linear fit with an R^2 value of 0.968, allowing for an accurate description of the fuel consumption between 1976 and 2015. Since then there have not been revolutionary developments in aircraft design, thus it is unlikely to have significantly shifted. However, the synthesis of the fuel economy makes the methodology not flexible, which for this reason can be manually adjusted to include decay.

During the COVID-19 recovery the passenger load factor reduced from 82.6% to 66.9% found IATA[9]. Given that the passenger load factor impacts the fuel economy, it is assumed that the fuel economy dropped a similarly to 81% of the 2019 value. Recovery occurs at the pace of the RPK after which the assumption is made for the baseline scenario that the efficiency improvements to the fuel economy will saturate over time. To accommodate flexibility in modeling the fuel economy, a decay factor (η) was introduced. The general implication of using a growth decay factors setting is found in Figure 4.9, where the temporal evolution of the fuel economy is shown for a host of decay factors. The dampening of the decay factor is already observably severe for η=0.98. There is a small bump in the year 1975, which is caused by the assumption that the fuel consumption reduced by 5% annually between 1975 to 1940. The fuel economy is not relevant in this time frame but is calculated for completeness The decay factor of 0.97 was used for the baseline, which displays significant decay but still retains a growth in fuel economy. This decay caused the fuel consumption to align with the business as usual from Grewe et al. [2021], which then allows for an intercomparison. Figure 4.10 shows the implications of the fuel economy upon the fuel consumption, which also included the fuel consumption

[9]IATA, URL: `https://www.iata.org/contentassets/c81222d96c9a4e0bb4ff6ced0126f0bb/iata-annual-review-2020.pdf`

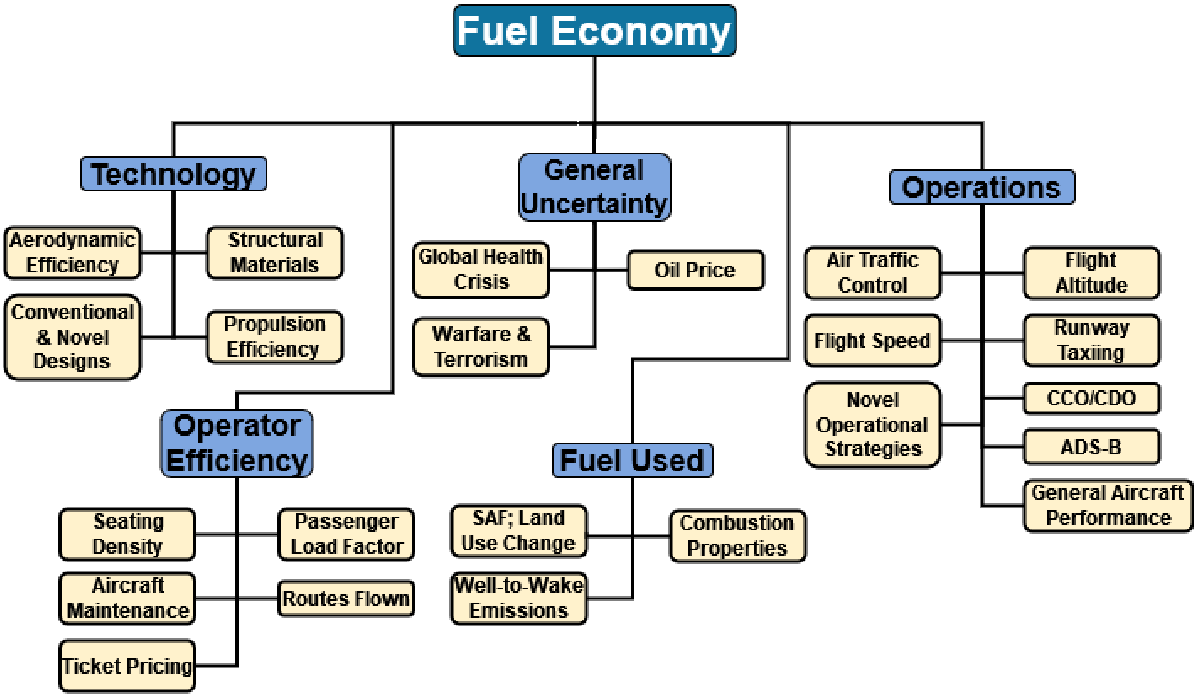

Figure 4.8: Breakdown of the general concept of the fuel economy efficiency outlining several sub-categories which could impact the fuel economy. The breakdown is an indication of what are the parts of the fuel economy, but aspects exists which are not named here.

trend. Also, the fuel consumption trend for the business as a usual scenario from Grewe et al. [2021] is plotted, which corresponds to the modeled baseline. Discrepancies exist around the 2020 to 2040 time period, caused by the COVID-19 period, after which trends start to differ significantly.

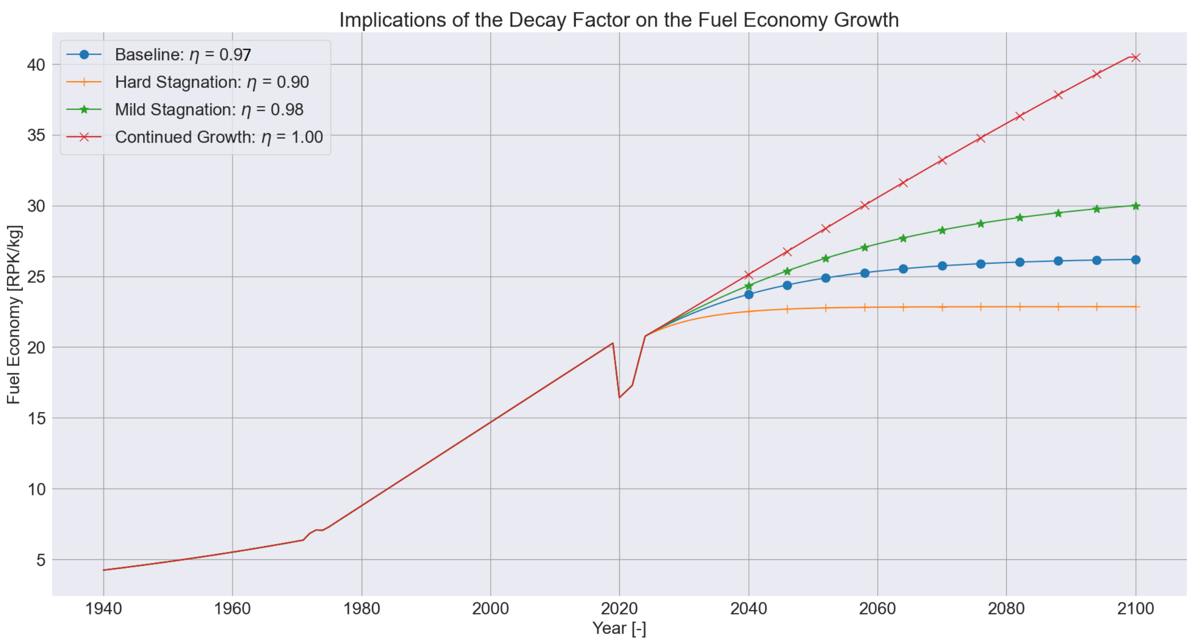

Figure 4.9: Effect of different decay factors on the total fuel economy in units of RPK/kg on the vertical axis and years on the horizontal axis, with an observable depression of the growth trend as a result of decay factors deviating from unity.

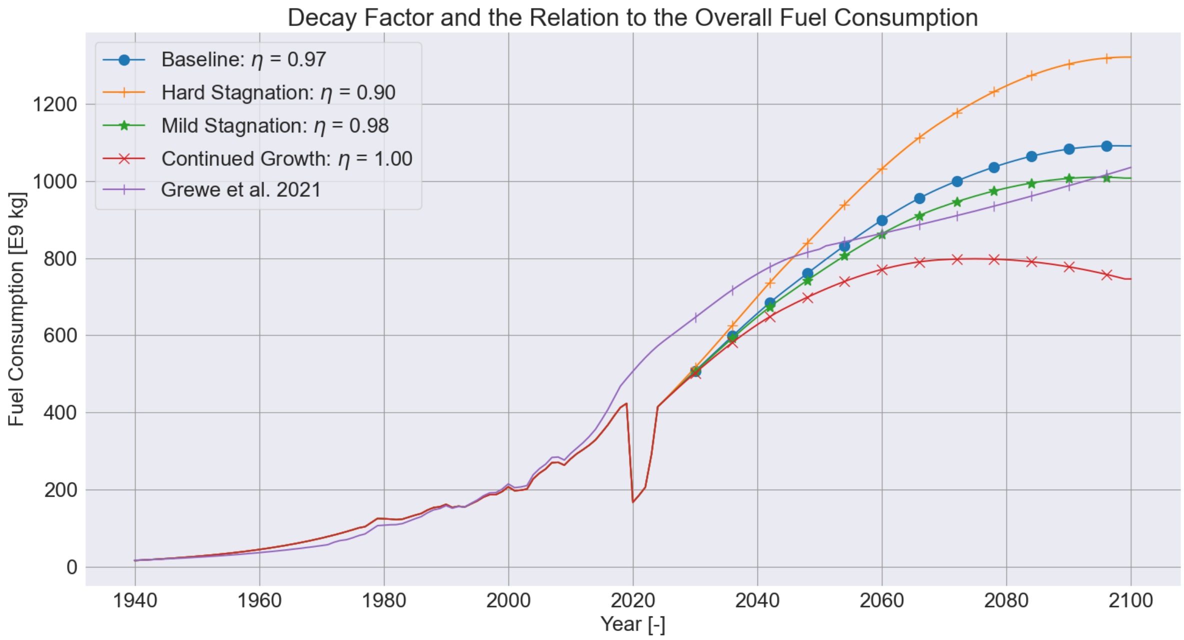

Figure 4.10: The effect of the choice of the decay factor on the fuel consumption, displaying a the high volatility of setting the boundary conditions of the fuel economy and the post-pandemic time-frame fuel consumption evolution. Including results from the business as usual case from Grewe et al. [2021] displaying large discrepancies around the COVID-19 period.

4.2.4. Final Downstream Parameters and Summary

The contrail coverage is calculated as a product of the 3-dimensional emission inventory and is scaled towards the scenario flown distance. Emissions at specific spatial locations can cause the formation of contrails, dependent on the local requirements being satisfied for contrail formation. After computation of the fuel consumption, the flown kilometers can be calculated using fuel efficiency. Since AirClim takes the fuel consumption and the 3-dimensional emissions data as the primary model inputs, only the flown kilometer for the inventory normalization year is relevant for the modeling setup. After the modeling setup, the flown kilometers and relevant parameters are scaled according to the temporal fuel consumption trend.

For completeness, the complete flown kilometers trend is synthesized. The efficiency values from Grewe et al. [2021] were used, which starts with fuel efficiency in 1940 of 8 kg/km and it improves to 4.61 kg/km in 2018. Between 2018 and post-COVID-19 there have been a lot of retirements of aircraft models which would otherwise not be retired yet. Rutherford [2020] estimated a 1.1% fleet-wide saving which would of course increase the fuel efficiency of the fleet. Since this is past the normalization year for flown kilometers, this will have to be integrated into the fuel consumption trend. Then the Emissions are a product of the fuel consumption with the respective emissivity index, wherein in this case the factors from Lee et al. [2021] were used. This implies an emissions index for CO_2 of 3.16 kg per kg fuel and NO_x the average of 14.63 g per kg fuel. These are then computed according to Equation 4.1 and Equation 4.2. These steps were taken within AirClim, but data was also generated in the datasheet to compare the consistency between AirClim and the data tool.

$$CO_2(year) = \text{Fuel}(year) \times \text{EI}_{CO_2} \tag{4.1}$$

$$NO_x(year) = \text{Fuel}(year) \times \text{EI}_{NO_x} \tag{4.2}$$

Through several steps, the data for the baseline has been generated. To review a clear overview of the model and its assumptions, a summary is provided in Table 4.3. The data of the baseline can be adjusted through pre-processing and post-processing to create scenarios and compared them respectively.

4.3. Baseline Scenario Manipulation Through External Modules

Now that the baseline has been established, there is a need to add external modules which can manipulate the input and output data. This can be in the form of policy, operations, and technology as has been established.

Table 4.3: Summary of the assumptions regarding the modeling of the primary data flow for subsequent scenario building

Parameter	Definition	Assumption(s)
Revenue Passenger Kilometer	The transportation of the number of paying passengers multiplied by the amount of flown total distance that was covered by all partaking aircraft	- Historical ICAO 1971-2017 frrom Data+ - Extrapolation to 1940 through use of 1971-2017 year-on-year average - COVID-19 according to own model - Post COVID-19 congruent to United Nations year on year population growth [United Nations, 2019]
Fuel Economy	Umbrella term defining the overall fleet fuel efficiency in signifying the amount of RPKs generated per liter or kilogram of fuel. Concept used extensitively in ITCC Reports from Zheng et al. [2019]	- Pre-1971 estimates computed by assuming an annual 5% increase of fuel, the quantities from then are relatively insignificant in comparison to the current fuel usage - Fuel economy computed on basis of fuel estimates through dat from Sausen and Schumann [2000], resulting in a linear increase and logarithmic decay of year-on-year growth - Logarithmic decay implemented to allow technological growth iterations - Fuel Economy reduction due to COVID-19 similar to load factor drop found by IATA - Freight mass not included in RPK
Total Fuel	The annual amount of fuel used by the entire fleet generating RPK	Fuel Economy = $RPK_{total}/Fuel_{total}$
Flow Kilometers	The amount of kilometers flown in a specific year. Important for the computation of contrail coverage.	- Fuel efficiency used from Grewe et al. [2021] - Full trend computed using linear change between 1940, 2020 and post-COVID. - Post-COVID YOY growth same as that of the fuel economy
Emissions	Aviation related emissions such as NO_x and CO_2	Emission indexes for CO_2 and NO_x from Lee et al. [2021]

The LUC mechanism is studied under policy measures since it is closely linked to schemes that advocate the use of SAFs. Furthermore, a simplified market model was used to observe the climate impulse as taxation iterates the demand. Most of the operational practices excluding CCO & CDO, and fuel tankering abolition, will be modules that require post-processing of the data. Offsetting of emissions can be dealt with easily through defining a temporal offsetting storyline in AirClim, which then performs CO_2-accounting, leaving all other non-CO_2-emissions unchanged. Table 4.4 has been generated in which all external modules are provided with the respective parameters they act upon.

Used Module	RPK	Fuel Burn	EI_{NO_x}	CO_2	Induced Temperature Change
Carbon Offsetting				x	
Market Based Mechanism	x				
SAF & Land Use Change		x		x	
Formation Flight		x	x		x
ISO + Lower Flight		x			x
IATA Technology Scenarios		x			

Table 4.4: Breakdown of the external modules used for data manipulation and the primary parameter on which they act

4.3.1. The Elementary Market Based Module

The elementary market model is essentially trying to link a rise in the ticket price to an alteration in demand for aviation, impacting the RPKs. Changing the ticket price can be interpreted qualitatively, for example as a rise in ticket price due to tax, or it can represent an abolition of tax exemption for aviation fuel. It could also represent the implementation of a frequent flyer tax, distance-based taxation, the increase of cost through the inclusion of previous externalities. The mode in which the ticket taxation is modeled is primarily logical in nature but has not been studied in an adequately detailed manner. More studies must be done regarding the market response and taxation relation. The type of taxation might, for example, affect the less wealthy, but not the top consumers, who hold the largest share of flight movements. Provided this method and later the sensitivity of respective model parameters are well documented, such that it is avoided that inaccurate implications will be made from the results.

As for this specific model, several aspects have been included such as the elasticity, the cost pass-through, the duration for the measure to take full effect, and the duration of the RPK reduction. The pass-through cost is essentially an absolute price increase resulting from a shift in pricing equilibrium. Costs such as take-off taxation, increased fuel taxation, or anything alike can be seen as operator cost increases. Here a static cost pass-through is assumed, which is an7 over-simplification not even including the dimension of having globally different market dynamics [Wang et al., 2018]. For this model to be accurate, it would have to include dependence on types of air transport (short-, medium- or long-haul), the economic areas, and even aspects such as national-level policies impacting airliner costs.

Similar to the cost pass-through, the demand elasticity is something very dynamic and it depends on many independent factors. The demand is inelastic if the price increases at a more rapid pace than the demand decreases, elastic behavior is the opposite. Elasticity in any regard is dependent on the alternatives available for the product demanded. The elasticity is thus bound to the personally perceived cost of the consumer, which can be monetary or time constraints as a matter of example. Brons et al. [2001] found an average elasticity from 204 observations obtained in different studies at -1.146 with a standard deviation of 0.619. In a study done by CE Delft [2019], values from an Intervistas (2007) studies showed elasticity of -1.23, -1.12, and -0.8 for domestic flights, flights within Europe, and intercontinental flights. An important assumption made in this report was the concept of a 0-net demand impulse. The 0-net demand impulse assumes that reduced taxes or increased taxes can increase or decrease the revenues of a sector, though the gains or losses just shift to another sector. Essentially this assumes that there is no loss in revenues, given the reduced air traffic is captured by increased train transport for example.

The RPK impact is calculated using Equation 4.3 which computes the total RPK-impact as a result of elasticity and cost pass-through rate. This RPK-impact is then linearly reduced over a 30-year time frame, which was arrived at through running the model at different settings and observing inconsistencies otherwise. If the RPK-impact were instantaneously implemented in the year of the taxation, this would result in an unrealistic reduction of RPK and alteration of future growth.

$$\text{RPK}_{impact} = \text{RPK}_{base} \times \text{Pass-Through Rate} \times \text{Price Elasticity} \tag{4.3}$$

The MBM is thus a qualitative exploratory narrative module looking into the impact of an RPK reduction, yielding a reduction in the temporal input of fuel consumption. Taxation causes a reduced revenue from the sector and will also affect other sectors, which causes a new equilibrium and could yield changes to the GDP. Changes in GDP might affect political decision-making, and this affects the spending capacity, tapping back into behavior. Choices between different political entities can have large effects given everything is inter-connected, thus to create a more accurate model the socio-economics should be accounted for. Regardless of the exactness between market and taxation, the module still provides relevant insights as it represents a depression or rise in RPK growth.

4.3.2. Land Use Change and Sustainable Aviation Fuels

The SAF module considers the fuels identical in the emissions characteristics with regards to conventional jet fuel, however, with a slight alteration of the EI_{CO_2} per findings from Blakey et al. [2011]. In the chapter 2 the conclusions and research done for the LUC and iLUC computations, to be used under the CORSIA scheme, were outlined. The large uncertainty regarding volume, externalities, and policy was outlined. For this module an assessment method has been created, allowing the modeling of a SAF uncertainty band through well-to-wake (WtW) estimates for different SAFs. This ratio between the baseline WtW of conventional jet fuel and the SAF types can be calculated, which is used to estimate hypothetical additional/reduced CO_2-emissions. The CO_2-emissions of a specific scenario can then account for this deficit. The artificial CO_2 emissions are computed by establishing a ratio called the SAF_{factor}, which indicates the proportion of the jet fuel WtW versus the SAF fuel WtW as indicated in Equation 4.4.

$$CO_{2_{LUC}} = CO_{2_{no-LUC}} \times SAF_{factor} \tag{4.4}$$

In Table **??** the SAF LCA emission projections for the year 2035 are given, used to compute the SAF_{factor}. For this parameter, the market share and the gCO_2-equivalent emissions per MJ of fuel, and SAF usage targets are taken from the European Green New Deal. This implies SAF update input points in 2025, 2035, 2050 where a specific percentage of SAF uptake is defined. Based on Table **??** an average market share normalized projection of 38.1 gCO_2e/MJ fuel was computed, by combining market share and WtW values of the 17 analyzed pathways. Leaving the 'other SAF' and 'other Regions' as free variables. The model will assume 33% of the SAF to be of the normalized average, and 66% percent will be filled in by e-fuels (as these are part of the EU New Green Deal) and a free variable which can be used to model worst and best-case scenarios. For the emission intensity for e-fuels estimates from Hombach et al. [2019] were used. Uncertainty exists for e-fuels, i.e. using wind energy for production in 2015 and 2030, emission intensities of 64.07 and 6.63 gCO_2e/MJ were found. A mixed grid emission intensity could go as high as 441.14 gCO_2e/MJ in 2015, and 148.2 gCO_2e/MJ in 2030 following their estimation method for light-duty vehicles in Germany. Processing for SAFs might be more intense as requirements are more stringent due to extreme operating conditions. To allow for modeling flexibility, the three above-described categories correspond to each other and can be changed within a matrix. Therefore, it is possible to model worse case and best case projections. Table 4.5 represents the SAF blend setup matrix, where the emission intensity and market share of each SAF can be selected. Changes in this matrix for volume share or any of the emission intensity inputs will change the artificial CO_2 emissions, accounting for LUC through the SAF_{factor}.

SAF Origin	Emission Intensity [gCO_2e/MJ]	2025 Volume Share	2035 Volume Share	2050 Volume Share	2100 Volume Share
CORSIA Regions Produced SAF	38.10	5%	33%	33%	33%
Aviation E-Fuels	Dynamic	0%	0.70%	28%	50%
'Other' SAF	X	95%	66.30%	39%	17%

Table 4.5: General representation of the SAF story-line matrix, allowing for the selection of different market shares per fuel type and different emission intensity of the fuel(s)

4.3.3. Formation Flight

The formation flight module will be a combination of several parameters, under which the number of flights performed in formation, the fuel savings, the year of implementation of formation flight, and finally the inclusion of NO_x saturation effects mentioned by Dahlmann et al. [2016a]. This module can be compared to Marks et al. [2021], which estimates an effective fuel saving of 5-6% and ATR_{50} of 20-23%. The results of both with and without contrail mixing should be assessed, and if they are consistent with previous studies before they are implemented congruently with other modules. Where generally the fuel consumption is computed through the RPK and fuel economy, the formation flight module applies a factor directly to the fuel consumption taking into account not all flights will be performed in formation as in Equation 4.5. Here FORM is the percentage of formation flights performed globally, and η_{fuel} indicates the fuel savings by the aircraft flying in formation. This equation thus adds the flights not flown in formation with the ones that were, and their respective savings. The assumption is made that formation flight can be implemented rapidly due to safety being the largest concern rather than capability, and it is therefore treated as an instantaneous action. It was found in the ecoDemonstrator project by Boeing, that minor adjustments to the collision avoidance system (TCAS) were sufficient for performing formation flights. It should however be understood that this assumes two simplifications congruently, which have to be outlined:

1. It is likely that if the test flights are successful and the hardware/software adjustments are straight forward, that formation flight can and will be implemented on a short-term basis. However, of course there is the question of formation flight alliances between competitors and which flight have a viability or mission profile to perform formation flight.
2. The current post-processing constitutes an instantaneous change to the contrail cirrus radiative forcing, first of all this reduction percentage might be based upon initialization criteria of the atmospheric

molecular concentrations, thus meaning that if the emission profile radically changes the contrail impact has to be modeled accordingly differently. This will most certainly be the case when considering the time-span as done in this studies, thus the modeling of formation flight lacks necessary resolution.

$$\text{Fuel Consumption} = (1 - \text{FORM}) \times \frac{RPK}{\text{FE}} + \text{FORM} \times (1 - \eta_{fuel}) \times \frac{RPK}{\text{FE}} \tag{4.5}$$

The module will apply manipulations on the fuel consumption with the generation of the primary input data, then during the pre-processing, there is the option to change the EI_{NO_x} as a result of contrail mixing. Furthermore, to account for the change in extinction time and ice mass a 48% contrail RF reduction as prescribed in Dahlmann et al. [2020] which is applied in the post-processing. Thus both changes to the inputs are made, taken into account during running AirClim, and some post-processing steps are performed on the contrail-cirrus near-surface temperature change.

4.3.4. Climate Impact Reduction through Flight Altitude Changes

The goal was to assess climate optimal routing, but that is a topic requiring in-depth studies altogether. For that reason, the strategy of changing cruise altitude was used as a lower limit of climate optimal routing savings. The altitude change and the impacts are reliant on the post-processing values provided in the literature specified in Table 2.1. The module in and of itself is rather simplistic, with post-processing applied through factorization, which can be changed based on the number of flights flying lower. Especially for the current generation of aircraft, a higher flight is more efficient but possibly redesigns of aircraft can allow for better accommodation of lower altitude cruise flight. Potential developments could permit aircraft to fly lower more efficiently, potentially even reducing fuel consumption if these strategies are applied congruently with ISO operations and aircraft redesign.

4.3.5. Intermediate Stop Operations

Performing flights through ISO is conceptually easy, but modeling it accurately is complex. As the performance of ISO would change the concentrations of emissions, due to different flight patterns. Also, the savings through ISO are dependent on aircraft types, stop options for ISO, wind conditions, the manner in deciding where to stop, and for example, extra fuel cost provided potential inefficiencies in the finding and approach of airports. It should already be clear from chapter 2 that ISO has a wide range of estimates on attainable fuel savings, and e.g. Linke et al. [2017] assesses it as an optimization problem taking into account more than just fuel savings, which finds that not just fuel consumption but the time and place of emissions are of importance when assessing the climate impact. The used model will take the values from the literature for fuel consumption reduction and use the findings from Matthes et al. [2021] on the impact of flying lower discussed previously. Opposed to the optimization from Linke et al. 2017, here it will be assumed that the light aircraft fly lower and those fuel consumption reductions can be achieved, of course, the lower flight with a lighter aircraft will be more sub-optimal than with a heavier aircraft. The redesign is required to make these lower flight conditions less disadvantageous or to reduce fuel consumption. A range of fuel consumption reductions will be implemented ranging from 0-10% to create a range of climate impact possibilities. Just as for formation flight and flying lower, the post-processing savings will in reality change as a result of changing operations altering the emission concentrations. For this global analysis, these post-processing values are kept constant and are not subject to temporal evolution.

4.3.6. Continuous Climb/Descent Operations & Fuel Tankering

To model the to-be-achieved fuel savings for both CCO/CDO improvements and fuel tankering restrictions, the data found and outlined in chapter 2 can be used to perform a calculation for the potential global fuel savings. Both modules are treated as fuel consumption impulses savings. It was found that 0.54% of the ECAC jet fuel burned in 2018 was caused by fuel tankering. The CCO/CDO studies done by EUROCONTROL and the potential savings of 340,000 tonnes of fuel burn could be related to the percentage of fuel tankering, which was 229,000 tonnes of extra fuel burn. These percentages are then assumed to be true for the whole world, implying that 0.54% for fuel tankering and 0.64% for CCO/CDO are multiplied by the fuel consumption of 2018 to obtain the value of fuel burn caused globally. However, the EU is already more wealthy and advanced, because of which CCO/CDO practices might already be more optimized, therefore a factorization of 1.3 is applied to the fuel consumption computed. This resulted in global savings for fuel tankering and CCO/CDO practices at 2.97 Billion and 3.52 Billion kilograms respectively. So, these modules only amount to slightly more than 1-1.5% of the 2018 fuel consumption budget. Likely, these small savings will not be of significant impact on the climate impact, which might be an important finding in its own right.

4.3.7. IATA Technology Scenario through CO_2-Intensity

The technology can be assessed in multiple ways, such as changing the EI_{NO_x} to represent technological advancements. Or the decay factor making up the fuel economy allows iterations between linearly increasing fuel economy and decaying fuel economy growth. These changes do not very clearly define the introduction of a specific aircraft into the market, but these are more qualitative in nature. A model was represented in the IATA roadmap to 2050, which was already mentioned in section 2.3. The IATA assembled four scenarios, which represent their baseline (T1), a conservative developments scenario (T2), radical configurations with turbofans and open rotors (T3), and an electrification scenario (T4a, T4b). The document converts fuel savings into a so-called CO_2-intensity (ICO_2), which is expressed in Equation 4.6 and is thus a ratio between annual CO_2 and annual RPK. These synthesized scenarios are only up to 2050, and thus do not cover the time frame up to 2100. Therefore, assumptions have to fill in the 2050-2100 period.

$$ICO_2 = \frac{\text{Fleet } CO_2 \text{ Emissions}}{RPK} \tag{4.6}$$

The first step was to convert the data between 2025-2050 to fuel consumption. Given the year-on-year improvement-rate can be extracted from the IATA scenarios, Equation 4.7 can be combined with Equation 4.6 to find Equation 4.8. This set of equations allows the computation of the fuel consumption as a function of RPK, which is known.

$$ICO_{2_{YOY}} = \frac{ICO_{2_i} - ICO_{2_{(\text{i - 1})}}}{ICO_{2_{(\text{i - 1})}}} \tag{4.7}$$

$$\text{Fuel Consumption} = \frac{(ICO_{2_{YOY}} + 1)}{EI_{CO_2}} \times \frac{RPK_i \times CO_{2_{(i-1)}}}{RPK_{(i-1)}} \tag{4.8}$$

The baseline derived from the top-down data architecture and the respective CO_2-intensity was compared to the baseline from the IATA document, given the underlying assumptions might differ. A similarity was found between the IATA ICO_2 and thesis baseline, as can be seen in Figure 4.11. Due to model similarity, no factorization of the CO_2-intensity was required. The respective scenarios were then computed and outputted in Figure 4.12 for the 2025-2050 time frame. There is minimal difference between T2, T3, and the T4a scenarios, which is logical since electrification does not occur over a large portion of the market. T4b shows a more differentiating reduction, even displaying a negative growth trend towards 2050 due to more optimistic electrification forecasts. An observable difference exists between the baseline scenario of this thesis and the IATA scenarios, following the more strivings technology and improvements expressed in CO_2-intensity.

For the latter part of the time-frame, spanning 2050-2100 the shape of the respective functions was extrapolated. The trend for T4b behaves relatively aggressive and it was decided that this trend would maintain a constant fuel consumption value.

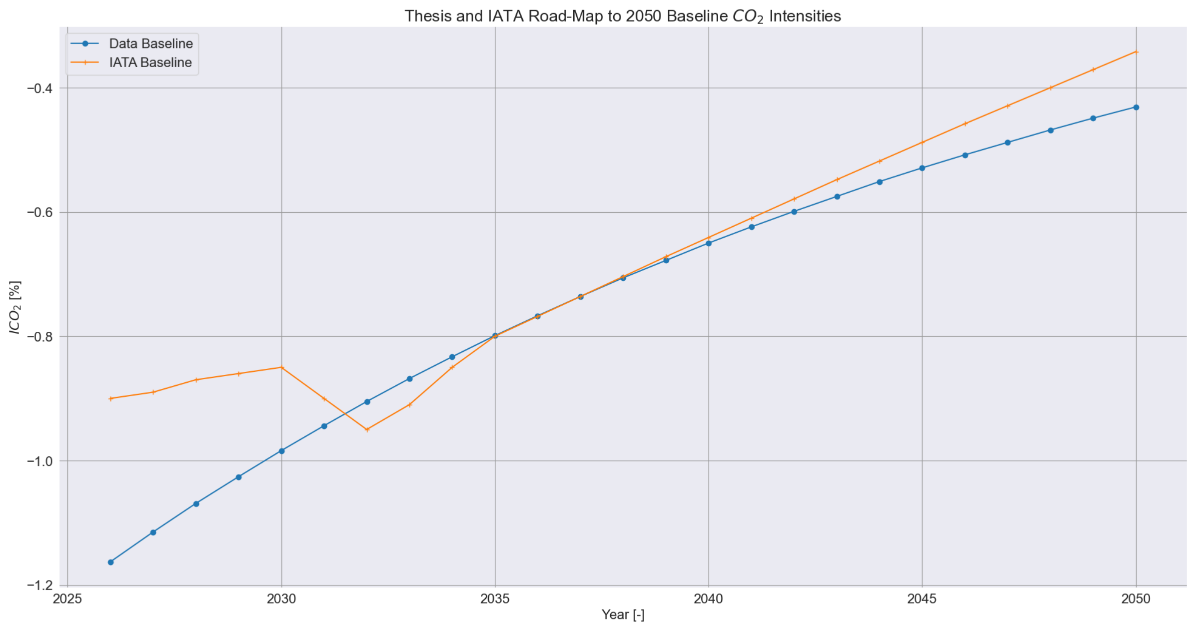

Figure 4.11: Representation of the CO_2 intensity within the time-frame from 2025 to 2050 for the studies baseline versus the IATA baseline

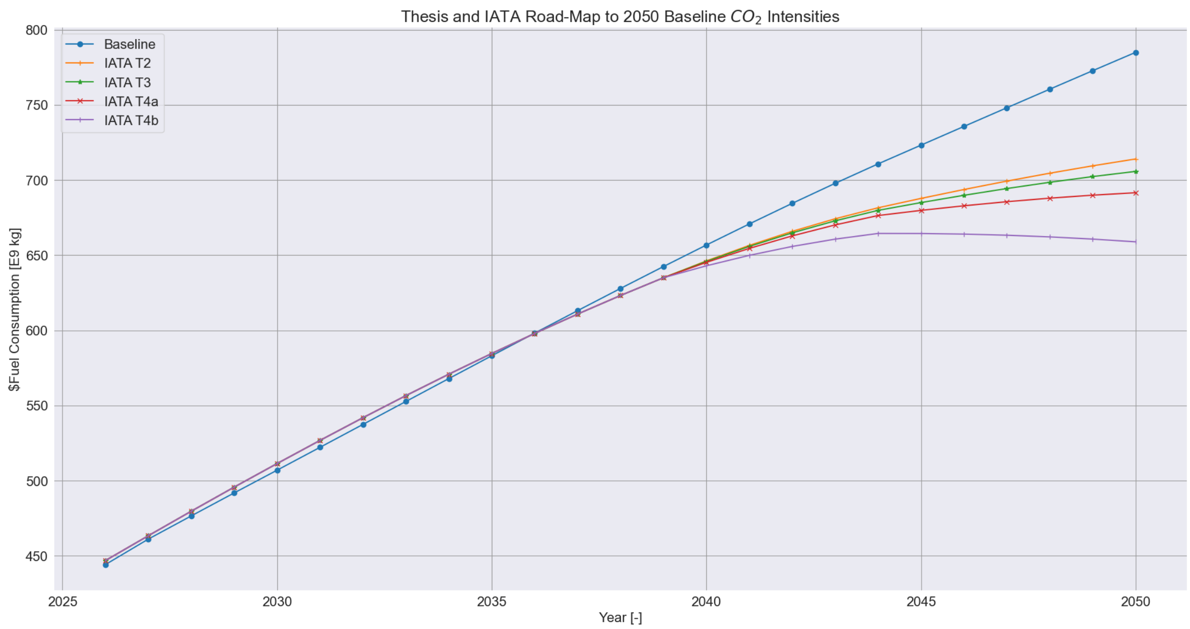

Figure 4.12: Representation of fuel consumption reduction for the specific IATA scenarios based on CO_2 Intensities

5
Verification & Plausibility Assessment of Modeling Approach

The verification & plausibility studies are done through running AirClim subject input data changes and subsequent inter-comparing between the results from baseline and non-baseline settings. Analyzing the sensitivity of parameter changes and module iterations is essential, as it could point to the effectiveness of modules or potential modeling deficiencies. Also, the model AirClim used for the simulation might display inherent tendencies which have already been treated in chapter 3, which can be further elaborated upon through visualization. Aspects such as the implications, uncertainty, and sensitivity inherent to input data changes should become clear. In essence, the following questions should be answered before moving on to reach conclusions about the research question.

1. How do individual model parameters change the temporal input data and what impact does this cause in the output parameter of temperature change?
2. Which temperature change inducing pathways are guiding the change of the model output?
3. What is the sensitivity of each parameter and is this caused by the fact that the parameter is a strong indicator to temperature change, or does it say something about the modeling approach being unstable?

For the visualization and answering of the questions posed above, several methods of outputting the data have been applied. It is important to understand the impact of a change on the temporal data upon results of near-surface temperature change obtained from AirClim. An inter-comparison is made at the end of the time frame in the year 2100, where the total induced temperature change (ITC) comprises the combined impact of CO_2, H_2O-vapour, Contrails (Cont), CH_4, O_3, PMO. The latter three are the net-NO_x-effects as was outlined in section 2.1. Furthermore, the sensitivity will be assessed where possible to understand the parameter and its response better. This is especially important to identify parameters that might be highly sensitive, given this could lead to either implication towards the reductive potential of a measure or parameter instability caused by the modeling approach.

5.1. Parameter Based Verification & Climate Impact Sensitivity

The parameter sensitivity analysis and verification to check if the responses to inputs are logical are essential for the later interpretation of the results. It allows the understanding of module applicability and where limits of the model display non-linearity. Even with relatively simple parameter descriptions and model changes, the output can allow the arriving at relevant implications with regards to climate impact and its drivers. Every external module and key parameter regarding the synthesis of the later result shall be tested, including checking the consequence of using a specific three-dimensional emissions inventory, RPK, fuel economy, external modules, and the response of AirClim to extreme scenarios.

5.1.1. The Importance of 3D-Emissions Inventories & Background Emissions

Three-dimensional emissions inventories were already touched upon in chapter 3, so it is important to understand how a different choice can affect the results. Therefore, the baseline was modeled with both the AERO2K and REACT4C inventory, which similarly served as a consistency check with previous studies. Furthermore, the baseline was modeled using two background emission profiles; The IPCC A1B and A1T CO_2 and CH_4 descriptions. The A1B background emissions are overall higher than the A1T background emissions, which will change the relative impact of aviation-induced climate change. In a scenario where the world is performing poorly on meeting climate ambitions, thus high background emissions, aviation emissions will relatively have a lower impact when compared to when there would be low background emissions. In Table 5.1 the relevant inventory specific data was summarized, showing the measurement year of the inventory and the distance, fuel consumption, and NO_x emissions. The baseline values used for this thesis are found under the 'BASELINE' column, and the REACT4C and AERO2K values are found the in adjacent box to the right. Taking the ratio between the baseline values and the respective inventory values allows for adequate scaling of the input data for computation with AirClim. There is a large discrepancy between the baseline in the years 2002 and 2006, which can be attributed to explosive growth in RPK within that time frame after the dip in 2001 due to 9/11. The year-on-year RPK growth between 2003 and 2004 was as high as 15.3%.

	Base	Distance Flown [E9 km]	Fuel Consumption [Tg]	NO_x [Tg]	Distance Flown [E9 km]	Fuel Consumption [Tg]	NO_x [Tg]
		BASELINE			REACT4C/AERO2K		
AERO2K	2002	40.1	198.1	2.90	32.82	173.47	2.21
REACT4C	2006	53.4	253.3	3.70	38.85	178.31	2.33

Table 5.1: Representation of the flown distance in billions of kilometers, fuel consumption, and NO_x emissions both in Teragrams for the AERO2K, REACT4C Inventories and Baseline. Representing the values of these parameters in the years of 2002 and 2006, which indicate the measurement year of AERO2K and REACT4C respectively.

For the result synthesis, the AERO2K inventory was normalized to its base year of 2002 and the REACT4C to the year 2006. A normalization to 2002 for the REACT4C inventory was also done to check the impact the normalization year could have. Running AirClim with respective baseline inputs yielded Figure 5.1, where it is visible that the REACT4C inventory induces a higher temperature change for normalization variants. Table 5.2 shows that e.g. the CO_2 emissions are identical, but especially the contrail and NO_x emissions deviate from one another. Where the AERO2K calculated 47.51 mK and 56.65 mK, the REACT4C 2006 arrives at higher values of 61.08 mK and 67.97 mK. The REACT4C 2002 yields an overall lower total ITC, which is still significantly higher than the AERO2K case. Differences were outlined in Figure 3.2, where indeed a larger concentration of emissions is present at higher altitudes in the REACT4C case. A study by Matthes et al. [2021] supports this statement, which showed that flying higher might reduce fuel consumption, but increase ozone and contrail radiative forcing.

Scenarios	ΔT_{total}	**Difference**	ΔT_{CO_2}	**Difference**	ΔT_{NO_x}	**Difference**	ΔT_{Cont}	**Difference**	ΔT_{H_2O}	**Difference**
REACT4C 2006	207.13	-	71.56	-	67.96	-	61.08	-	6.53	-
REACT4C 2002	202.95	-2.02%	71.56	-	67.97	-	56.89	-3.58%	6.52	-
AERO2K 2002	182.55	-11.87%	71.56	-	56.65	-16.64%	47.51	-22.22%	6.84	4.75%

Table 5.2: Representation of the near-surface temperature (ΔT) change of respective species in milikelvins (mK), presented with the respective percentage change when compared to the baseline value indicated as the 'Difference'. Near-surface temperature change is presented for the total temperature change and all constituent components, for the scenarios assessing the impact of selecting the REACT4C and AERO2K three-dimensional emission inventories.

There is an observed 25 mK near-surface temperature change difference between the two inventories when normalizing to the inventory measurement year, and about 20 mK when normalizing both inventories to 2002. This difference is consistent with findings from Dahlmann et al. [2016a], which found that the peaks from the AERO2K and the TRADEOFF/QUANTIFY differ anywhere from 10-20 mK in the frequency density function of the ATR_{100}. Furthermore, the baseline near-surface temperate change can be compared to Grewe et al. [2021], which also used AirClim and a time frame up to 2100. Findings from that study are presented in Figure 5.2, which show five different scenarios. The primary focus for this assessment is the BAU (dark blue) case, which stands for Business As Usual and encapsulates a similar conceptualization of the baseline

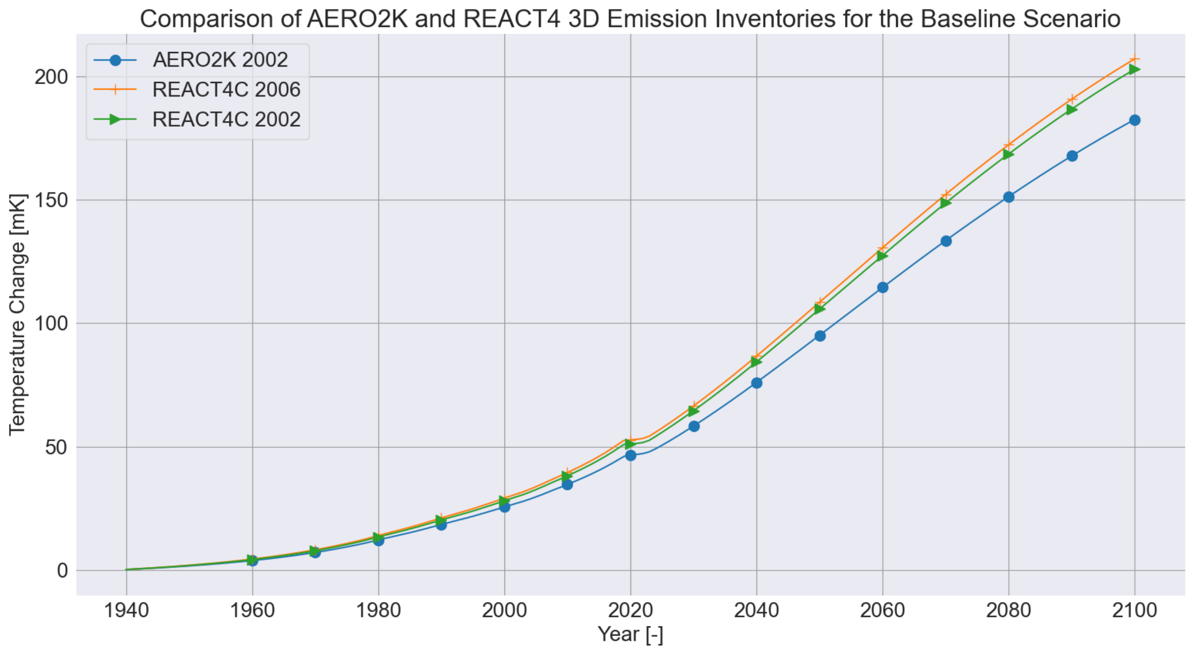

Figure 5.1: Visual representation of the near-surface temperature change with temporal change in years on the horizontal axis and temperature change in milikelvin (mK) on the vertical axis. Respective lines represent the impact of three-dimensional emission inventory selection over the time frame of the years 1940 to 2100 for the AERO2K and REACT4C inventories.

scenario. The figure shows a 50 mK lower ITC when comparing the BAU and the baseline scenario outputs in 2100. Besides the absolute difference, there is also an optical difference regarding the slope, which for the BAU scenario is much more flattened, thus indicating a slow or near-stagnated growth of aviation-induced climate impact. It was furthermore mentioned in the studies that the contribution of CO_2, contrail-cirrus, NO_x and H_2O was 41%, 22%, 36% and 1% respectively. In the baseline scenario using the REACT4C inventory, the NO_x and contrail-cirrus contributions to the climate impact were 31% and 27% respectively. H_2O is around 3% of the contribution, and the remaining 39% is taken up by CO_2. Thus the inventory used for the BAU displays behavior similar to the AERO2K 2002 model. This difference could also be explained by potentially differing computation methods for computing flown kilometers or assumptions regarding the NO_x emissions. In chapter 6 the Flight Path 2050 goals will be converted into data and plotted in a similar matter to allow for further comparison and as a consistency check. But for now, the different modeling choices in terms of input generation, emission inventory, and other relevant boundary conditions create an absolute difference in the order of 50 mK, and the total ITC growth is reducing visually in the BAU case.

5.1.2. Revenue Passenger Kilometer; Demand and Fuel Consumption

This initial parameter analysis is more thorough, given findings from this parameter assessment might repeat, or additional context is required to explain the manner of interpretation. Later findings are distilled as continuously repeating similar results is redundant. The foremost parameter assessed is the revenue passenger kilometer, as it is the backbone of the data structure. Changes are made to the RPK by changing the post-COVID-19 boundary parameter, which is 5% year-on-year growth for the baseline. Changes in fuel consumption resulting from this parameter change will be provided since this is the primary input to modeling the near-surface temperature change. The REACT4C and AERO2K inventories were used for modeling, to further the results regarding the discussion in the last section. Also, the model of the last section was generated using the IPCC A1B background. Here the IPCC A1T background is used, such that the baseline scenarios can be inter-compared. In subsection 4.2.2 the baseline scenario and several RPK forecasts were shown, which suggested that the RPK estimate was in line with other estimates, although other estimates generally did not extrapolate until 2100. The guiding assumption post-COVID was the RPK growth being in line with the UN population growth, and the setting of the year-on-year growth post-pandemic. The year-on-year growth is a volatile parameter, varying from above 8% in 2015 down to 2% in 2008 due to the financial crisis. Post-pandemic estimates are conservative, which thus resulted in setting a 5% growth rate, which will be

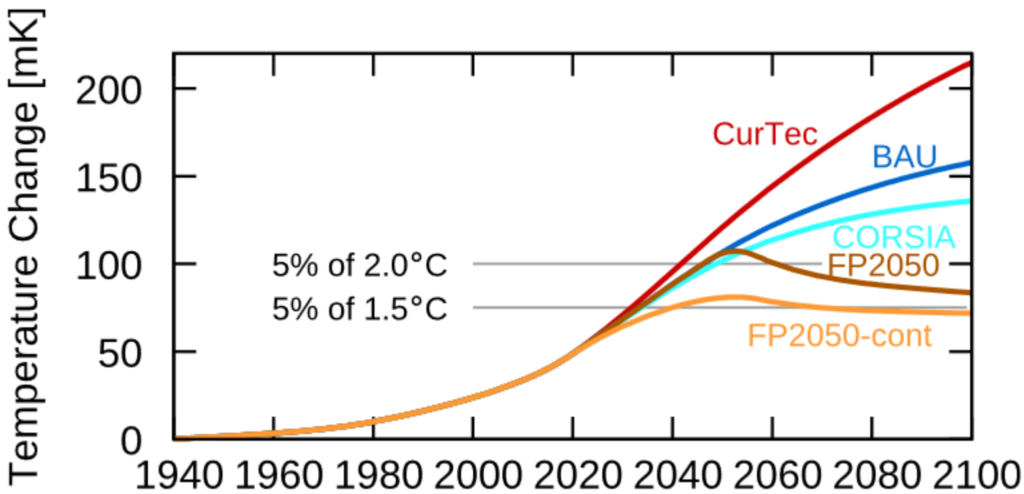

Figure 5.2: Near-Surface temperature change representing temporal change in years on the horizontal axis and temperate change in milikelvin (mK) on the vertical axis. Including representation of scenarios assuming future aviation uses current technology (CurTec; red), improves at business as usual rates (BAU; blue), assuming the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA; light-blue), and finally the Flight Path 2050 ambitions presenting a sudden (FP2050; brown) and constant improvement (FP2050-const; orange) towards the goals set in the plan. All scenarios include both CO_2 and non-CO_2-effects, using the RCP2.6 background and an in-house synthesized 3D-emissions inventory synthesized using WeCare Grewe et al. [2021].

varied between 6% and 4%. The correlation between the year-on-year growth and the fuel consumption was provided earlier in Figure 5.3. Substantial differences materialize due to the logarithmic nature of the RPK growth. Considerable deviation in the order of 300 E9 kilograms of fuel is the result of minimal changes.

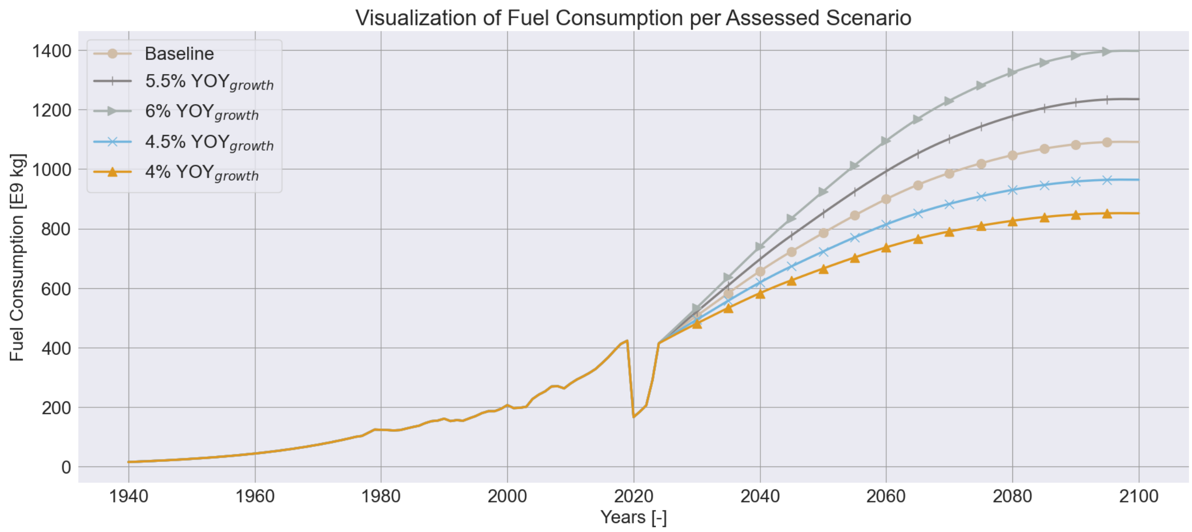

Figure 5.3: Temporal fuel consumption of the various revenue passenger kilometer scenarios showing the time frame on the horizontal axis on an annual basis, and the fuel consumption in billions of kilogram on the vertical axis. Due to changing of the year-on-year RPK growth parameter the fuel consumption of each case widely varies.

What this difference in fuel consumption means for the overall ITC is shown in Figure 5.4, showing that the change from the YOY growth parameter from 5% to 6% can yield up to around a 40 mK temperature increase. Table 5.3 provides a breakdown displaying the ITC per different emissions or emission-effect and the respective change to the baseline in the year 2100. The increase/decrease of the total ITC is an accumulation of all the different species changing caused by the emission inventory scaling and fuel consumption change. It can be seen that the net-NO_x-effects and CO_2 emissions yield the largest overall ITC. The net-NO_x-effects and water vapor (H_2O) induced climate impact, are fluctuating the most when considering a percentage-based change compared to the baseline. The reduction of the YOY$_{growth}$ to 4% reduces the ITC less than an inverse increase does, which is because the RPK growth is a non-linear relation, causing the fuel consumption to reduce less than it increases for both extremes. The fuel consumption grew by 305 megatonnes versus a 240 megatonnes decrease. The sensitivity of each specie compared to the baseline values is provided in Figure 5.5 where all values are shown as absolute values for legibility. E.g. the 4% YOY$_{growth}$ is a reduction of 20% from the baseline, which causes a reduction -0.75% of ITC per percent of parameter change. What this figure implies is that the increase and reduction of the YOY$_{growth}$ does not behave linearly, with an increasing cause a higher per percentage parameter increase. However, it can be observed that the sensitivity does not change dramatically indicating a stable model behavior.

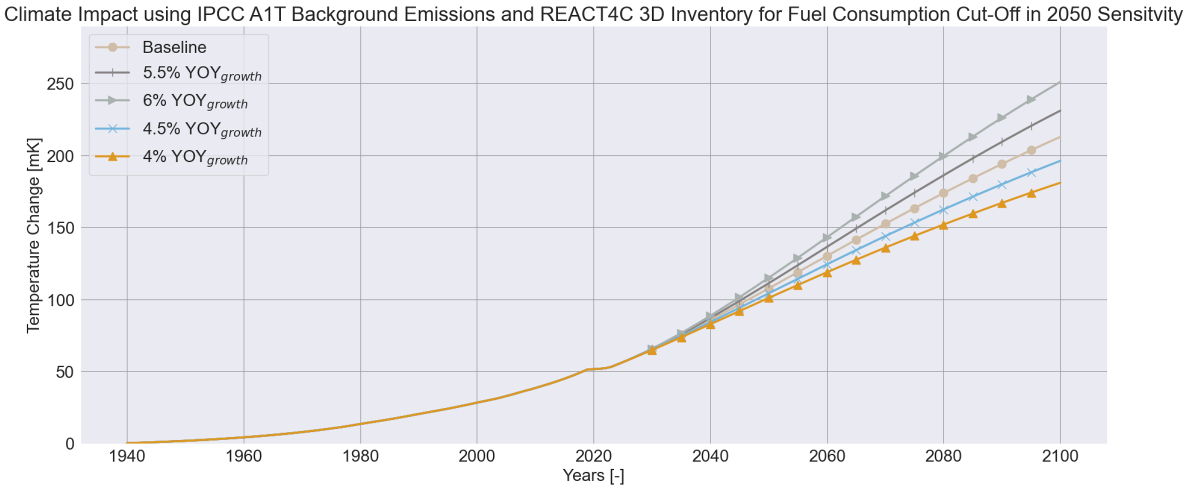

Figure 5.4: Temporal near-surface temperature change resulting from changing the revenue passenger kilometers year-on-year growth, showing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions, displaying similar overall behavior but varying slopes for each different scenario.

Scenarios	ΔT_{total}	**Difference**	ΔT_{CO_2}	**Difference**	ΔT_{Cont}	**Difference**	ΔT_{H_2O}	**Difference**	ΔT_{NO_x}	**Difference**
6% YOY$_{growth}$	250.90	17.92%	94.93	15.65%	65.47	12.83%	8.10	24.05%	82.40	24.60%
5.5% YOY$_{growth}$	230.98	8.56%	88.20	7.45%	61.68	6.29%	7.27	11.37%	73.84	11.64%
Baseline (5%)	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
4.5% YOY$_{growth}$	196.13	-7.82%	76.52	-6.78%	54.52	-6.04%	5.86	-10.16%	59.22	-10.45%
4% YOY$_{growth}$	180.93	-14.96%	71.46	-12.94%	51.17	-11.81%	5.27	-19.24%	53.02	-19.83%

Table 5.3: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying the RPK year-on-year growth between 4% and 6%.

As already mentioned earlier, the net-NO_x-effects and H_2O ITC change the most. However, it says nothing of the contribution of the total ITC. It is important to identify the contribution of each species towards the total temperature change, both for the sake of inter-comparison with other studies and understanding the optimization problem. I.e. if there is a 20 mK change, it would be useful to know how big the contributions were per specie to that change. Table 5.4 provides this breakdown, where it is shown that for each of the cases the ratios remain similar. The net-NO_x-effects contribute most, followed by CO_2, contrail-cirrus and H_2O respectively. As a result of fuel consumption change caused by the input changes, the ratios change only minimally, with the contrail-cirrus and net-NO_x-effects changing their ratio when we move the scenarios with lower climate impact. Given the fuel consumption is reduced, the flown kilometers are scaled-down, and thus there is less flown coverage and opportunity to generate contrail-cirrus. Also, the net-NO_x-effects are reduced as a result of lower fuel consumption. These fluctuations seen within net-NO_x-effects and not in CO_2 related ITC could be explained by a combination of the lifetime of particular molecules and the background of the emissions building up.

Thus the RPK and changing the RPK with a focus on the RPK growth factor on a year-on-year basis causes a near-surface temperature change according to a change in fuel consumption dictated by the change in RPK

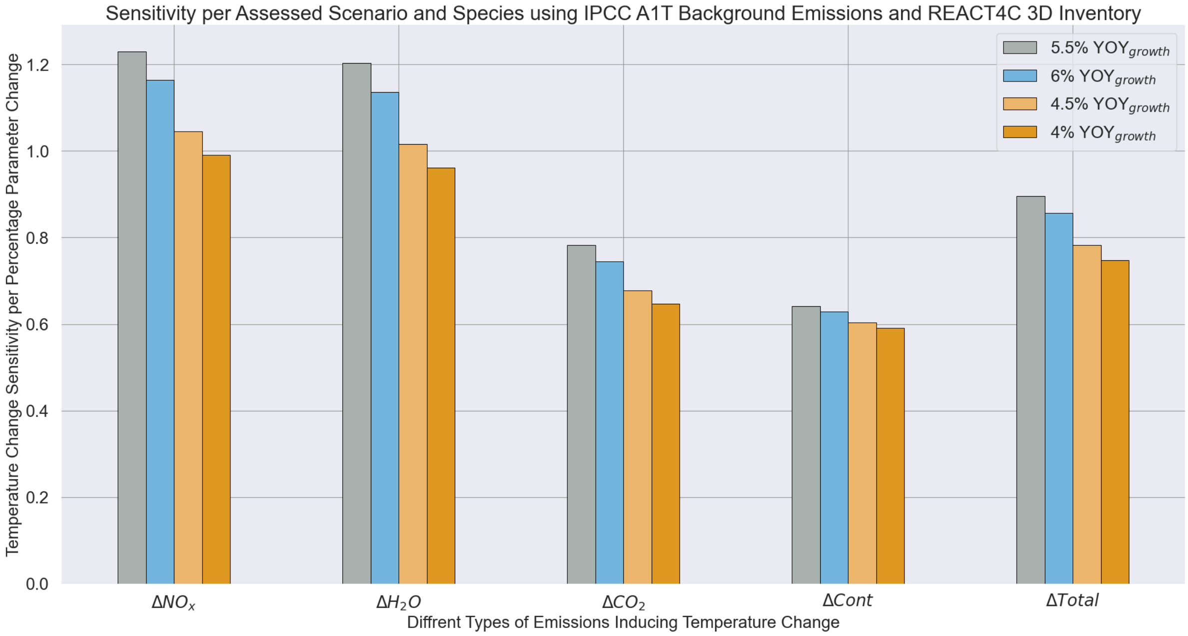

Figure 5.5: Sensitivity of the respective revenue passenger kilometers year-on-year growth scenario showing the species along the horizontal axis and the temperature change sensitivity on the vertical axis, indicating the relation between parameter change versus change in total induced-temperature change.

Scenarios	ΔCO_2	$\Delta Cont$	ΔH_2O	ΔNO_x
6% YOY$_{growth}$	33.70%	19.51%	4.12%	42.67%
5.5% YOY$_{growth}$	33.61%	20.04%	4.06%	42.28%
4.5% YOY$_{growth}$	33.41%	21.03%	3.97%	41.53%
4% YOY$_{growth}$	33.35%	21.51%	3.96%	41.17%

Table 5.4: Indication of the contribution to the total induced temperature change of respective scenarios for the RPK parameter assessment using the REACT4C inventory and the IPCC A1T background emissions, varying the year-on-year RPK growth post-COVID-19. The percentage indicates proportion to which that specie was responsible the total change induced temperature change. E.g. when there is a total increase of 20 mK and the ΔNO_x column indicates 40%, this implies that net-NO_x-effects have caused 8 mK of the total temperature change in that specific scenario.

growth. Throughout historical records, the year-on-year growth has varied and the manner of growth will be uncertain. The RPK parameter has been shown to behave stably, as seen in Figure 5.5 through the only slight differences in the sensitivity. In case there would be an unstable sensitivity, this would be very apparent in the sensitivity plot through widely varying bar lengths. Due to the potentially large parameter variation, this can cause an output variation. The temporal evolution was found in Figure 5.4 and the 2100 snapshot in Table 5.4. Furthermore, it was seen that fuel consumption changes cause changes to all species as could be expected if the source of emissions is to be changed. In this setup, the change in net-NO_x-effects and CO_2 ITC dictate climate impact, with net-NO_x-effects being smaller as an absolute contribution to the total ITC, yet appears to dictate the change in total ITC as a result of fuel consumption changes.

Sensitivity AERO2K 3D Emissions Inventory for Identical Scenarios

The differences between the inventories were already discussed in section 3.2 and the sensitivity as well in subsection 5.1.1. The conclusion was that the REACT4C yields a higher overall total ITC, primarily caused by differences in net-NO_x-effects and the contrail-cirrus ITC. This fact is supported by a comparison of Table 5.5 and Table 5.3. Furthermore, it is expected that the contribution per specie towards the near-surface temperature change would differ, as shown when comparing Table 5.4 and Table 5.6. It was indeed previously established that the contrail-cirrus and net-NO_x-effects were significantly lower, causing the overall better climate impact performance for the AERO2K inventory. It is observed that the CO_2-emissions are larger for both the REACT4C and AERO2K models, which show identical results. This is the result of the use of the IPCC

A1T background emissions, instead of the IPCC A1B description.

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
6% YOY$_{growth}$	222.71	17.82%	94.93	15.65%	51.14	12.71%	8.48	23.98%	68.17	24.52%
5.5% YOY$_{growth}$	205.11	8.50%	88.20	7.45%	48.20	6.22%	7.61	11.32%	61.10	11.62%
Baseline (5%)	189.04	-	82.08	-	45.38	-	6.84	-	54.74	-
4.5% YOY$_{growth}$	174.36	-7.76%	76.52	-6.78%	42.68	-5.94%	6.14	-10.14%	49.02	-10.45%
4% YOY$_{growth}$	160.98	-14.84%	71.46	-12.94%	40.12	-11.60%	5.52	-19.21%	43.88	-19.84%

Table 5.5: Near-surface temperature breakdown in milikelvin (mK) using the AERO2K and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying the RPK year-on-year growth between 4% and 6%.

Scenarios	ΔCO_2	$\Delta Cont$	ΔH_2O	ΔNO_x
6% YOY$_{growth}$	38.15%	17.13%	4.87%	39.85%
5.5% YOY$_{growth}$	38.08%	17.55%	4.79%	39.58%
4.5% YOY$_{growth}$	37.90%	18.40%	4.70%	38.99%
4% YOY$_{growth}$	37.85%	18.75%	4.67%	38.70%

Table 5.6: Indication of the contribution to the total induced temperature change of respective scenarios for the RPK parameter assessment using the AERO2K inventory and the IPCC A1T background, varying the year-on-year RPK growth post-COVID-19. The percentage indicates proportion to which that specie was responsible the total change induced temperature change.

5.1.3. The Behavior of the Fuel Economy Parameter

The fuel economy can be altered through the decay factor, which essentially changes the description of the correlation between the RPK and the fuel consumption. A comprehensive description of the fuel economy parameter was already presented in subsection 4.2.3. Changing the decay factor artificially changes the technological advancement, and thus the fuel consumption is changed to stagnate (due to the efficient aviation system) or to grow more significantly than the baseline. Also, the trend for the fuel economy is built on historical data, thus shifts in the fuel economy trend are assessed.

Implications of Changing the Decay Factor

For the baseline, the η was equal to 0.97. Values ranging from 0.8 (near-instant stagnation) up to 1.0 (continuous linear growth) were analyzed for the sensitivity analysis. The change of the decay factor translates into the following fuel consumption shown in Figure 5.6. To understand how the fuel economy changes as a result of the change in the decay factor, reference back to Figure 4.9. The figure shows that the minor adjustments to the decay, have significant implications on the fuel consumption. A difference of up to 300-350 billion kilograms of fuel burn is the result, comparable to the fuel consumption difference seen in the RPK assessment. For this assessment of the fuel economy, the range is not because the η-values are of particular interest, since e.g. it is unlikely that the case of η=0.8 (near stopping of technological development) will occur in our reality. It is more important to understand the behavior of this model regarding the change of model parameters and at extreme values.

The different scenarios and their ITC are found in Table 5.7, which shows that a full stagnation of fuel economy growth yields around 37 mK (17.5%) of ITC. Inversely, a temperature change reduction of 35 mK (-16.4%) was found compared to the baseline for the linear growth of the fuel economy scenario. It should also be noted that the 4% YOY$_{growth}$ scenario from the RPK analysis was added, which has been done given the close resemblance to the η=1.0 scenario. The only difference between the two cases is the temporal evolution of fuel consumption caused by the specific manipulation of data. Comparing the respective cases in Figure 5.3 and Figure 5.6 that there exists around a 100 E9 kilogram of fuel consumption difference at the end of the time frame. The η=1.0 fuel consumption line lies consistently higher until around 2070 when the line starts to decrease due to continuously growing efficiency improvements and a slower rate of RPK increase as modeled. The only slight difference of around 3 mK can be explained that the bulk reduction for the η=1.0 case occurs at the end of the time frame, besides the fact that there is more atmospheric CO_2 accumulation due to faster growth. The reduction in fuel consumption will only be expressed in full with a 30-year response delay.

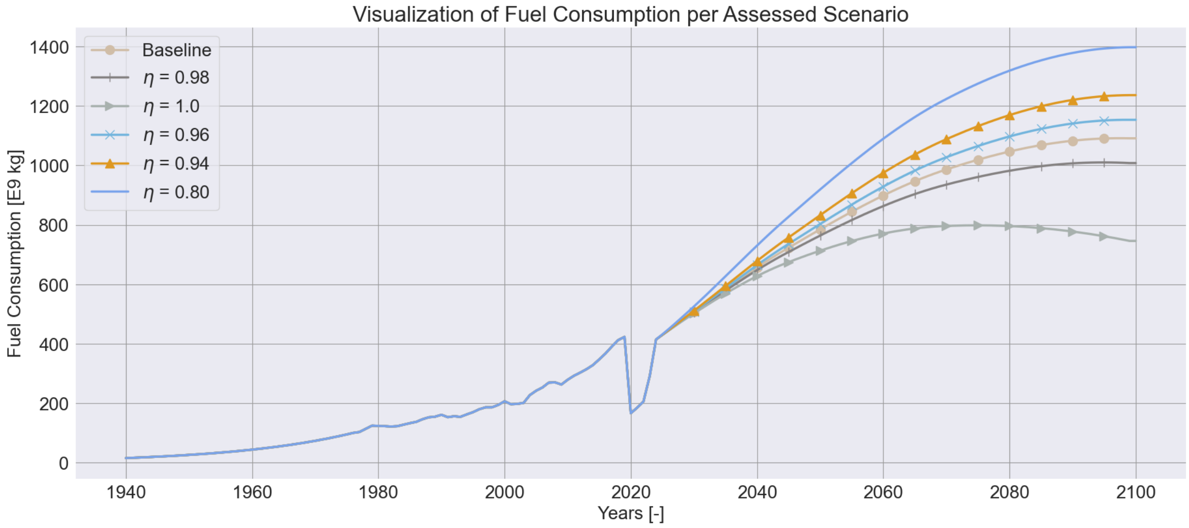

Figure 5.6: Temporal fuel consumption resulting from various decay factors selected for the fuel economy, showing the time frame on the horizontal axis on an annual basis, and the fuel consumption in billions of kilogram on the vertical axis. Where η= 0.8 represents a stagnation of technological development, and η= 1.0 represent a linear growth of improvement of fuel economy resulting in a low decreasing fuel consumption.

Allowing to include Table 5.8, this fact is further outlined given for the case observed for the RPK parameter the contribution of CO_2 and net-NO_x-effects on the ITC were 33.35% and 41.17% respectively. For the η=1.0 case, this was 26.97% and 46.50% respectively. Thus indicating a similar reduction in the latter case is more caused through net-NO_x-effects, which take much shorter to express. Also, the contrail-cirrus has increased in total ITC reduction as a result of lower fuel consumption and thus less flown distance.

Scenarios	ΔT_{total}	**Difference**	ΔT_{CO_2}	**Difference**	ΔT_{Cont}	**Difference**	ΔT_{H_2O}	**Difference**	ΔT_{NO_x}	**Difference**
$\eta = 0.8$	249.99	17.49%	94.43	15.04%	65.32	12.57%	8.07	23.59%	82.17	24.25%
$\eta = 0.94$	229.20	7.72%	87.14	6.16%	61.37	5.77%	7.21	10.48%	73.48	11.10%
$\eta = 0.96$	219.58	3.20%	84.11	2.48%	59.44	2.43%	6.81	4.35%	69.22	4.67%
$\eta = 0.97$ (Baseline)	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
$\eta = 0.98$	203.99	-4.13%	79.58	-3.05%	56.15	-3.23%	6.16	-5.58%	62.10	-6.11%
4% YOY$_{growth}$	180.93	-14.96%	71.46	-12.94%	51.17	-11.81%	5.27	-19.24%	53.02	-19.83%
$\eta = 1.0$	177.91	-16.38%	72.68	-11.45%	50.20	-13.48%	5.10	-21.91%	49.93	-24.51%

Table 5.7: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying decay factor values ranging from η= 0.8 to η= 1.0.

Scenarios	ΔCO_2	$\Delta Cont$	ΔH_2O	ΔNO_x
$\eta = 0.8$	33.18%	19.59%	4.14%	43.10%
$\eta = 0.94$	30.80%	20.39%	4.14%	44.67%
$\eta = 0.96$	29.81%	20.70%	4.11%	45.37%
$\eta = 0.98$	28.47%	21.30%	4.10%	46.01%
$\eta = 1.0$	26.97%	22.43%	4.10%	46.50%

Table 5.8: Indication of the contribution to the total induced temperature change of respective scenarios for the RPK parameter assessment using the REACT4C inventory and the IPCC A1T background, varying the fuel economy decay factor changing the post-COVID-19 technological development. The percentage indicates proportion to which that specie was responsible the total change induced temperature change.

The sensitivity of the fuel economy decay factor is high, which is indicated by Figure 5.7 where a large spread is observed between the respective scenario bars. As opposed to the RPK scenario the bars reach a factor

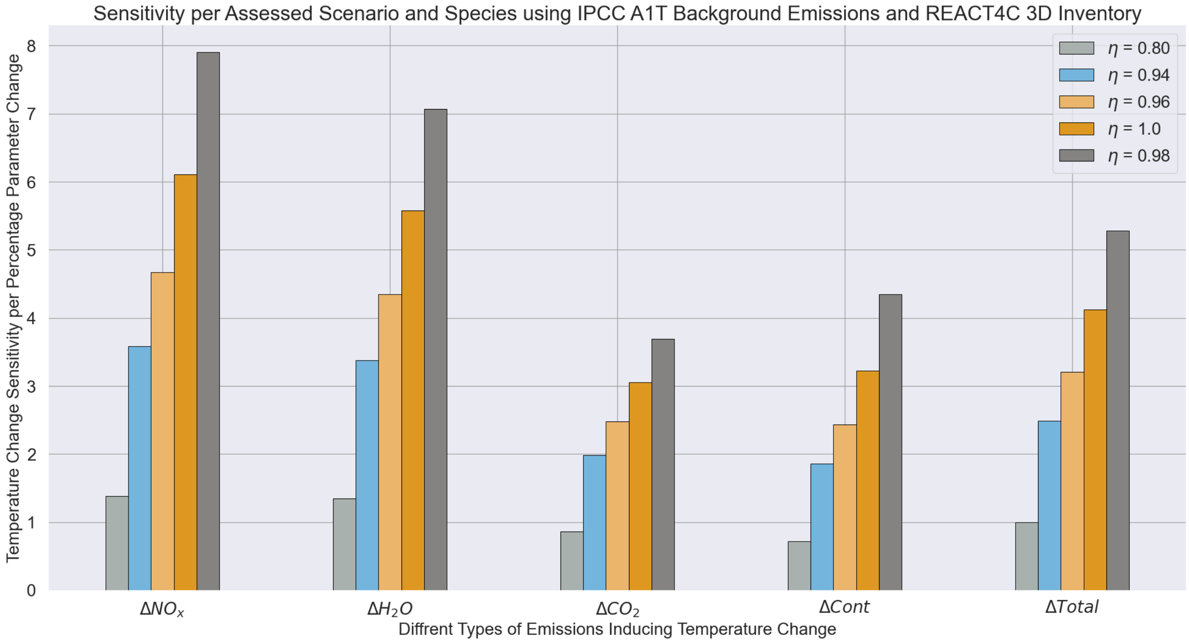

Figure 5.7: Sensitivity of the respective fuel economy decay factor scenario showing the species along the horizontal axis and the temperature change sensitivity on the vertical axis, indicating the relation between parameter change versus change in total induced-temperature change. The respective bars display large spread and a high nominal value, displaying parameter instability and importance to output near-surface temperature change

of up to around 5 for the total temperature change in case the decay factor is 0.98. This implies a strong impact of changing the decay factor on the eventual temperature change. Also, where for the RPK analysis the contrail-cirrus and CO_2 sensitives were similar, here the contrail-cirrus bar is higher. Thus a temperature change is related to the temporal evolution of fuel consumption and the species-related impact. Outlining an important question regarding staying below certain thresholds, as the atmospheric chemistry and the response might differ as a result of the temporality of emissions, requiring further investigation into the time-based component of emissions. In short, the decay factor is a parameter that can change the relationship between RPK and fuel consumption, thereby being a driving parameter that allows a more global investigative analysis. The choice of this parameter can cause variations up to 37 mk increase and 35 mK decrease in case of a stagnating ratio and a linearly growing ratio.

Implications of Changing the Fuel Economy Function

The function change implies shifting of the trend downwards or upwards. Essentially a percentile change to the baseline, scaling the vertical function components by a factor, shifting the function to a higher or lower RPK per kilogram of fuel. A scaling factor of unity plus and minus 20% is used, to both increase and decrease the fuel economy trend. Scaling is not done during obtaining of final results, but is done to understand the limitations of using a trendline, and what it would mean if the estimated trendline is either over or under-estimated. Only a shift occurs, thus not the general shape of the function is changed, besides the shape change caused by the decay factor. This results in a fuel consumption trend as shown in Figure 5.8, where the trend shift can be seen as all lines display and offset. Emissions in the normalization year for the emission inventory also differ due to differences in fuel consumption, which causes different normalization factors. Table 5.9 summarizes the result for the end of the year 2100.

Due to the deviation occurring pre-2025, the temperature change temporal evolution also deviates as depicted in Figure 5.9. The trends behave similarly, only displaying slight differences in slope and an offset caused by the changed fuel consumption. Around a 20 mK difference exist in the year 2025 between the extreme cases. With the trend reduced by 20%, the fuel consumption grew, and the total ITC increased by 21.6% to a total of 258.7 mK. When shifting the trend 20% upwards, the total ITC reduced to 181.3 mK with 14.82%. Looking at the contribution breakdown in Table 5.10, it shows that all CO_2 emissions contributions are about 43%, showing the importance of temporal trend and that the scaling did not change consistency between the scenarios.

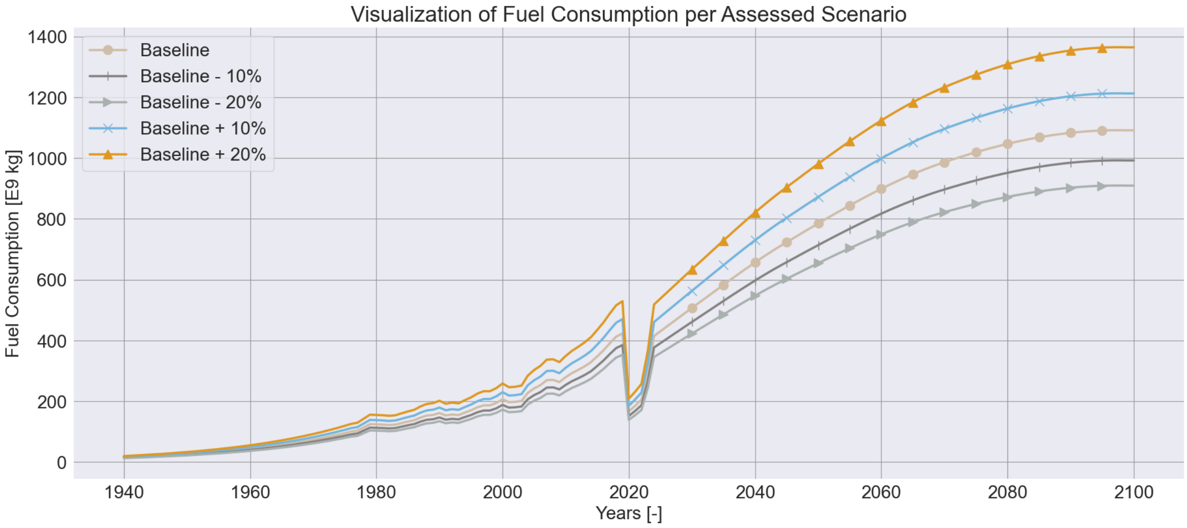

Figure 5.8: Temporal fuel consumption resulting from various shifts of the fuel economy trend, showing the time frame on the horizontal axis on an annual basis, and the fuel consumption in billions of kilogram on the vertical axis. The modifiers indicate the vertical shifts of the fuel economy trend by a specific percentage, thus 'Baseline + 10%' simply represents a scaling of the vertical fuel economy component by a factor of 1.1

Scenarios	ΔT_{total}	**Difference**	ΔT_{CO_2}	**Difference**	ΔT_{Cont}	**Difference**	ΔT_{H_2O}	**Difference**	ΔT_{NO_x}	**Difference**
Trend -20%	258.68	21.58%	102.28	24.60%	66.17	14.03%	8.16	25.00%	82.08	24.10%
Trend -10%	233.34	9.67%	91.08	10.96%	61.77	6.45%	7.25	11.12%	73.24	10.75%
Baseline Trend	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
Trend + 10%	195.69	-8.03%	74.70	-8.99%	54.78	-5.59%	5.94	-9.08%	60.27	-8.87%
Trend + 20%	181.25	-14.82%	68.52	-16.52%	51.91	-10.53%	5.44	-16.70%	55.38	-16.27%

Table 5.9: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

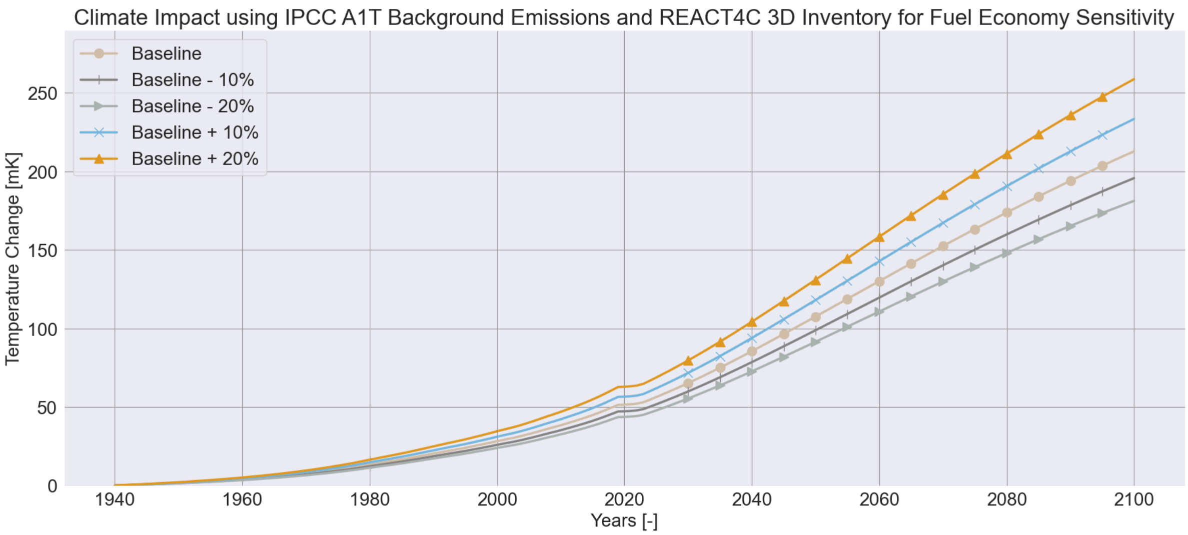

Figure 5.9: Temporal near-surface temperature change resulting from fuel economy trend factorization, showing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions.

5.1.4. The Behavior of the Market Based Mechanism Module

The market-based mechanism is included for the undeniable link between aviation demand driving emissions and the market. It is understood that taxes for either short- or long-range flights can have a complex

Scenarios	ΔCO_2	$\Delta Cont$	ΔH_2O	ΔNO_x
Trend - 20%	43.98%	17.73%	3.55%	34.72%
Trend - 10%	43.75%	18.18%	3.55%	34.56%
Trend + 10%	43.21%	18.97%	3.45%	34.37%
Trend + 20%	43.02%	19.38%	3.46%	34.14%

Table 5.10: Indication of the contribution to the total induced temperature change of respective scenarios for the RPK parameter assessment using the REACT4C inventory and the IPCC A1T background, varying the fuel economy trend height to test assumption implications. The percentage indicates proportion to which that specie was responsible the total change induced temperature change.

result such that the model outlined in subsection 4.3.1 was devised. It is acknowledged that there is a lack of adequate high-detail models, besides the market economy not being an area of professional expertise, which has resulted in a simple model with a static elasticity, price change, and the pass-through rate to serve as a simplified representation. Within this model, ticket pricing and elasticity are relevant parameters. Since the cost-pass through and the elasticity are essentially scalars of one another, changing one will imply enough about the behavior of the other. It is relevant to understand the impact of the market-based module on the RPK, and thus the fuel consumption. Furthermore, these results should be consistent with all previous findings as it is just scaling the fuel consumption in a particular manner.

The Impact of Changing the Price to Fly

For reference to how the price change induces a change in input data, refer back to subsection 4.3.1. In short, a tax incentive gets translated into an absolute change in RPK, which is added or subtracted to the annually growing RPK in a distributed manner. This is done because a sudden direct decrease in demand would not be consistent with the logic of the logarithmically growing RPK. The implications on the fuel consumption of the increase and decrease of 20% ticket price are shown in Figure 5.10, here the price increase is called taxation and the inverse a subsidy. One sees that the trends deviate only slightly and that the incremental decrease in RPK depresses the growth gradually over 30 years. This fuel consumption then yields the temperature change as outlined in Table 5.11, which shows that the ITC behavior is linear across all cases with a reduction and increase of the total ITC of around 5.8% to 225.1 mK and 200.33 mK respectively.

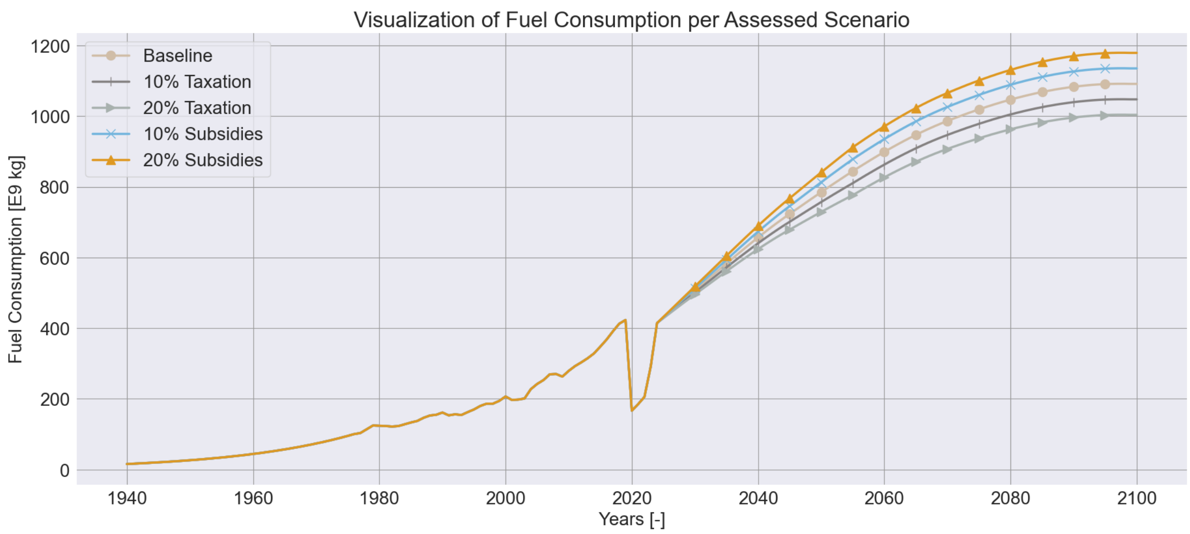

Figure 5.10: Temporal fuel consumption resulting from changes in ticket pricing through taxation and subsidies, showing the time frame on the horizontal axis on an annual basis, and the fuel consumption in billions of kilogram on the vertical axis. The elasticity is set to 1.46 and the pass-through rate at 0.6, which are kept constant.

There is a difference when looking at Table 5.12 in comparison to the previous analysis. Here the CO_2 contribution lies around 35-36%. The RPK analysis arrivers at a reasonably similar percentage of around 33-34%, and the fuel economy decay analysis displays an even lower CO_2 contribution to the temperature change. Between these cases, there is however a markable difference in the temporal evolution of the fuel consumption. For both the RPK and fuel economy assessments, the fuel consumption changes were much larger, causing

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
20% Subsidies	225.06	5.78%	86.50	5.39%	60.48	4.23%	7.02	7.51%	71.06	7.45%
10% Subsidies	218.94	2.90%	84.29	2.69%	59.27	2.14%	6.77	3.75%	68.60	3.73%
Baseline	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
10% Taxation	206.57	-2.92%	79.87	-2.70%	56.75	-2.19%	6.28	-3.74%	63.66	-3.74%
20% Taxation	200.33	-5.85%	77.65	-5.40%	55.45	-4.44%	6.04	-7.49%	61.18	-7.49%

Table 5.11: Near-surface temperature breakdown looking at artificial ticket price change in milikelvin (mK), using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

Scenarios	ΔCO_2	$\Delta Cont$	ΔH_2O	ΔNO_x
20% Taxation	35.96%	20.02%	3.99%	40.03%
10% Taxation	35.82%	20.10%	4.05%	39.87%
10% Subsidies	35.65%	20.48%	3.87%	39.84%
20% Subsidies	35.61%	20.66%	3.94%	39.79%

Table 5.12: Indication of the contribution to the total induced temperature change of respective scenarios for the RPK parameter assessment using the REACT4C inventory and the IPCC A1T background, as a result of assessing the market based mechanism for different configurations. The percentage indicates proportion to which that specie was responsible the total change induced temperature change.

non-CO_2 based contributions to dominate the ITC change. For the market-based model, the contribution of CO_2 is higher, which could be caused by the smaller and more incremental change in fuel consumption, which does not radically shift the contribution change to more short-term-based effects. Even with these smaller changes in fuel consumption, net-NO_x-effects still contribute most to the changing ITC but comparatively less than in the other contribution breakdowns.

The behavior of the pricing model is stable within the tested range. CE Delft [2019] assessed through their model the impact of including VAT in a host of countries, where they computed demand shifts according to VAT changes. For example France, in a market of 81.5 million passengers, 10% VAT translated into 7% demand reduction. Many other countries displayed a one-to-one relationship, with the VAT change being in line with the demand change. The model used for this thesis, with the settings of cost-pass through and elasticity, responds similarly to the estimate for France. However, the manner of implementation has not been related to any current market models and is illustrative of a particular change in a qualitative manner. The sensitivity is given in Table 5.11, which shows that in the case of taxation and subsidies, the module behaves linearly, implying all scenarios have similar sensitivity and the parameter change causes a stable change to the inputs. In the current setting the model provides what is required; A marginal reduction of RPK in a non-abrupt manner.

Market Based Mechanism Dynamics of the Elasticity Parameter at 20% Price Change

Now instead of the price, the elasticity is changed, which will then influence the demand change. The elasticity (ϵ) was changed from the baseline of 1.146 down to 0.458 (very non-elastic behavior) to 1.834 (elastic behavior), with a programmed price increase of 20%. Table 5.13 clearly shows that the deviation as a result of this change is minimal in terms of ITC. The total temperature change only changes by around 3.7%. The baseline here constitutes the original baseline but then with a 20% price increase. It was found that the behavior is still linear and that large variations in the elasticity do not iterate the results much. When comparing Table 5.13 and Table 5.11 it can of course be seen that a 20% price setting with a higher or lower elasticity will create a difference to that value found there.

5.1.5. Behavior and Impact of Changing Nitrogen Oxides Factorization

The NO_x adjustments are simply changes in the factorization of the EI_{NO_x} used for the baseline, for which the precision could be up to changing the EI_{NO_x} on an annual basis. Lowering the factorization implies a reduction of the NO_x emissions per burnt fuel. This analysis provides an insight into the relation of NO_x emission reduction and the subsequent reduction in climate impact. The EI_{NO_x} is changed instantly to another setting from 2050 on-wards to generate a general mapping of this change on the climate impact. The sensitivity is hard to assess for this parameter, given the many variable options that could underly the tempo-

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
$\epsilon = 0.458$	207.81	3.74%	80.31	3.42%	57.01	2.81%	6.33	4.85%	64.16	4.86%
$\epsilon = 0.802$	204.08	1.87%	78.98	1.71%	56.24	1.42%	6.19	2.43%	62.67	2.43%
Baseline ($\epsilon = 1.146$)	200.33	-	77.65	-	55.45	-	6.04	-	61.18	-
$\epsilon = 1.490$	196.56	-1.88%	76.32	-1.71%	54.65	-1.44%	5.89	-2.43%	59.70	-2.43%
$\epsilon = 1.834$	192.78	-3.77%	74.99	-3.43%	53.84	-2.90%	5.74	-4.87%	58.20	-4.88%

Table 5.13: Near-surface temperature breakdown looking at artificial ticket price change in milikelvin (mK), using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

ral EI_{NO_x} trend. The changes in EI_{NO_x} are kept elementary, where the post-2050 the EI_{NO_x} is reduced for up to 60%. Table 5.14 shows that the total ITC reduction increases in an approximately linear way, implying that every 10% of NO_x emissions reduction, the ITC also reduces linearly. Initially at 3.20%, growing to slightly less than double at 6.31%, finally reducing the total ITC by 12.71%. Besides the reduction in NO_x emissions, chaning the EI_{NO_x} has an impact on the ITC of H_2O, significant in relative change but relatively insignificant overall. Thus, a reduction in NO_x emissions through whatever pathway is a worthwhile endeavor, showing a near one-to-one relation between post-2050 reduction in EI_{NO_x} and NO_x-effects. The previous simulations for the RPK and fuel economy showed a reduction in the order of 20-25% for the net-NO_x-effects, resulting from a relatively much higher reduction in fuel consumption. Furthermore, the CO_2 induced temperature change components still dominates and the NO_x is most significant in changing the induced temperature change. If less NO_x-heavy technology receives focus in parallel significance with fuel consumption reductions, this would be a great oppurtunity to reduce the ITC related to NO_x emissions. The potency of the NO_x emissions reduction technologies and the impact is closely related to the absolute fuel consumption. This means that if the fuel consumption has already been reduced significantly before NO_x reducing technologies are introduced, they are still helpfull but reduce the NO_x emissions less in an absolute scale.

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
100% EI_{NO_x}	212.77	-	82.08	-	58.02	-	6.53	-	66.14 -	
90% EI_{NO_x}	205.95	-3.20%	82.08	-	58.02	-	5.91	-9.44%	59.94	-9.37%
80% EI_{NO_x}	199.34	-6.31%	82.08	-	58.02	-	5.34	-18.26%	53.89	-18.51%
70% EI_{NO_x}	192.56	-9.50%	82.08	-	58.02	-	4.74	-27.41%	47.71	-27.86%
60% EI_{NO_x}	185.74	-12.71%	82.08	-	58.02	-	4.14	-36.53%	41.49	-37.27%

Table 5.14: Near-surface temperature breakdown looking at the impact of changing nitrogen oxides emissions in milikelvin (mK), using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

5.1.6. The Behavior of the Formation Flight Module

The implementation formation flight is the first assessed module that involves multiple parameter changes. It changes both fuel consumption and the NO_x due to contrail mixing. Furthermore, some post-processing is performed, following the findings from the literature. This result in the following fuel consumption trend as seen in Figure 5.11, which then results in the ITC from Figure 5.12. Fuel consumption is reduced instantaneously and does not affect the later fuel consumption growth since the factorization applies after calculating the model parameter. One can observe an abrupt change in 2025 upon the introduction of formation flight resulting from the reduced fuel consumption. The oversimplifications of this manner of modeling were outlined in the methodology section in subsection 4.3.3. Also, the fact that a full fleet is non-sensical as this will be impossible to achieve, but it has been done to perform simple analysis. The trend with the higher fuel savings yields a lower temperature change and the slope of the respective lines differs. Table 5.15 confirms what was mentioned in subsection 4.3.3, which stated findings from using these settings, that a 5-6% effective fuel consumption reduction, with contrail mixing and reduction of contrail potency, would yield about an ATR_{50} of 20-23% [Marks et al., 2021].

The behavior of the formation flight module is modeled as an instantaneous change, dominated by the post-processing step entailing a direct factorization for contrail climate impact. Figures show that the output trend

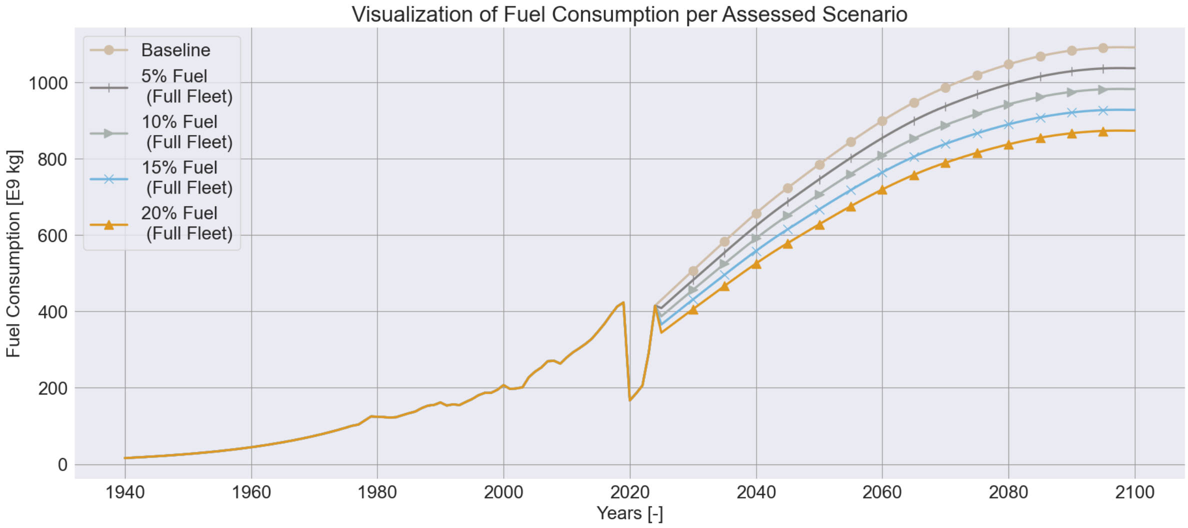

Figure 5.11: Temporal fuel consumption for the assessment of formation flight strategies, showing the time frame on the horizontal axis on an annual basis, and the fuel consumption in billions of kilogram on the vertical axis. Percentages indicate the fuel savings, assuming formation flight of the full fleet.

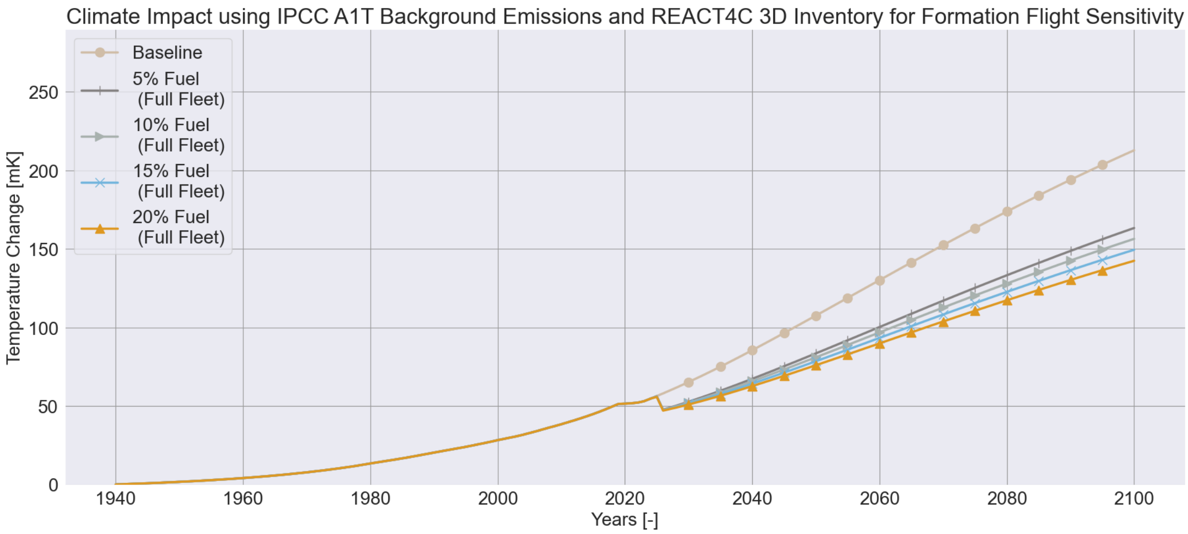

Figure 5.12: Temporal near-surface temperature change resulting full fleet formation flight with contrail mixing, showing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions.

Scenarios	ΔT_{total}	**Difference**	ΔT_{CO_2}	**Difference**	ΔT_{Cont}	**Difference**	ΔT_{H_2O}	**Difference**	ΔT_{NO_x}	**Difference**
Baseline (No Formation)	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
5% Fuel Savings	163.33	-23.24%	72.11	-12.15%	29.30	-49.50%	5.55	-15.01%	56.37	-14.76%
10% Fuel Savings	156.42	-26.49%	69.21	-15.69%	28.40	-51.05%	5.27	-19.33%	53.54	-19.04%
15% Fuel Savings	149.46	-29.75%	66.30	-19.22%	27.47	-52.65%	4.98	-23.67%	50.70	-23.34%
20% Fuel Savings	142.46	-33.04%	63.40	-22.76%	26.51	-54.31%	4.70	-28.00%	47.85	-27.64%

Table 5.15: Near-surface temperature breakdown looking at the impact of formation flight with respective fuel savings and contrail mixing, provided in milikelvin (mK), through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

does not change much in shape. The sudden reduction caused by fuel reductions and factorization shifts the trends downwards, and as one parameter of the total ITC is factorized the slope becomes less steep compared to the baseline. Looking back at Figure 5.4, which is the result of a large change in fuel consumption, the difference between all curves is notable as each case mobilizes a change in each species ITC. Table 5.15 shows that the variation between scenarios is driven by CO_2 and net-NO_x-effects impacts changing, resulting from overall lower fuel consumption, which is a behavior observed previously. This module has a high sensitivity, which is caused by the assumptions of fuel implementation and factorization during the post-processing. In this specific case, the full 48% contrail cirrus climate impact reduction is applied following the full fleet formation flight assumptions, as the formation flight will be performed by fewer aircraft this factorization reduces. The formation flight is turned either on or off, meaning that benefits are applied across the whole aviation impact. This is done to look at the achievable result when taking overly-optimistic assumptions. A more realistic outlook will be provided later.

5.1.7. The Impact of Flying Lower; A Lower Boundary for Climate Optimal Routing

Since climate optimal routing would require a complex model and an altogether different approach for interacting with AirClim, the lower flight is a minor showcase of the importance that re-routing could hold to mitigate climate impact. Studies have estimated the climate impact shift of flying 600 meters lower, but this is not a directly optimized vertical shift of altitude, and more could potentially be gained. The results from the studies by Matthes et al. are integrated into the post-processing of the results. For the assessment of lower flight, the modifiers are applied upon the baseline, again through the assumption of full fleet participation in lower flight. This analysis is thus omitting any form of optimization based on aircraft type and finding an optimal altitude reduction on a case-by-case basis, as this is outside the scope of the research question. The findings from this section will then be superimposed and combined to generate the ISO module discussed later. The ITC can be found in Table 5.16 through applying the values from the literature, a reduction of 11.12% of the total ITC was found, which is lower than the expectation from the literature. Lower flight is expected to lower the NO_x, H_2O and contrail cirrus related effects. It should be noted that the CO_2 ITC remains similar here because only the non-CO_2 effects were integrated into post-processing. Also, although the drag increase resulting from lower flight increases the fuel burn, the CO_2 ITC was not estimated to increase much. The lower flight allows for a good intermediate option, which would require air traffic control and economic incentive re-structuring, however, it should not require much technological change concerning the aircraft itself. As technologies are being produced through technological advances, operational tools at our disposal should be used to already reduce the measurable impact and lower flight shows a promising candidate.

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
Baseline	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
Lower Flight	189.11	-11.12%	82.08	-	51.64	-11.00%	4.78	-26.70%	50.60	-23.49%

Table 5.16: Near-surface temperature breakdown looking at the impact of flying 600 meters lower, following findings from Matthes et al. [2021]. Induced temperature changes are provided in milikelvin (mK), obtained through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

5.1.8. The Behavior of the Intermediate Stop Operations Module

In specific sources the ISO strategy caused an increase in the total ITC, which was primarily subject to the assumptions in that particular study, causing an increase in fuel consumption resulting from lighter aircraft having a higher optimal cruise altitude. Higher flights reduce fuel consumption given lower drag but increase the climate impact due to non-CO_2-effects. For the ISO is assumed that aircraft optimizations for a lower flight will allow ISO to achieve the benefits discussed in the last section. Thus, ISO reduces the fuel consumption following the general outlines of the concept, besides which the aircraft will also fly lower. The lower flight module was not combined with formation flight, as the values from the literature regarding contrail mixing would be non-sensical. The fuel consumption will be identical to Figure 5.11, as the percentage change is applied to the total fuel consumption. The principle is the same as formation flight, including a fuel consumption reduction and post-processing modifier, therefore the temperature change temporal trend also looks like Figure 5.12. Table 5.17 showing the expected scenarios in 2100 if the fuel consumption is reduced from 0-10%. The total ITC could be reduced by up to 38.4 mK with a 10% fuel consumption reduction and application of the modifiers from Table 2.1. The post-processing here is applied as if the entire fleet performs ISO, which is done similar to formation flight to show a maximal output, this will not be the case in reality.

There is a relatively significant difference between ISO and formation flight caused by the severe reduction in contrail-cirrus RF expected for formation flight.

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
Baseline	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
5% Fuel Savings	181.75	-14.58%	78.84	-3.95%	50.15	-13.57%	4.55	-30.27%	48.21	-27.10%
10% Fuel Savings	174.33	-18.06%	75.59	-7.91%	48.61	-16.23%	4.32	-33.82%	45.82	-30.73%

Table 5.17: Near-surface temperature breakdown looking at the impact of performing fleet wide intermediate stop operations. Induced temperature changes are provided in milikelvin (mK), obtained through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

5.1.9. The Model Behavior with Carbon Offsetting

To assess the impact of carbon offsetting in a general manner, and to compare it in different settings, the assumption of a constant carbon offsetting rate from 2025 onwards was assumed. Four modes were generated, each scenario increasing the offsetting by 25% beginning from no offsetting of CO_2 emissions. Table 5.18 shows the result of implementing offsetting from the year 2025. Results show a reduction of 30.82% in the total ITC, corresponding to 66.6 mK reduced CO_2 related ITC following the full offsetting plan. Even when offsetting all emissions starting from 2025 onwards, it can be seen that there remains a residual of 16.13 mK, which still constitutes around 20% of the 1.5 ^{o}C Paris Agreement goal, assuming aviation to cause 5% of all climate impact.

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
Baseline	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
25% Offset	196.51	-7.64%	65.82	-19.81%	58.02	-	6.53	-	66.14	-
50% Offset	180.16	-15.32%	49.48	-39.72%	58.02	-	6.53	-	66.14	-
75% Offset	163.72	-23.05%	33.04	-59.75%	58.02	-	6.53	-	66.14	-
Full Offset	147.19	-30.82%	16.13	-80.23%	58.02	-	6.53	-	66.14	-

Table 5.18: Near-surface temperature breakdown looking at the impact different offsetting scenarios from 2025 onwards at a constant offsetting rate. Induced temperature changes are provided in milikelvin (mK), obtained through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

5.1.10. Sustainable Aviation Fuel

The SAF module does not present a scenario of itself but should be seen as adding another dimension to the output plot. The extra dimension shows the potential gains and downsides of using SAFs, based upon the LCAs on the biofuels LUC discussed in section 2.5. Table 5.19 shows the matrix for the SAF composition settings derived from EU legislative conceptualization, where the emission performance of the so-called CORSIA regions and the 'other SAF' stay constant, where the e-fuels change according to year.

Years	Emission Intensity [gCO_2e/MJ]	2025 Volume Share	2035 Volume Share	2050 Volume Share	2100 Volume Share
CORSIA Regions Produced SAF	38.10	5%	33%	36%	40%
Aviation E-Fuels	Dynamic	0%	0.70%	23%	30%
'Other' SAF	150	95%	66.30%	41%	30%

Table 5.19: Breakdown of the settings which can be used modeling the SAF uncertainty band when assuming an optimistic SAF emission performance. Emission intensities are presented in gCO_2 per Megajoule, the volumes per specified year indicate the percentage of market-share held by a specific type of fuel adding up to 100%. The matrix allows for computing of theoretical reduced/increased CO_2 emissions as a result of the use of biofuels.

First, the positive scenario is assessed, checking the effects of the 'Other SAF' being equal to the 'CORSIA Regions Produced SAF'. This matrix is applied to varying cases of SAF uptake as presented in Table 5.20. For the (currently) unrealistic case of 100% SAFs use, a reduction of 14.55% in the total ITC can be achieved, dictated by a 37.73% reduction in CO_2 ITC. The ITC reduction going from the 25% to the 100% SAF uptake scenario behaves linearly. For the later scenario-based assessment dynamic changes in SAF uptake will be used, which might build-up to 100% through several steps. It must be said that attaining 100% as early as 2025, which subsequently only achieves a CO_2 reduction of around 40% and a total climate impact reduction of 14.5% could be seen as quite small. Even cleaner SAFs could become available, which would improve this picture dramatically, but at the end of the day, it is clear that CO_2 is not the only relevant dimension. Now, what would happen if the SAFs available are not clean at all, which could be both the source of inaccurate or worse falsified assessment.

Scenarios	ΔT_{total}	**Difference**	ΔT_{CO_2}	**Difference**	ΔT_{Cont}	**Difference**	ΔT_{H_2O}	**Difference**	ΔT_{NO_x}	**Difference**
Baseline	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
25%SAF	204.89	-3.70%	74.20	-9.60%	58.02	-	6.53	-	66.14	-
50%SAF	197.10	-7.36%	66.42	-19.09%	58.02	-	6.53	-	66.14	-
75%SAF	189.41	-10.98%	58.72	-28.46%	58.02	-	6.53	-	66.14	-
100%SAF	181.80	-14.55%	51.12	-37.73%	58.02	-	6.53	-	66.14	-

Table 5.20: Near-surface temperature breakdown looking at the impact of SAF uptake rates under the assumption of an overall optimistic SAF emission performance in gCO_2/MJ. Induced temperature changes are provided in milikelvin (mK), obtained through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

For the pessimistic assessment, 150 gCO_2e/MJ is assumed for all SAFs used. This should not be seen as a realistic scenario, but to test an extreme case and also to describe the module behavior. This test is based upon the idea that unbeknownst or known, SAFs become available which are only SAFs in name, but do not underline the principle of the 'sustainable' aspects. This could occur in the case of large investments where facts are left out for economical gains, poor policy, uncertainty in science, or a combination of the three. Bottom-line is the fact that it could happen poorly performing SAF becomes available for use, the question is what the impact of this would be. It is deemed unlikely, however, that this would avoid discovery for a prolonged amount of time. Table 5.21 shows the outputs of this trial, displaying an increase of 15.9% in the total ITC, constituted by a growth of the CO_2 ITC by 41.1%. The inverse of the earlier statement here is true, so even in a scenario where SAFs are used having very poor performance, the total ITC increase 'only' by 14.6%. The increase, given the extreme conditions, is not insurmountably large, of course, it remains an undesirable one. The total ITC can not be fixed through one solution, the political landscape, and scientific know-how will shape the future of the climate impact reduction which could be achieved by SAFs. Every viable chance to diversify the energy supply and demand is vital, especially given the volatile market surrounding oil pricing, but not less important than the climate impact.

Scenarios	ΔT_{total}	**Difference**	ΔT_{CO_2}	**Difference**	ΔT_{Cont}	**Difference**	ΔT_{H_2O}	**Difference**	ΔT_{NO_x}	**Difference**
100% SAFs	246.49	15.85%	115.80	41.08%	58.02	-	6.53	-	66.14	-
Baseline	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-

Table 5.21: Near-surface temperature breakdown looking at the impact of SAF uptake rates under the assumption of a pessimistic SAF emission performance in gCO_2/MJ. Induced temperature changes are provided in milikelvin (mK), obtained through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

5.1.11. AirClim Response to Fuel Consumption Extremes

The previous sections are focused on parameters and modules, but it is also important to understand the model's response to extreme input changes. Two scenarios were tested, abruptly keeping the fuel consumption constant and discontinuing all activities post-COVID (2025). These two were selected to see what an extreme halt to fuel consumption growth would do and to visualize the lasting effect of forgone emissions. Figure 5.13 shows the temporal ITC with tabulated data in Table 5.22. Even when the fuel consumption is constant after 2025, the total ITC would still increase to 119.4 mK, and discontinuation of all aviation would yield 17.9 mK of ITC. After a prolonged time of no emissions, only the ITC of CO_2 persists. The NO_x and H_2O emissions contribute minimally, displaying a longer-lasting effect. About 75 years after a complete stop to flying, there is still about 15% of total ITC lefts compared to the baseline. The Constant Fuel case does cause a slope change over a duration of time, but still shows a continued growth, which can be attributed to the increasing ITC of CO_2. It is important to note that even though the Constant Fuel case retains around 400 E9 kilograms of fuel consumption, and the baseline grows to around 1100 E9 kilogram of fuel consumption, contrails decrease only by 38.35%. A linear response would likely see around a reduction of more than 50% of contrail ITC, but the contrail components show a highly non-linear response. This can both be inherent to atmospheric formation criteria of contrails, or inherent to the modeling method.

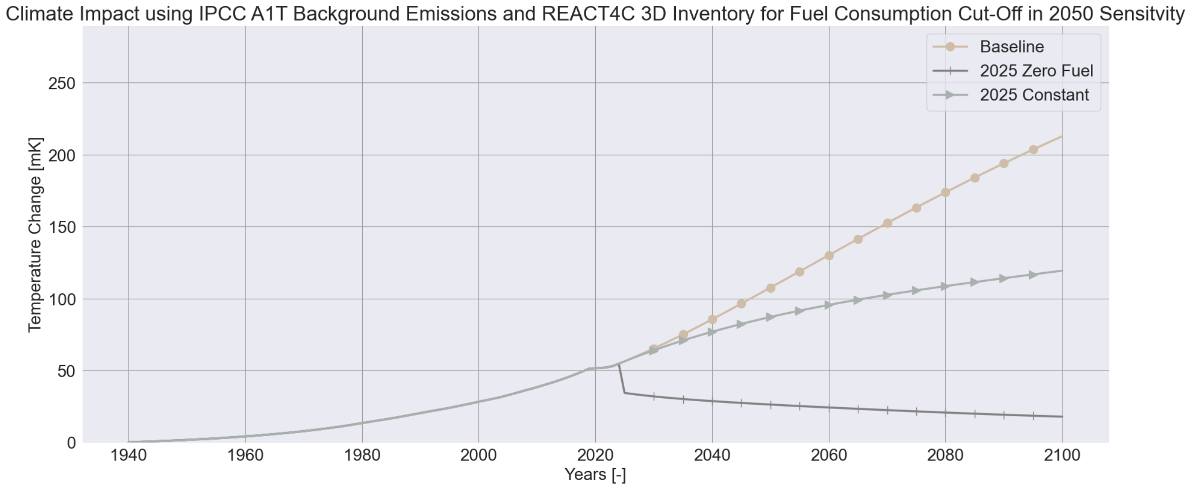

Figure 5.13: Temperature change per assessed scenario between 1940-2100 as a result of constant fuel consumption and total aviation stop/or fuel consumption free. Lines remain similar until after the COVID-19 recovery in 2025 after which deviations start to form.

Scenarios	ΔT_{total}	Difference	ΔT_{CO_2}	Difference	ΔT_{Cont}	Difference	ΔT_{H_2O}	Difference	ΔT_{NO_x}	Difference
Baseline	212.77	-	82.08	-	58.02	-	6.53	-	66.14	-
Constant Fuel	119.37	-43.90%	51.46	-37.31%	35.78	-38.35%	3.00	-54.09%	29.14	-55.94%
Zero Fuel	17.93	-91.57%	16.50	-79.89%	0.00	-100%	0.18	-97.27%	1.24	-98.12%

Table 5.22: Near-surface temperature breakdown looking at the model output prone to extreme modeling input assumptions. Induced temperature changes are provided in milikelvin (mK), obtained through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

It can also be noted that the trend for constant fuel usage from 2025 onwards shows a strong reduction response between 2025-2060, after which shows more constant behavior. Similarly, this delayed response from the impulse change causes a temporal ITC trend change which is particularly visible in the first 30-year. Further concluding statements will be kept for the final result and discussion, but it is least to say problematic to see that even a very optimistic scenario, assuming a constant fuel consumption from 2025 on, still yields a total ITC of above the 5% mark of 2 ^{o}C of 100 mK, which is the upper limit of the Paris Agreement. On the other hand, there are still plenty of mechanisms that focus more directly on the reduction of a single component in this accumulation, e.g. carbon offsetting, EI_{NO_x} changes, and operational practices such as formation flight. Together with large fuel consumption reductions, these could yield more promising results.

5.2. Summary of Modeling Approach Verification Plausibility

The purpose of this chapter was to understand and analyze the model behavior and to check the response with literature. Providing AirClim with several inputs has yielded a host of behavior data and showed which modules and which respective parameters are most sensitive to change, either because of inherent modeling or due to physical properties of the change causing a deviation from the baseline. Table 5.23 summarizes all tests outlined above. An entry on this table can be interpreted in the following way; E.g. the 3D emissions inventories are tested by changing the 3D-emissions inventory from the baseline REACT4C to the AERO2K module. This causes a reduction to the baseline of 25 mK when using the AERO2K inventory. For the fuel economy, both the decay factor and the linear function were changed. The decay factor has a baseline value of 0.96 and was iterated between 1.0 and 0.8, which generated an increase in ITC of 34.9 mk and a reduction of 37.2 mK respectively. The analysis performed provided a backlog of information, which can also be used to understand the initial response and to adequately synthesize scenarios. Some modules are more qualitative, such as the market module, but at least the modeling method and implications are now clearly understood. Care had to be taken when using modules together to assure the response remains sensible. The knowledge outlined can be used to interpret the upcoming results and allows the interpretation with uncertainties in mind.

Input Module	**Iterated Parameter(s)**	**Baseline Values**	**Parameter Range Extremes**	**ΔITC_{out} vs Baseline**
3D Emission Inventories	Inventory Type	REACT4C	AERO2K	+/- 25 mK
RKP	Year-on-Year Growth	5%	Max: 6%	+38.1 mK
			Min: 4%	-31.8 mK
Fuel Economy	Decay Factor	$\eta = 0.96$	Max: $\eta = 1.0$	-34.9 mK
			Min: $\eta = 0.8$	+37.2 mK
	Changing Linear Function	FE = -0.008ln(year - 1975) + 0.0445	Max: Baseline + 20%	+49.9 mK
			Min: Baseline - 20%	-31.5 mK
Market Based Mechanism	Ticket Price Changes	No Modification	Max: 20% Increase	+12.3 mK
			Min: 20% Decrease	-12.4 mK
	Demand Elasticity	$\epsilon = 1.146$	Max: $\epsilon = 1.834$	-7.55 mk
			Min: $\epsilon = 0.458$	+7.48 mK
NO_x	EI_{NO_x}	Lee et al. 2021	Min: 60%	-27.0 mK
Formation Flight	PrP[1]: Fuel Consumption & Contrail Mixing	Baseline Fuel & No Mixing	-20% Fuel Consump. & 89% EI NO_x	-70.3 mK
	PoP[2]: Contrail ITC	Full Contrail ITC	48% Reduction	
Lower Flight	Pop: Contrail, Methane, PMO, Ozone & Water Vapor	No Post-Processing	-11% Contrail, -14.3% Methane, -3.6% PMO, -6.7% Ozone, -26.7% Water Vapor	-23.7 mK
ISO	PrP: Fuel Consumption	Baseline Fuel Consumption	Max: -10%	-38.4 mK
	Pop: Contrail, Methane, PMO, Ozone & Water Vapor	No Post-Processing	See Lower Flight	
Offsetting	ITC CO_2	All CO_2 Contributes	100% Offsetting	-52.6 mK
SAF	High WtW	No SAF	150 gCO_2e/MJ + Dynamic Changing	-7.01 mK
			Static 150 gCO_2e/MJ	+33.72 mK
	Low WtW		38.10 gCO_2e/MJ + Dynamically Changing	-31.0 mK
Extreme Scenarios	Constant Fuel Consumption	Baseline Fuel Consumption	-	-93.4 mK
	Zero Fuel Consumption	Baseline Fuel Consumption	-	-194.8 mK

Table 5.23: Pop = Post Processing, PrP = Pre-Processing; Summary of all the modules and the respective properties, provided a color coding for the highly sensitives, high impact modules

It is not possible to provide a simplistic breakdown for this complex analysis on the certainty of each module. Each module has different manners of generating inputs or adding post-processing to outputs. This verification brings together different disciplines, ranging from the political to the economical sector, and it can be understood that the modules towards these ends become of lesser resolution. The market mechanism is a clear example, where it is desired to study a response, however, response models are lacking. For this reason and the general complexity of the problem itself, this is something that can not be achieved for the current purpose. Furthermore, it has to be stated that any module using post-processing might be too simplistic, and studies were done on e.g. formation flight, ISO, and lower flight have only been done through theoretical simulations. The values used do not represent the dynamic reality of changing atmospheric concentrations and the post-processing percentage itself is not flexible or changing. Finally, AirClim contains radiative forcing minimum, mean, and maximum values due to the inherent uncertainty of finding an exact solution per species, here the mean values were used but there is no certainty on the correctness of this assumption. Figure 2.1 was shown at the beginning of the thesis including the confidence levels. This section clearly outlines the leading contribution of CO_2, NO_x, and contrail-cirrus in the aviation climate impact, with H_2O only forming a minor part of the impact. Out of these mechanisms, both the net-NO_x and the contrail-cirrus in high-humidity regions are of low confidence and, therefore could still yield better or worse results than shown in these figures. Thus already an inherent uncertainty exists regarding the species (with CO_2 effects having a higher certainty), which could already change the net radiative forcing by about 80 mW/m^2, half of the mean estimated radiative forcing.

III

Part III: Climate Impact of Commercial Aviation and Result Implications

6
Scenario Based Climate Impact & Implications

6.1. Framework of Result Representation

This thesis aims to contribute to and understand the aviation-induced climate impact, to allow for a more timely response to the crisis. Specific scenarios have been assembled to represent different underlying setups, trying to answer what the absolute climate impact might be but also the importance of the dimension of time. The result section will logically build up the final synthesized scenarios through a step-wise approach. The primary mechanisms will be looked at first where this was not already done in the previous chapter, starting with an ambitious goal called the Flight Path 2050 (FP2050). The first section begins by analyzing expert ambition, assessing if the goals will be sufficient when analyzed through this framework. Furthermore, FP2050 has also been modeled by Grewe et al. [2021] and thus serves as a comparison to establish differences in behavioral response related to the model setup. The following sections outline the outlined models and allow insight into how tangible changes live up to the ambitions set. Initially, major modules such as CORSIA and the IATA Technology projections are modeled, as they create a good starting point. After which more minor modules can be appended in unity with the major moduels, to see the effect when stacking conceptual modules into a story-line

To summarize the scenarios, which differ in terms of the number of modifications applied to the input and output data through pre-and post-processing, Figure 6.1 is included as a reference point. The modifications to scenario data become more complex downstream of the figure, moving from base modules, to primary scenarios, to finally represent scenarios including more than one module. There is also a distinction regarding the EI_{NO_x} trend observed in the second row under the primary scenarios, as they have a significant influence on the results. Secondary scenarios are scenarios where at least two modules were combined such as the 40% taxation module with the CORSIA+ story-line, combining the tax module and the CORSIA module with the specific CORSIA+ story-line. Finally, the higher-order modules contain more climate impact reducing measures than the DoU-Future, containing iterations to the EI_{NO_x}, RPK-incentives, formation flight processing, and CORSIA. It should be noted that eventually some modules such as ISO + Lower Flight were not used, as the previous section provided enough insight.

6.2. Setting An Ambitious Goal: The European Commission Flight Path 2050

The ambition of the European Flight Path 2050 is a 75% reduction of CO_2 per passenger kilometer and 90% reduction of NO_x per passenger kilometer using the year 2000 as the reference year. Three scenarios were modeled to assess the dimensions of implementation speed and post-2050 impact; The first scenario gradually builds up the reduction from 2025 to 2050 after which the same ratio of CO_2 per passenger kilometer is maintained, implying that an RPK growth still causes the fuel consumption to increase. This scenario is reproduced but then maintains the same fuel consumption level as 2050 to see the impact of a nongrowing fuel consumption afterward. Finally, the FP2050 is also assessed in a non-realistic manner, where the CO_2 and

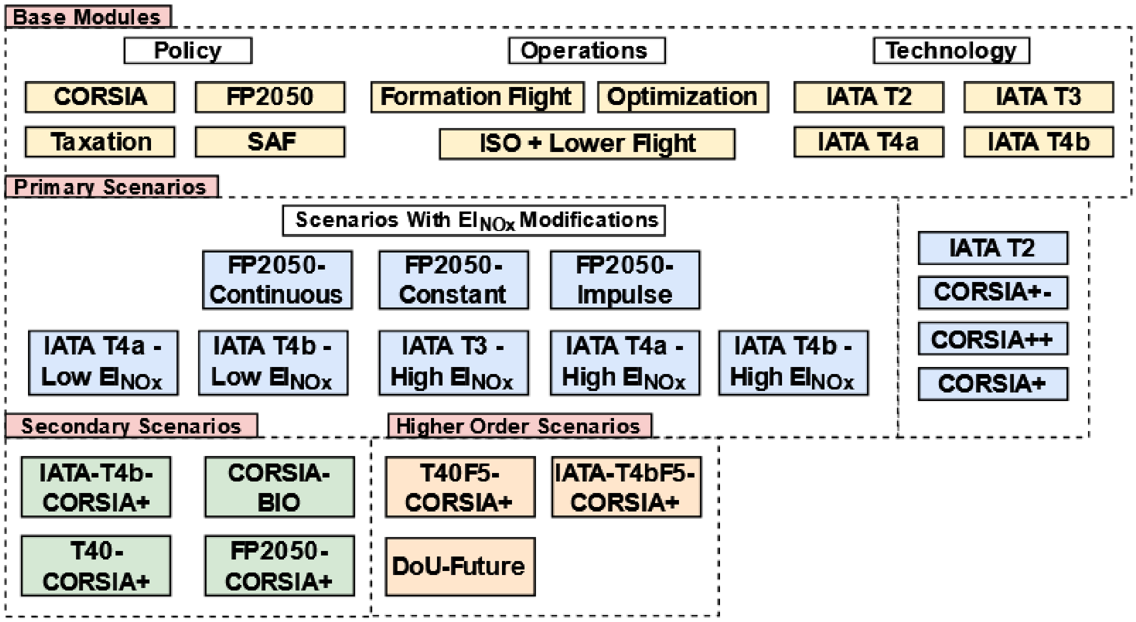

Figure 6.1: Structural breakdown of all scenarios represented in the result section and the respective order. There is a division into three rows, representing from top to bottom the base modules, the primary scenarios, the secondary scenarios, and the higher order scenarios. Each provided with unique identifies which are also used for later data reference. Every row represents the degree of abstraction of the scenario, moving down the scenarios become more complex.

NO_x reduction are modeled as an impulse in 2050. Table 6.1 provides a breakdown of what was described above, for visualization the EI_{NO_x} temporal evolution is presented in Figure 6.2.

Scenario Name	**Scenario Description**
FP2050-Continuous	This scenario adheres to goals set by the EC to reduce the CO_2 per passenger kilometer by 75% and the NO_x by 90% with assuming the year 2000 as the baseline values. The reductions are achieved at a continuous pace from 2025 up to 2050, thus assuming 25 year realization through whatever means possible. Then the same CO_2 and NO_x per passenger kilometer values are maintained on wards to 2100.
FP2050-Constant	Same as FP2050-Continuous but after 2050 the fuel consumption does not increase. Thus assuming that the efforts to reduce the CO_2 and NO_x ratios per passenger kilometer are not stopped.
FP2050-Impuls	Same goals but they are attained through an impulse in 2050 after which the ratio is kept constant as FP2050-Continuous. This allows for showing the difference between late and sudden change versus continuous and gradual change.

Table 6.1: Description of the Flight Path 2050 related scenarios studied, containing a scenario with continuous technological improvement with constant margins after 2050 (FP2050-Continuous), a scenario similar to FP2050-Continuous but constant fuel consumption after 2050 (FP2050-Constant), and finally a scenario where the post-2050 growth is business as usual, after which the FP2050 guidelines are achieved (FP2050-Impuls).

Since these scenarios have a very specific method of changing the emissivity index of NO_x as a function of the fuel consumption and the RPK, it is visualized for each scenario in Figure 6.2. Here it can be seen that it is not strictly a continuous improvement, but incremental with a 5 year time-span in between improving.

Figure 6.3 shows the outcome of the simulation of the FP2050 realisation for the reduction of CO_2 and NO_x. FP2050-Impuls yields the worst climate performance in 2100, followed by the FP2050-Continuous, and the best performance is from FP2050-Constant. Thus, observing an expected outcome where substantial growth in climate impact exists due to the growing fuel consumption for the FP2050-Continuous and Impuls. The outcome observed from FP2050-Constant is consistent with the extreme cases from subsection 5.1.11, summed up in Figure 5.13 where the fuel consumption was assumed constant from 2025 without NO_x reduction

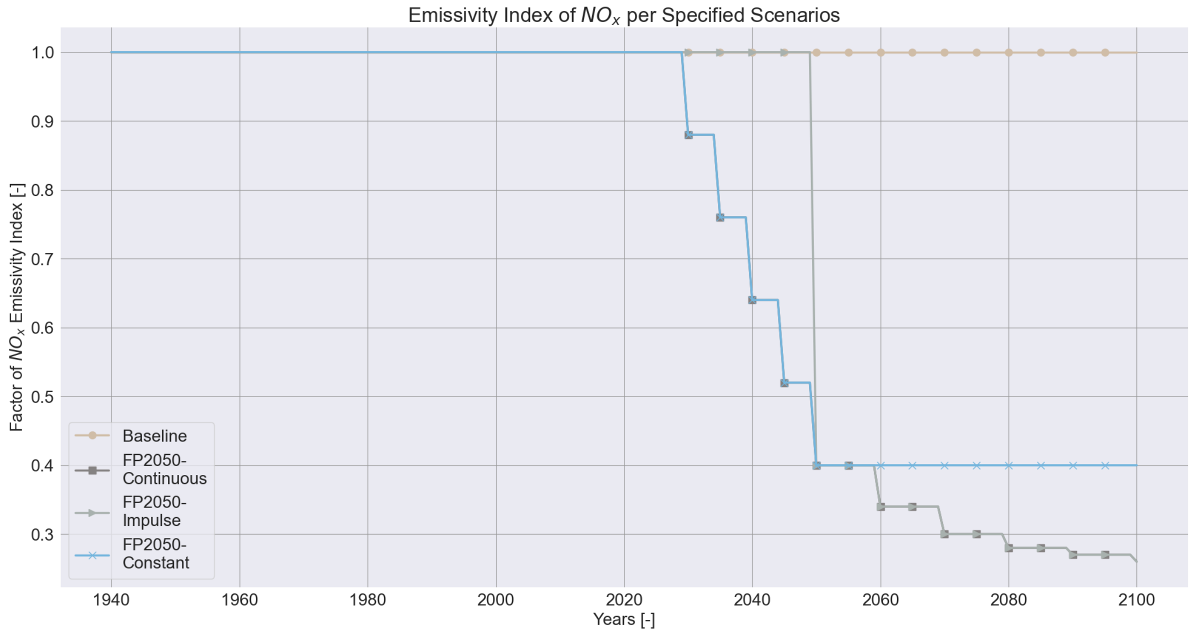

Figure 6.2: Temporal change of the factorization of the EI_{NO_x} for the Flight Path 2050 scenarios outlined in Table 6.1, displaying the factor applied to the NO_x emissions on the kilogram of fuel burn

applied. Large impact reductions that can be seen compared to the baseline, of up to 58.3% for FP2050-Constant, are achieved through fuel consumption reduction, causing the decrease in CO_2 emissions and flown kilometers induced contrail-formation. The CO_2 and contrail climate impact are reduced by 44.4% and 46.4% respectively, corresponding to a 45.7 mk and 31.1 mk reduction. The net-NO_x ITC is reduced by 83.6% to 10.9 mK of ITC, following the large reductions in the EI_{NO_x}. A results breakdown can be found in Table 6.2.

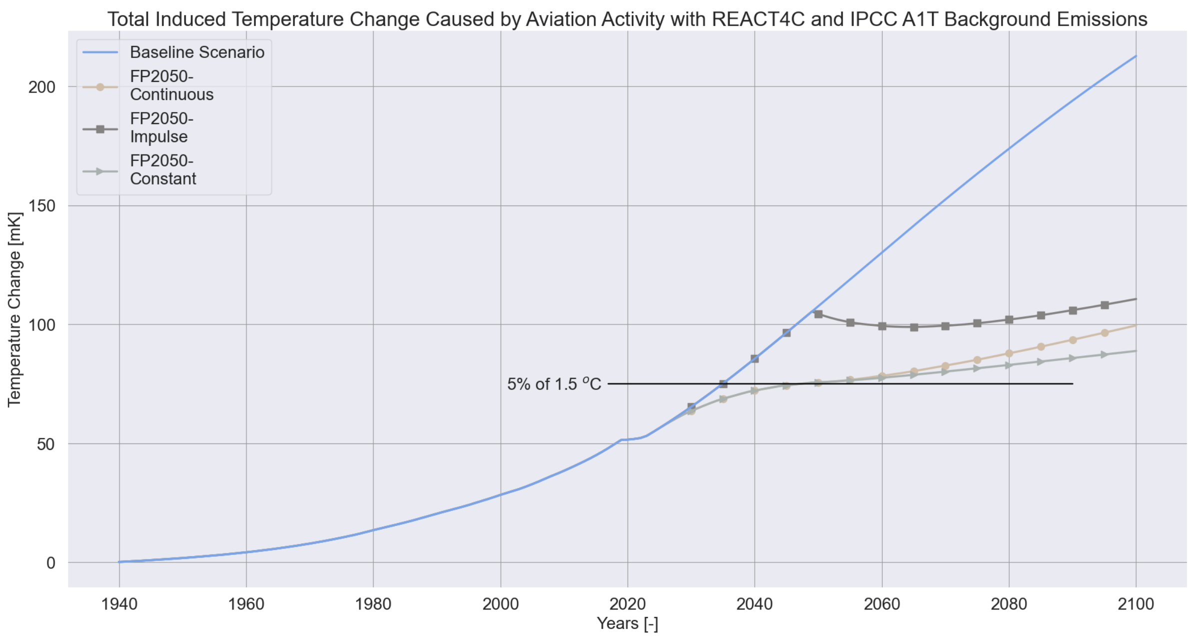

Figure 6.3: Temporal near-surface temperature change for the pre-defined Flight Path 2050 scenarios outlined in Table 6.1, showing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions, displaying similar overall behavior but varying slopes for each different scenario.

Scenarios	ΔT_{total}	**% Diff**	ΔT_{CO_2}	**% Diff**	ΔT_{NO_x}	**% Diff**	ΔT_{Cont}	**% Diff**	ΔT_{H_2O}	**% Diff**
Baseline	212.771	-	82.082	-	66.136	-	58.025	-	6.528	-
Impulse	110.647	-48.00%	57.618	-29.80%	12.654	-80.87%	38.828	-33.08%	1.547	-76.30%
Continuous	99.521	-53.23%	50.073	-39.00%	11.078	-83.25%	37.146	-35.98%	1.225	-81.23%
Constant	88.813	-58.26%	45.673	-44.36%	10.861	-83.58%	31.078	-46.44%	1.201	-81.60%

Table 6.2: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions for the Flight Path 2050 scenarios from Table 6.1.

FP2050-Continuous and FP2050-Impulse differ in the method and time frame of technological implementation. The former is a scenario where continuous improvement is achieved through available measures, and the latter represents a scenario where this is not the case, and all technological advancements occur instantaneously. It is observed that through the impulse, the sudden change causes depression in ITC growth, which picks up again due to the continued fuel consumption growth. The continuous case has lower fuel consumption and NO_x emissions moving towards 2050, but as the scenarios equalize in fuel consumption, the difference between the scenarios in 2100 is only 11 mK. Closer observation into the CO_2 and contrail-cirrus ITC allows more insight through Figure 6.4 and Figure 6.5 respectively. The net-NO_x-effects ITC remains unchanged and is on par with the net-NO_x-effects ITC of scenario with constant fuel post-2050 due to the EI_{NO_x}. The CO_2 ITC grows following the increase in fuel consumption, with both (Impulse & Continuous) scenarios showing similar growth shapes. The contrail cirrus impact was also reduced for the continuous case as a result of the reduced fuel consumption, which scales the flown kilometers according to its growth in the 3D-emission inventory REACT4C. Over the duration of the time frame, the contrail ITC of the continuous scenario draws closer to the impulse scenario. The contrail-cirrus ITC does not suddenly jump but displays a time-bound response, which underpins earlier statements regarding the post-processing of contrail climate impact directly through factorization. The overall story tells us that the CO_2 climate impact is changed for the FP2050-Continuous, the contrail-cirrus ITC gets breached over time. At the root of this response lies the long extinction time of CO_2 emissions, dictating a slower dissipation and thus long-duration impact.

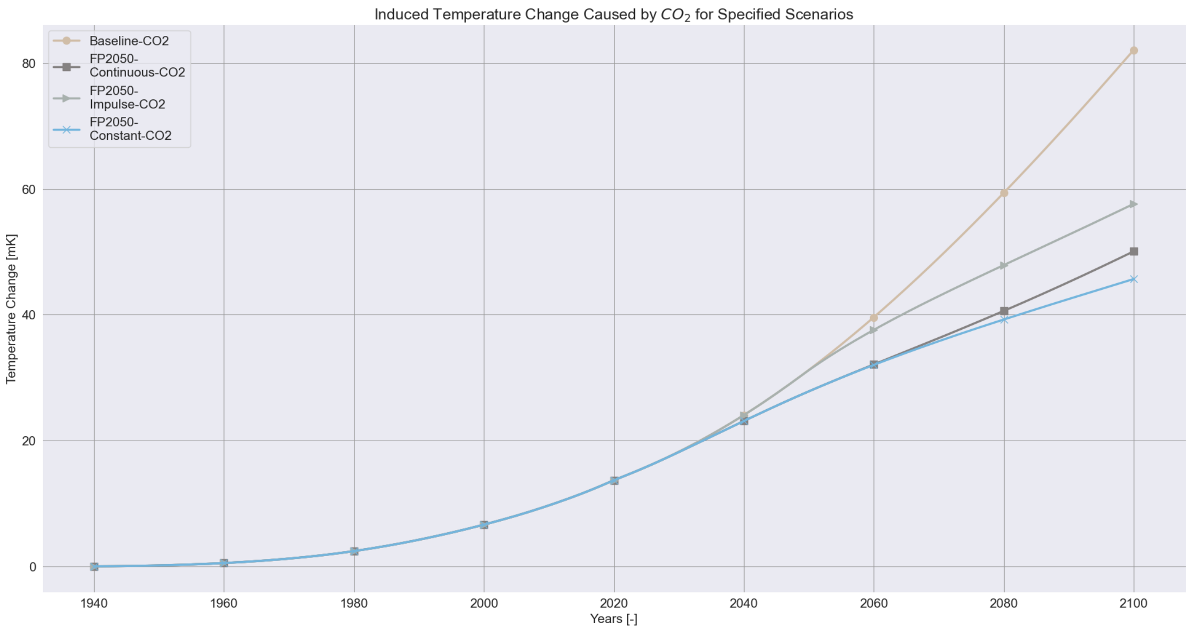

Figure 6.4: Temporal induced temperature change attributed to CO_2 emissions originating from aviation for the respective Flight Path 2050 scenario, showing years on the horizontal axis and temperature change on the vertical axis in milikelvin

It is shown that progress between 2025 and 2050 through continuous improvement of technology is rapidly breached, with the trend seemingly becoming near parallel in 2100. An effective reduction in CO_2 ITC can be achieved through quick response, whereas for contrails more systematic measures are needed to either reduce the formation or the overall impact through fully understanding formation place and time importance.

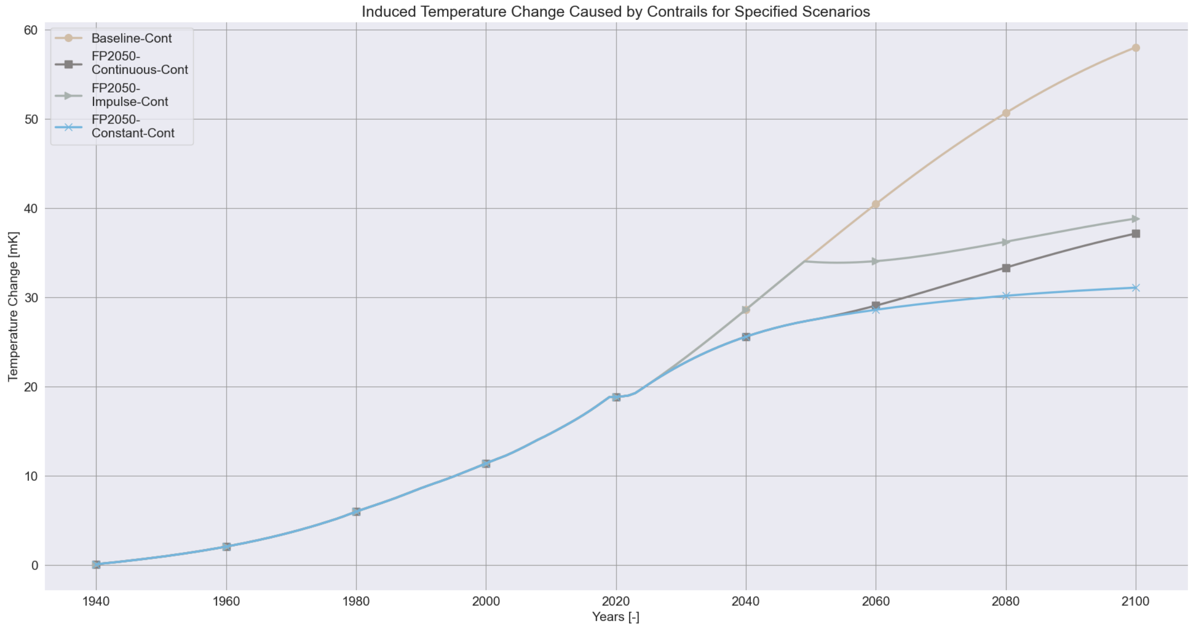

Figure 6.5: Temporal induced temperature change attributed to contrails formation within the framework of the Flight Path 2050 scenario, showing years on the horizontal axis and temperature change on the vertical axis in milikelvin

Even when keeping fuel consumption constant without applying further NO_x emission factorizations, the contrail cirrus-related impact remained large, as was seen in the analysis of the extreme case. A reduction of 11 mK (13% of the aviation budget of 75 mK) seen between the Continuous and the Impuls, as well as the Continuous and Constant scenarios, is not trivial when comparing relatively. The Flight Path 2050 shows a host of promising results, which will be returned to later.

6.3. Scenario Based Assessment of Climate Impact Mitigation Strategies within Aviation

6.3.1. Carbon Offsetting and Reduction Scheme for International Aviation

Carbon offsetting was already treated in subsection 5.1.9, where the analysis looked at a constant offset from the year 2025. Substantial reductions could materialize since CO_2 is the largest component of the overall climate impact, similarly, it does not nearly constitute the total climate impact as it was no more than 39% of the ITC in the baseline. This analysis contains different dimensions, understanding how time effect climate performance and what the effect of poor offsetting might be. CORSIA is implemented, but aspects such as participation, potential carbon leakage, policy pathway outside of CORSIA coverage, and pandemic constraining economic resources are taken into qualitative account. To scope several modes CORSIA could be expressed, some scenarios focusing on the time and quantity of offsetting are assembled. Also, CORSIA comes with rules on SAF use, where the use of SAFs would allow airliners to change their accounting for offsetting, which is not taken into account when establishing the SAF uncertainty range. Table 6.3 outlines the scenarios shortly with relevant input parameters and assumptions.

Figure 6.6 shows the result of each scenario, with the component ITC in Table 6.4 for a precise comparison at the end of the time frame. ITC growth still increases in 2100, which is in contrast to other works as will be discussed later. Carbon offsetting causes significant reductions of up to 52.6 mK when taking the difference between CORSIA+ and the baseline scenario. The difference between CORSIA+ and CORSIA++ only constitutes 5.6 mK. Faster transition is preferred, especially given the uncertainty of emissions such as NO_x which would likely reduce following technological advancement, however, for offsetting the robustness, policies, agency capacity to raise a tax, and the avoidance of leakage are vital. This is shown by the difference between CORSIA+- and CORSIA+, where CORSIA+ achieves slightly more than twice the ITC reduction of CORSIA+-.

The biofuel uncertainty range computed through the SAF module based upon the emissivity performance settings can be seen in Figure 6.6 represented by the green band, which surrounds the CORSIA+ line. It was

Scenario Name	Scenario Description
Baseline	RPK growth as leading parameter following real-time data and estimates into the future following the UN population growth. Assumes business as usual for demand growth and technology but expects that conventional technologies and their development will plateau. This scenario represents a full halt or failure at an attempt to fight climate change
CORSIA+	This scenario is the more likely realistic scenario. Due to the fact that CORSIA only includes international flights it will unlikely cause 100% offsetting, but might induce better national policies as well for pathways not covered by CORSIA. It is expected that after the pilot phase (2023) not all offsets are directly realized and it will take up to 2040 to create a scenario where all CO_2 emissions are offset. All other developments stay as in the Baseline.
CORSIA++	Similar to CORSIA+ but assumes instantaneous 100% offsetting from 2023 on-wards.
CORSIA+-	Similar to CORSIA+ with the time frame with the offsetting altering between 2023 and 2040, however no full offsetting is realized. Only 50% of the aviation CO_2-emissions is offset. This can replicate both a failure of CORSIA or a failure in CO_2 accounting.
CORSIA-BIO	The CORSIA-BIO is not a physical line but is used to generate an uncertainty band for the usage of SAF within the EU55 plans of 2% in 2025, 5% in 2030 and 63% in 2050. Estimated 100% in 2100 at the end of the time-frame. Both a case is presented where extremely poor SAFs are used (150 gCO_2e/MJ) either due to wrong LCAs or pushed policies. Also a case with well performing SAFs is assumed (38.10 gCO_2e/MJ).

Table 6.3: Story-lines of all scenarios related to the Carbon Offsetting Reduction Scheme for International Aviation with their respective description. Assuming a full offsetting from 2040 (CORSIA+), instanly full offsetting from 2023 (CORSIA++), only 50% offsetting in 2040 (CORSIA+-) and draws an uncertainty band following EU55 plans for SAFs (CORSIA-BIO).

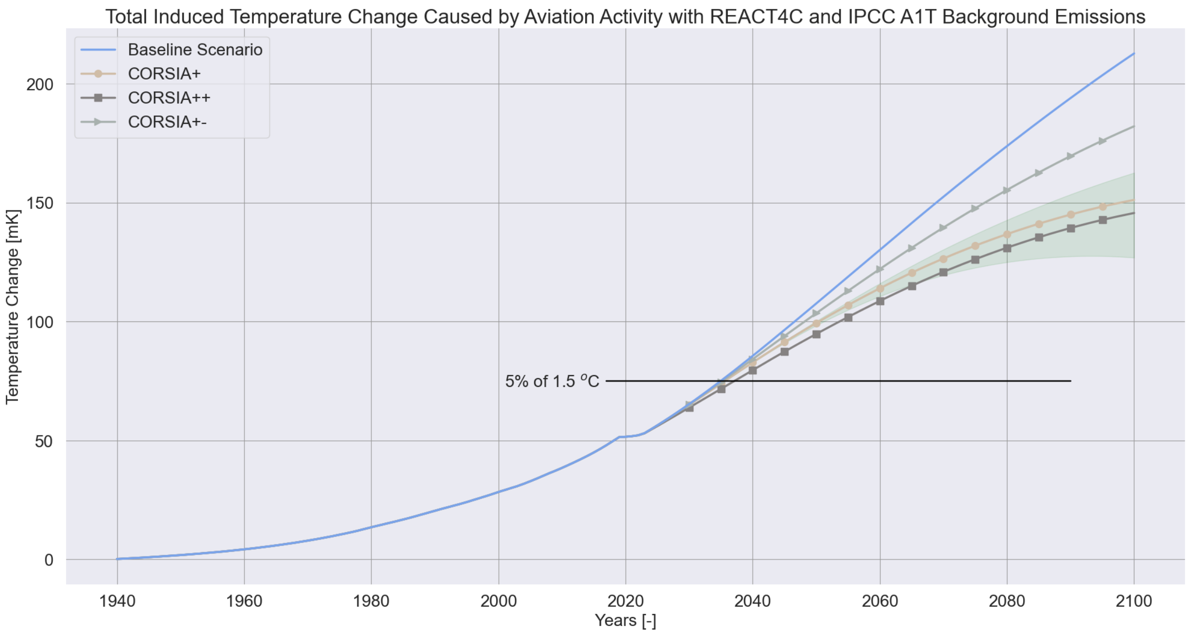

Figure 6.6: Temporal near-surface temperature change for the CORSIA cases outlined in Table 6.3, showing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions. In addition the uncertainty band is represented for the CORSIA+ scenario, displaying the change in temporal temperature change following SAF module assumptions.

calculated that the poor performance SAF blend could increase the ITC by 11.4 mK but might also reduce it by 22.3 mK. When looking at earlier years the band remains very narrow which is due to the low uptake of SAFs, but from which it can be concluded that SAFs do have the potential to increase the temperature change negatively if the emission performance is poor or if the LCAs are not fully representative. It is a worthwhile endeavour, especially in the light of recent events such as the Ukrain-Russia conflict, to diversify the supply for energy requirements. This does not mean that one source has to be fully replaced by the other, which is also the manner in which SAFs should be approached.

Scenarios	ΔT_{total}	**% Diff**	ΔT_{CO_2}	**% Diff**	ΔT_{NO_x}	**% Diff**	ΔT_{Cont}	**% Diff**	ΔT_{H_2O}	**% Diff**
Baseline	212.771	-	82.082	-	66.136	-	58.025	-	6.528	-
CORSIA+-	182.138	-14.40%	51.449	-37.32%	66.136	-	58.025	-	6.528	-
CORSIA+	151.173	-28.95%	20.484	-75.04%	66.136	-	58.025	-	6.528	-
CORSIA++	145.655	-31.54%	14.966	-81.77%	66.136	-	58.025	-	6.528	-

Table 6.4: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions for the CORSIA scenarios from Table 6.3

Thus assuming carbon offsetting, it has the potential to reduce the climate impact caused by CO_2 emissions. Within a scheme that slowly moves towards a full offset, thus realizing the goal of CORSIA of CNG, the temperature change can be reduced by 31.5% down to 145.7 mk compared to the baseline, which is a reduction of 81.8% down to 15 mK of CO_2 ITC. This strategy leaves other large components of the climate impact, such as contrail-cirrus and net-NO_x-effects untouched. The FP2050 goal with the heavy NO_x-reduction focus could cover one of these two bases, and besides reducing the NO_x through technology pathways, the fuel consumption reduction is significant compared to the baseline. Thus, to achieve the mold of the Flight Path 2050, CORSIA is a necessary pathway, which should however not suppress the need to keep reducing fuel consumption.

6.3.2. IATA Technology Road-Map to 2050 and the Climate Impact Implications

The ambition, the CO_2-focused CORSIA has been modeled, and minor modules have been discussed. It is important to sketch the future according to experts' conceptualization. Technological improvements are of the highest importance since improvements through policy and operations are not always sustainable or encapsulating. The IATA roadmap to 2050 outlined the future of technology in the aviation sector, from where fuel consumption trends were drawn. These trends were related to particular scenarios, ranging from electrification to the introduction of novel aircraft concepts. Besides copying these trends, further elaborations were made concerning the EI_{NO_x}. Table 6.5 provides an overview of the scenarios in this section drawn from the IATA roadmap, appended with the defined assumptions.

Scenario Name	**Scenario Description**
IATA-T2	This represents the T2 scenario extracted from the IATA Road-Map to 2050. This presents the conservative assessment from the document including own assumptions post 2050. For this case no specific NO_x reductions have been assumed
IATA-T3	This represents the scenario in which some new configurations are introduced with a low NO_x reduction trend not represented by the document.
IATA-T4a	This scenario contains electrification of aircraft following the Zumen Aero forecast with hybrid-electric propulsion becoming available for a narrow range of seat classes. This scenario is modeled with the same low NO_x trend as the latter case as well as the Flight Path 2050 computed required NO_x reductions to meet the goals.
IATA- T4b	T4b represents a scenario in which besides hybrid-electric also fully electric flight is realized following Wright's Electric forecast. Similar to T4a this is modeled with a low NO_x reduction as well as the FP2050 goals.

Table 6.5: Breakdown of all assessed IATA technology scenarios with respective story-line, appended with EI_{NO_x} assumptions which are not inherently part of the IATA roadmap conceptualization. Representation of more basic scenarios with general technological improvement, to a large degree of conceptual changes in aircraft geometry and/or propulsion systems such as hybrid-electric propulsion.

The technological improvement suggested in the roadmap were discussed in subsection 2.3.1 and converted into fuel consumption trends through the variable of CO_2-intensities. The scenarios T2 through to T4a did not yield large differences in fuel consumption up to 2050, after which the trend was appended through assumptions outlined in subsection 4.3.7. The verification and plausibility studies have shown clearly that the reduction of fuel consumption is vital, as it impacts all facets of emission-induced climate change, thus simply modeling the reduction allowed through fuel consumption as defined in the IATA roadmap would not yield new insights. It is important to display the reality of the aviation-induced climate impact but also the possibilities of specific scientific or political pathways, hence the IATA roadmap concept was appended with EI_{NO_x} temporal story-lines. Combining both the philosophies to reduce fuel consumption driven by cost and the results outlining that NO_x-effects are not trivial, although still subject to high uncertainty related to emission location and time of emission. Thus the fuel consumption is computed through data from the report, the EI_{NO_x} assumptions are shown graphically in Figure 6.7 per scenario.

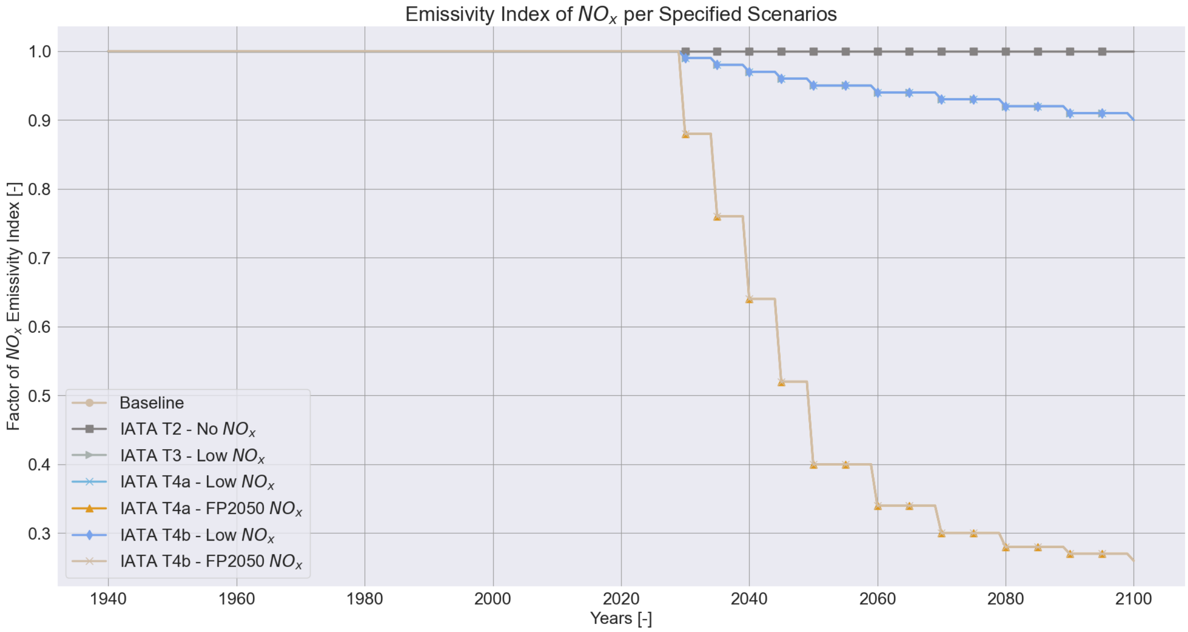

Figure 6.7: Temporal EI_{NOx} descriptions for every specific scenario showing the No NO_x, Low NO_x and FP2050 NO_x pathways

Figure 6.8 shows that with minimal EI_{NO_x} factorization, corresponding to technologies not focusing much on NO_x emission reduction, the difference is only around 4.8 mK between the T2 scenarios with no EI_{NO_x} changes and the T3 scenario. The T4b trend with the FP2050 NO_x story-line reductions provides the best outcome in terms of temperature change in 2100, but still lies significantly above the 88.8 mK temperature change found for the Constant FP2050 case at 130 mK temperature change. At the core of this difference lies the much lower fuel savings for the IATA scenarios compared to the FP2050 synthesized scenario. It is clear that only reducing the fuel consumption alone will not be sufficient, for which one can refer back to the analysis of the extreme case with the constant fuel consumption from 2025 onwards trend. Even for the T4b scenario, the CO_2 ITC remains sizable. With the NO_x ITC mitigated, strategies to reduce the CO_2 such as CORSIA and any strategy which lowers the fuel consumption or aims at tackling the contrail impact such as formation flight, flying at a lower altitude, or simply reducing flight demand, for example, could yield the desired result. These mechanisms are essentially trade-offs, depending on what the constraining factors are. For example, CO_2-trading is a relatively cheap option, since there is no need for infrastructural change, as long as there is an abundance of CO_2-certificates on the market. However, over-indexing on the carbon trade could deprive effort to update air traffic management to look into climate efficient routing, or it could complement each other as the carbon trade could serve as a pilot to introduce other emission trading schemes in the future. One should aim to be ahead of economic reforms, as the outlined results up to this point are a testament to.

Thus Table 6.6 provides the performance of each scenario in the year 2100. The best-case scenario fuel consumption reduction caused by T4b allows a reduction of up to 17.9% resulting in a total CO_2 ITC of 67.4 mK, compared to 82.1 mK for the baseline. The contrail impact is reduced from 58 mK to 46.1 mK by 20.5%. The net-NO_x-effects ITC went down from 66.1 mK to 14.8 mK by about 77.6%, which is a result of the stringent EI_{NO_x} doctrine and lower fuel consumption, which allows a near-surface temperature change of 130 mK compared to the baseline of 212.8 mK. The difference between the T4b with minimal NO_x emission reduction and the high NO_x reduction is sizable at about 41 mK, outlining the effect of changing the EI_{NO_x}.

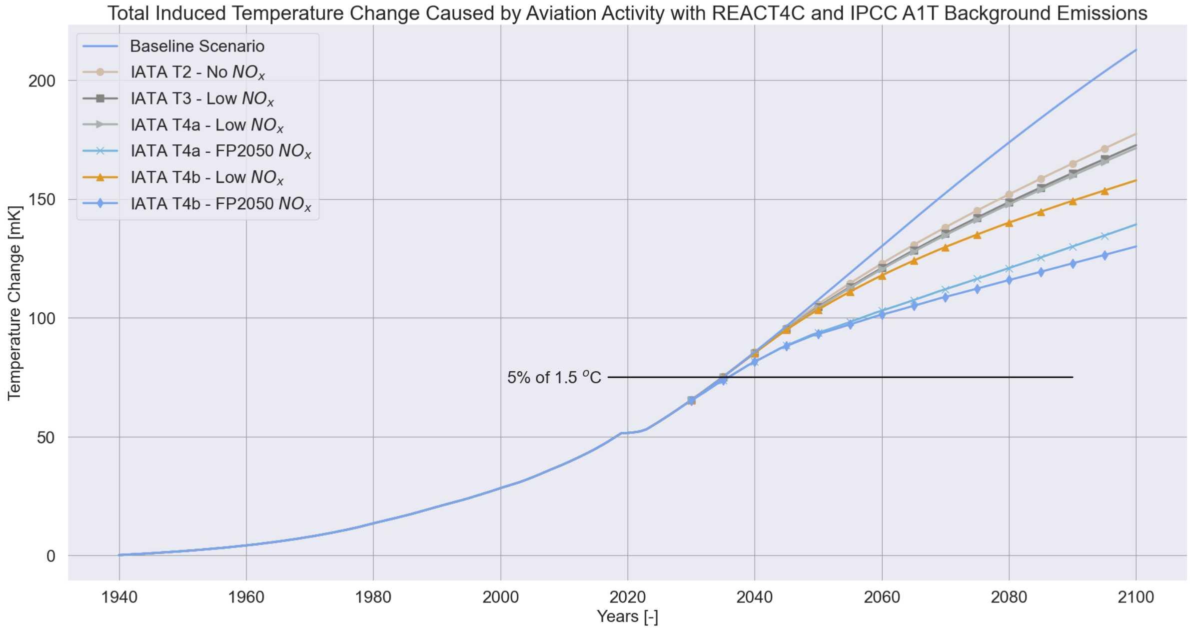

Figure 6.8: Temporal near-surface temperature change for the technology roadmap to 2050 scenarios from Table 6.5, showing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions, displaying similar overall behavior but varying slopes for each different scenario.

Scenarios	ΔT_{total}	**% Diff**	ΔT_{CO_2}	**% Diff**	ΔT_{NO_x}	**% Diff**	ΔT_{Cont}	**% Diff**	ΔT_{H_2O}	**% Diff**
Baseline	212.771	-	82.082	-	66.136	-	58.025	-	6.528	-
IATA T2 - No NO_x	177.448	-16.60%	71.820	-12.50%	50.461	-23.70%	50.089	-13.68%	5.078	-22.21%
IATA T3 - Low NO_x	172.651	-18.86%	71.585	-12.79%	46.432	-29.79%	49.927	-13.96%	4.707	-27.90%
IATA T4a - Low NO_x	171.441	-19.42%	71.166	-13.30%	45.974	-30.49%	49.638	-14.45%	4.663	-28.57%
IATA T4b - Low NO_x	157.845	-25.81%	67.394	-17.89%	40.166	-39.27%	46.138	-20.49%	4.146	-36.49%
IATA T4a - FP2050 NO_x	139.300	-34.53%	71.166	-13.30%	16.646	-74.83%	49.638	-14.45%	1.851	-71.65%
IATA T4b - FP2050 NO_x	130.030	-38.89%	67.394	-17.89%	14.811	-77.61%	46.138	-20.49%	1.687	-74.16%

Table 6.6: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions for the IATA roadmap to 2050 scenarios from Table 6.5

6.3.3. Hybrid Scenarios; Bringing Climate Impact Reduction Strategies Together

section 6.2, subsection 6.3.1 and subsection 6.3.2 in respective order have shown that not a single assessed scenario within those sections has provided a satisfactory reduction of climate impact. These results are the result of using mean values outputted from AirClim, which for the model setup used the A1T CO_2 and CH_4 background emissions, together with the REACT4C three-dimensional emission inventory taking 2006 as the baseline year, and input data generated following chapter 4. Aviation-induced temperature change is caused primarily by emissions such as CO_2, net-NO_x-effects resulting from NO_x emissions, and contrail-cirrus resulting from water vapor emissions in specific regions. Each of the previously modeled scenarios had a primary focus, such as CORSIA primarily looked into reducing the ITC of CO_2, and technology changes were modeled through changing the fuel consumption. This section aims to generate hybrid cases to understand both the question of what is necessary to support the goals set in the Paris Agreement with the assumption that aviation covers 5% of anthropogenic warming, and also to create an understanding of where this leaves us given the current scenario. It is vital to compare the temporal behavior of the studied model and output against the Grewe et al. [2021] output to understand potential differences derived from the modeling setup and the impact of the input data.

Several scenario combinations were assessed, under which the earlier described CORSIA+ storyline in combination with a 40% taxation of aviation, which should be interpreted as a demand reduction stimuli. Furthermore, the best case technology trend T4b was applied together with CORSIA+. Furthermore, the FP2050 was kept the same where besides the fuel savings, also carbon offsetting was practiced. It is more likely that both the carbon offsetting and fuel consumption reductions will work in unison to achieve the Flight Path 2050 goals, so this represents a hyper-optimistic scenario. Finally, the formation flight module is applied, assuming fleetwide implementation, to the technology case. The storyline summaries are provided in Table 6.7, all these storylines follow the FP2050 EI_{NO_x} temporal evolution and similar SAF uptake evolution as earlier described with CORSIA-BIO.

Scenario Name	Scenario Description
T40-CORSIA+	'T' Indicates taxation with the number implying the percentage of 40%. This scenario causes a demand/RPK reduction of around 48% equally split over 30 years. The CORSIA+ template from earlier is applied to cause CO_2 offsetting
T40F5-CORSIA+	Same as T40-CORSIA+ with the addition of 'F5' which represents formation flight causing a reduction of 5% fuel consumption.
FP2050-CORSIA+	FP2050 as modeled earlier with the CORSIA+ offsetting applied
IATA- T4b-CROSIA+	IATA T4b with the CORSIA+ offsetting applied
IATA- T4bF5 CROSIA+	T4b with additional formation flight causing 5% fuel consumption reduction

Table 6.7: Reference abbreviations and respective story-line belonging to specifically studied scenarios, combining multiple modules to arrive at higher complexity climate impact scenarios.

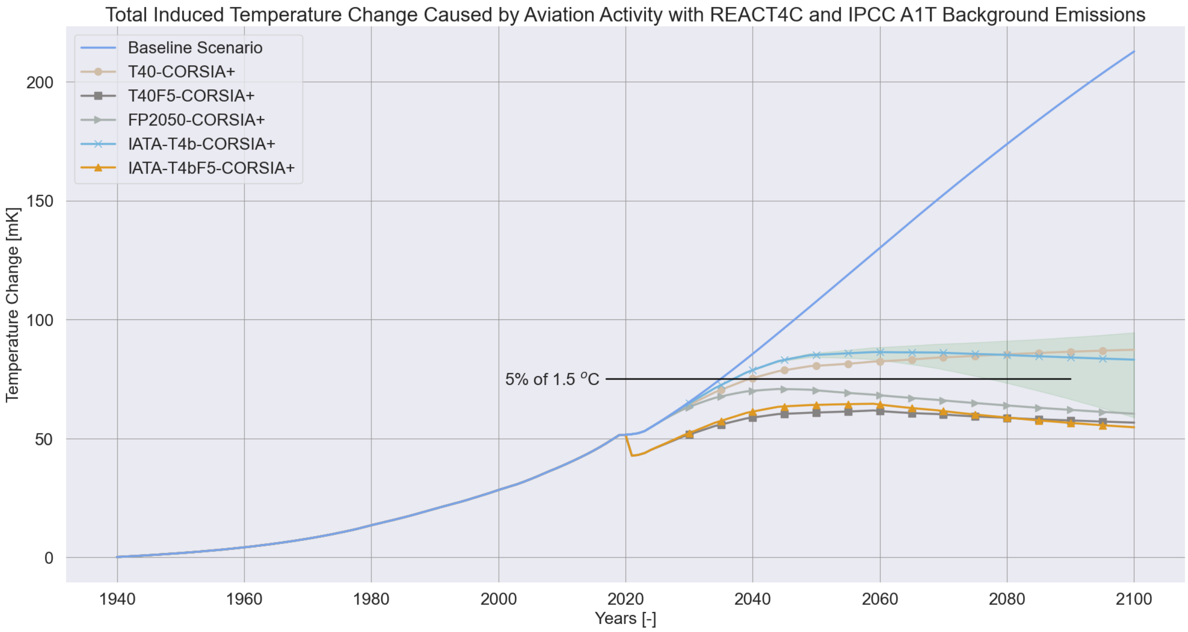

Figure 6.9: Temporal near-surface temperature change for the hybrid scenarios including an uncertainty band over the IATA-T4b-CORSIA+ trend to indicate the uncertainty posed by the use of sustainable aviation fuels, showing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions. Abbreviations correspond to those represented in Table 6.7

Figure 8.2 outlines a result that has been arrived at through the synthesis of previous chapters and the knowledge gained from the model behavior in chapter 5. These scenarios each try to combine strategies to reduce all emission contributions causing aviation climate impact. Figure 8.2 provides the temporal evolution of the near-surface temperature change, showing for all cases a large climate impact decrease to the baseline scenario. Combining FP2050 with offsetting incentives results in a package that performs satisfactorily and within the Paris Agreement goals, reading from Table 8.1 that the total ITC is only 60.4 mK which constitutes a 71.61% reduction. Furthermore, the temporal evolution shows that the trendline has a negative slope, and the maximum does not exceed the 5% budget criteria. These are the first scenarios to display a temporal reduction of the total ITC. Both T40F5-CORSIA+ and IATA-T5bF5-CORSIA+, which are scenarios including

Scenarios	ΔT_{total}	**% Diff**	ΔT_{CO_2}	**% Diff**	ΔT_{NO_x}	**% Diff**	ΔT_{Cont}	**% Diff**	ΔT_{H_2O}	**% Diff**
Baseline	212.771	-	82.082	-	66.136	-	58.025	-	6.528	-
T40-CORSIA+	87.275	-58.98%	20.179	-75.42%	16.406	-75.19%	48.905	-15.72%	1.785	-72.66%
IATA-T4b-CORSIA+	83.138	-60.93%	20.503	-75.02%	14.811	-77.61%	46.138	-20.49%	1.687	-74.16%
FP2050-CORSIA+	60.409	-71.61%	19.743	-75.95%	8.577	-87.03%	31.078	-46.44%	1.011	-84.51%
T40F5-CORSIA+	56.664	-73.37%	19.984	-75.65%	10.765	-83.72%	24.663	-57.50%	1.251	-80.84%
IATA-T4bF5-CORSIA+	54.704	-74.29%	20.315	-75.25%	9.921	-85.00%	23.261	-59.91%	1.208	-81.50%

Table 6.8: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions for the synthesized scenarios represented in Table 6.7.

formation flight, reduce the total-ITC down to 55.6 mK and 54.7 mK respectively. Modeled without formation flight implementation as in T40-CORSIA+ and IATA-T4b-CORSIA+, the total-ITC is reduced to 87.3 mK and 83.1 mK. A fact already found earlier was that formation flight shows a high potential to reduce climate impact using the assumptions from literature, with a large part of the impact deriving from contrail-cirrus RF reduction of 48%. Since the fuel consumption is much lower in this case, 48% in the post-processing amounts to much less in absolute terms. This scenario still assumes a full fleet formation flight, which will be re-assessed as this assumption is misleading and can not be made. T4b-CORSIA+ shows total-ITC negative growth, thus showing the potential to diminish climate impact over time. The latter set of scenarios does not meet the threshold, but this could change if other boundary conditions of 5% of the Paris Agreement in the current modeling setup. Since all scenarios use the CORSIA+ storyline, the CO_2 ITC is near identical since only slight deviations exist up to 2040 for all scenarios. Thus the primary difference between the scenarios is caused by the differing contrail ITC, which amounts to 48.9 mK for the T40-CORSIA+ scenarios, and for the scenario including formation flight (T40F5-CORSIA+) this was only 23.3 mK. 15.7% reduction and 60% reduction respectively caused by additional post-processing.

The scenarios presented previously allow for some assumptions which might be called ambitious or downright unrealistic, therefore it was of interest to include a scenario that would check overly optimistic assumptions. Such as all political instances agreeing globally might be an unrealistic outlook, it is unlikely global agreement will cause a well-optimized plan for climate impact reduction. Also, even if the intentions and actions are aligned, uncertainties in scientific knowledge could cause a less desirable outcome than expected. The following scenario can be seen in many different conceptualizations, and it contains an exploratory nature based on the synthesized modules. This scenario serves to provide a balanced discussion of the findings from Figure 8.2, given those narratives assumed very favorable offsetting, low fuel consumption, and high reductions from formation flight. This scenario will allow for modeling of all strategies imperfectly, implying e.g. not 100% offsetting but only 80%. The EI_{NO_x} reduces from 2025 onward with the factorization decreasing every five years by 0.04 down to 0.40, which will cause the NO_x emissions to be reduced much less. Formation flight is performed, but 50% of the fleet realizes formation flight at a 5% fuel consumption reduction, with post-processing thus only applying to half the fleet, which diminishes the impact of the formation flight module. Aviation is also taxed through qualitative taxation, but only by 20% as opposed to 40% earlier. Furthermore, the SAF uptake is changed to 2% in 2025, 5% in 2030, 50% in 2050, and 70% in 2100. This is compared to 2%, 5%, 63%, and 100% respectively. This complete model will be named the Degree of Uncertainty Future (DoU-Future), given measures are implemented by displaying leakage, failure, or impossibility of the strategies. The temporal near-surface temperature change is presented in Figure 6.10 with the tabulated breakdown of 2100 in Table 6.9.

Scenarios	ΔT_{total}	**% Diff**	ΔT_{CO_2}	**% Diff**	ΔT_{NO_x}	**% Diff**	ΔT_{Cont}	**% Diff**	ΔT_{H_2O}	**% Diff**
Baseline	212.771	-	82.082	-	66.136	-	58.025	-	6.528	-
DoU-Future	104.898	-50.70%	30.914	-62.34%	30.519	-53.85%	40.185	-30.75%	3.281	-49.74%

Table 6.9: Near-surface temperature breakdown in milikelvin (mK) using the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions for the Degree of Uncertainty Future scenario.

The result for the DoU-Future is still a significant improvement from the baseline scenario but presents a large difference from previous scenarios with overly optimistic assumptions. The total-ITC is reduced by 50.7% to 104.9 mK, with a large segment of the contribution being the contrail-cirrus ITC only reducing by

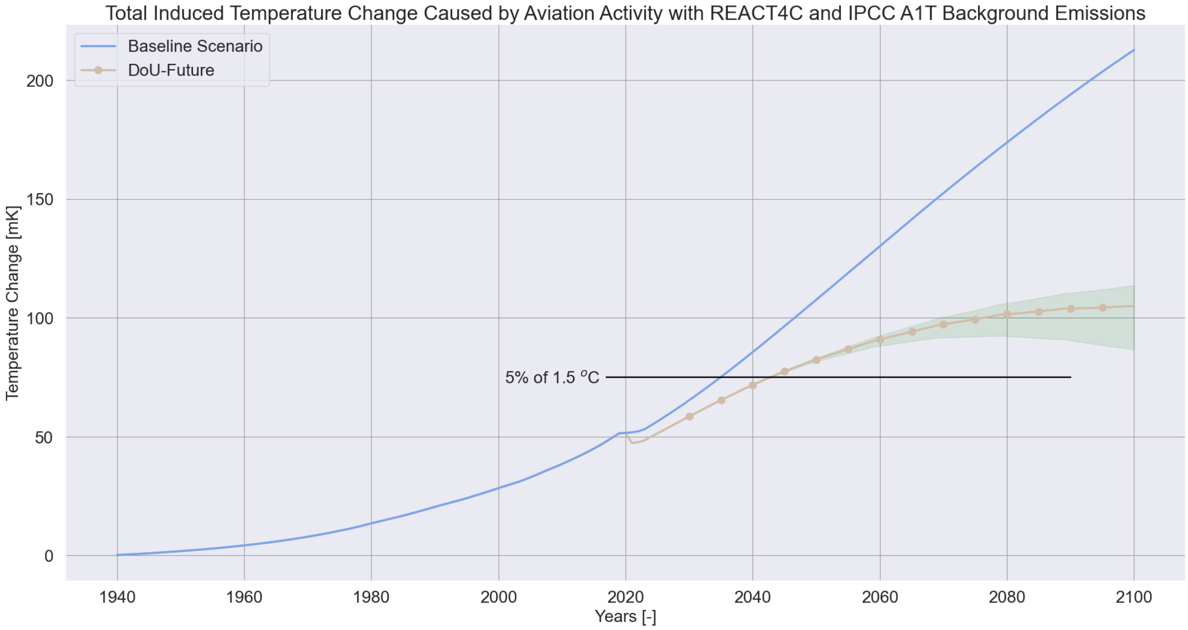

Figure 6.10: Temporal near-surface temperature change for the Degree of Uncertainty scenario, displaying a more realistic sociopolitical iteration to the previously outlined scenarios. Providing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions.

30.75% as opposed to 60% in the previous cases. Compared to the CO_2 ITC which is reduced by 62.34% compared to around 75% for cases from Table 8.1. The net-NO_x-effects ITC also displays a large difference, where for the FP2050-CORSIA+ was reduced by 87.03% and for the DoU-Future this is 53.85%. The implications remain the same and will be discussed in upcoming chapters. Through the layers of analysis, dictated by the terms of used software and initialization, the CO_2 is the only emission component that has a high scientific understanding, thus resulting in a minimal uncertainty range. The fact remains that both the impact of net-NO_x-effects and contrail cirrus are prone to large uncertainty for radiative forcing and simply missing resolution of used models, which means that if one of these expresses substantially different from the mean the climate impact could vary significantly. Unfortunately, as these externalities are not fully grasped, the doctrine of higher economic efficiency, such as lowering fuel costs for airliners, remains to be attributed of higher importance.

7

Discussion of Uncertainties of Modeling Climate Impact of Commercial Aviation

Within the current analysis and in general, whenever scenario building is done, many uncertainties could be derived from the assumptions. Throughout this thesis, it was identified that there was a literature study that has led to input data generations based on it, and then the subsequent use of AirClim to simulate the output results. It was also found that even though similar trajectories were modeled, such as the Flight Path 2050 within this thesis and in relevant other literature, the results were subject to an absolute difference, although the behavior observed was similar. All these findings allow the synthesis of a discussion related to the uncertainties regarding the approach and eliminate topics for further research, either derived from this research or simply because they were left out of the scope.

The primary tool for the analysis is the climate evaluation tool AirClim, on which already relevant verification and comparison with other software were mentioned and therefore do not need to be repeated. It was clear that there were multiple input streams, out of which the 3D emission inventories, the temporal background emissions for CO_2 and CH_4, and, finally, the self-generated temporal input data. The current manner in which AirClim was set up and used, given this thesis was essentially performing analysis through the use of AirClim without iterating the internal functionality of the code itself, limited the number of scenarios that were assessed. The parameters such as the flown distance and the NO_x-emissions were scaled according to the growth of the fuel consumption. Where NO_x-emissions could be changed through the use of the emissivity index. However, the flown kilometers were used to compute the contrail coverage, which only can decrease through the reduction of fuel consumption. Changes to the impact of contrails were only done through the post-processing steps, removing time-based components and simplifying the mechanics. This left the question unanswered if the output was a result of the inherent relation between fuel consumption and flown kilometers, or purely based on atmospheric interaction. A more detailed relation between flown kilometers and fuel consumption should be available. Furthermore, the current manner of modeling ISO and formation flight was done unrealistically, both in the sense that in the sensitivity analysis 100% ISO or formation flight was assumed, which is implausible. To more accurately assess a temporal climate impact, the three-dimensional emission inventory would have to be temporally changed based on measures taken in a scenario. For both ISO and formation flight it is essential that large-scale analyses are performed, which go into more depth taking into account the impact of the changing background emissions on the changing scenario, rather than simply scaling the inventory as was done. Currently, it is assumed to obtain the benefits of an operational strategy, which in and of itself changes the atmospheric concentrations as to where they are emitted. Finally, with regards to the selected input streams, it has to be acknowledged that the 3D emission inventory and the background emissions are of large influence on the output results. It was made generally understood and it was shown what the influence of input conditions could be on the output, for which an in-depth study could generate a mapping of different combinations of background emission inventories and 3D emission inventories. There needs to be a normalized framework that clearly defines a climate impact study and associates it with a methodology used for computation to generate uniformity of findings. Also, studies will have to be performed concerning the impact of 3D emission inventory resolution, as was shown within the inter-comparison of AirClim with the E39/CA model, potential lower methane and ozone radiative forcing could be the cause of different spatial resolution, for which it is both important to understand if a better spatial resolution shows that previous estimations were under-estimations or over-estimations of the climate impact, besides the fact that it might point out that spatial resolution increase does not significantly change the outcome. Furthering knowledge on the emission mapping framework might improve efforts to accurately estimate climate impact, without the need for unnecessary investment into e.g. higher resolution mappings.

There was also a qualitative effort to model the impact on the climate through economical choices made, through the taxation of tickets. This model was too simplistic to allow only to observe a very simplistic mechanism, for which both the mechanism through which it reduced the RPK and the magnitude was impossible the verify due to the immense complexity of the scenario. Economical changes are highly dependent on aspects such as the alternative modes of transport, local infrastructure, bordering countries' policy, airliner decision making, cultural norms, and many more aspects. Further research is required to synthesize a model which takes into account these aspects to some degree, which would allow for a more realistic relationship between the aviation demand and the changing in ticket pricing. It is the question of how to model human behavior to a degree of certainty, which exactly underlies the importance of qualitative assessment as human behavior is highly fluid.

To remain on the topic of modeling, also a qualitative assessment was done in a highly idealized manner regarding sustainable aviation fuels. There is a need for further assessments and continuous updating of the knowledge on the life-cycle assessments of sustainable aviation fuels, as currently, no consensus exists on the best accounting manner of co-products, which has a large impact on the eventual outcome. The analysis showed that the impact when assessing the CO_2 emissions was not extremely large, because the impact only slowly built up under the assumption of the EU55 pathway. More in-depth analysis will have to be performed on both the emission performance of the life-cycle of sustainable aviation fuels, besides the impact when there could be adverse effects on the climate impact. Also, the question of availability was not analyzed, which could dramatically reduce the climate impact performance of this option. Availability for the aviation sector biofuels is one thing, besides this other sectors will also require biofuels to realize their future climate goals. It was also not assessed what could be the impact of sustainable aviation fuels having potentially different emission characteristics, thus having a different emission profile, which could allow for both much worse or much better performance of the strategy.

Also, an obvious comment and general uncertainty can be derived from the uncertain times this thesis was written. It is currently still unclear what the recovery of the aviation sector from the pandemic will look like and if it will slow down air traffic demand, or potentially even cause explosive growth as the status of the pandemic diminishes. Choices made for the baseline and subsequent following scenarios are not able to model the turbulence of the situation as the scale and time frame of this pandemic is unseen throughout modern history. Extreme cases tested in AirClim have shown the slow response adaptation of CO_2 climate impact, but the relatively rapid recovery of non-CO_2 climate impact. Thus, what can be stated is that if aviation returns to similar modes of operation, the pandemic has only slowed down the growth for the moment unless structural changes are introduced.

8

Can Aviation Support the Paris Agreement Goals; Discussion

This chapter aims to bring together the findings from both the verification and plausibility study from chapter 5 and the results from chapter 6. The primary implications and obvious trends which seem to optimize the climate performance with a clear understanding of the modeling limitations will be outlined in chapter 7.

Revision of Global Outline and Literature Comparison

The implication of the results have already been noted along the way to a minimal degree, but before moving on to a revision and appending of these implications, it is important to state once more the underlying framework which will lead to these implications and the relation to other studies. This thesis is built upon a top-down data generation method with the precursor being the revenue passenger kilometers, which were found to agree with Figure 4.7, where deviations existed due to modeling assumptions and the exclusion of the COVID impact depression on the growth. AirClim was utilized as a climate evaluation tool, using temporal fuel consumption found through RPK figures and fuel economy implications, with artificial growth decay assumptions covering the last 50 years of the time frame. From Table 5.23 can be read that deviations to the RPK year-on-year growth synchronization parameter could yield variation in the order of 40 mK increase and 30 mK decrease in temperature change. Changing the decay for the fuel economy trend-line between stagnation and linear improvement could yield similar changes as for the RPK deviations. Besides fuel consumption, an inventory is required to describe the location of relevant emissions for computation of changes in atmospheric chemistry, for which the REACT4C 3D-emission inventory was used, and simulations showed that the inventory choice could already create a 25 mK uncertainty. Rigorous testing upon different initialization settings of the above-described parameters has not been done, which was mentioned in the uncertainties. Finally, to compute the impact of aviation, an assumption has to be made about the state of the world. Meaning that a storyline of the background emissions for both CH_4 and CO_2 were required. The background emissions choice can dictate and change the nature of the results, as they create a relative framework to compare the aviation emission too.

Although these settings were not iterated, the comparison of Figure 6.3 and Figure 5.2 can provide an insight into what the boundary conditions can imply on the result and the importance of further studies on the differences. In the studies done by Figure 5.2, which will be implicitly referred to in the coming segment, an in-house emissions inventory, a background emissions from the Representative Concentration Pathway (RCP) 2.6 and own calculations for further input parameters were used. RCP 2.6 is a background where the CO_2-emissions decline from 2020 on-wards to zero in 2100. CH_4 has to go to half the levels of the 2020 values. The complexity of establishing required assumptions is touched upon in a step-wise approach in van Vuuren et al. [2011], where the amount of assumptions needed to arrive at a trend such as RCP 2.6 is derived, e.g. one has to decide on population growth and economic growth. The RCP 2.6 represents a low emission scenario also because the population size is estimated at the lower end of what the UN population growth points out, and there is a relatively higher GDP. Figure 8.1 shows the background annual emissions for both the CO_2- and CH_4-emissions. The IPCC A1T inventory used for this thesis lies close to the RCP 4.5 besides the trend of the CO_2-emissions in the last 20 years of the time frame. The choice of an emission background changes the relative impact of CO_2-emissions, causing a lower overall impact when there is a higher background emission. It could be seen in subsection 5.1.1, comparing it to the analysis of the RPK parameter, that indeed when switching from the IPCC A1B to IPCC A1T background emissions, the CO_2 ITC increased by around 10 mK, where A1B has higher background CO_2. CH_4-emissions are closely related to NO_x-emissions and the net-NO_x-effects. NO_x emissions lead indirectly to the formation of ozone, which for its formation amongst other species indirectly requires CH_4 and thus depletes it, which decreases warming stemming from CH_4 and increases the O_3 warming. On the other hand, a reduction of CH_4 is a precursor for the reduction of O_3 decreasing the background O_3 called the Primary Mode Ozone (PMO) Grewe et al. [2019]. Stevenson et al. [2004] showed this fact in that a reductive perturbation of CH_4 signified a negative impulse in the O_3. The A1T inventory has a higher background of CH_4-emissions, which will impact the relationship between these modes in which the temperature change is increased and decreased.

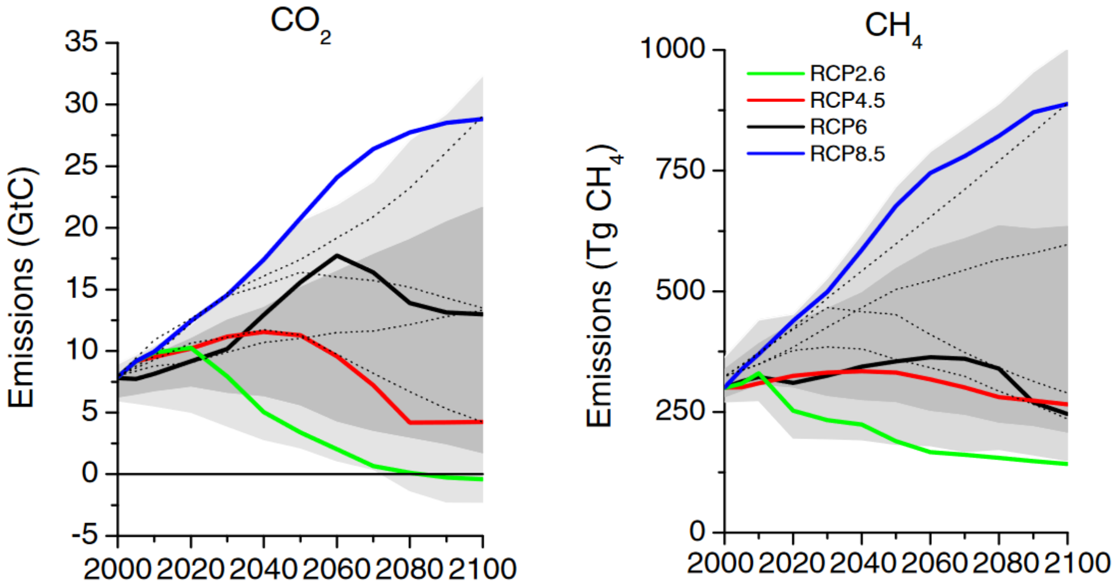

Figure 8.1: Depiction of the conceptualization of the IPCC Representative Concentration Pathway 2.6 for the annual CO_2-emissions (left) and the annual CH_4-emissions (right), showing years on the horizontal axis and the emissions in gigatonnes (10^12) of kilograms CO_2 and billions of kilograms CH_4 van Vuuren et al. [2011]

The baseline scenario in comparison with the BAU has a higher near-surface temperature change induced by CO_2, which is interesting provided for the BAU the RCP 2.6 was used. Figure 4.10 might provide a reason, where it can be observed that the baseline fuel consumption is higher for the last 60 or so years, however, it still leaves a large gap between the two results. With the BAU being around 65 mK and the baseline 82 mK of CO_2 ITC. The net-NO_x-effects also induce more temperature change, which is however plausible given this is defined by the emission inventory. The effects caused by a difference in trend, even though the final value builds up to similar fuel consumption, were already outlined in subsection 5.1.3. There it was shown that a lower fuel consumption eventually could still yield a higher CO_2-induced impact resulting from trend differences. Besides, there might also be a reason within how AirClim computes the emission perturbation data based on the temporal evolution, which has caused the difference in these results, such as the factorization to the three-dimensional emission inventory base year, which could cause the anomaly perceived for the CO_2-impact. It was seen in Figure 5.1 that there does exist a difference when normalizing an emission inventory towards a different base year, although it yielded a minor difference in that specific example.

Returning to Figure 6.3 and Figure 5.2 a comparison can be drawn between the respective FP2050 scenarios, which are based upon similar temporal assumptions. The FP2050-Impulse and FP2050-Continuous scenarios are subject to similar assumptions compared to the FP2050 and FP2050-cont in the work of Grewe et al. [2021]. As was already mentioned, the baseline scenario corresponds with the BAU but displays a much more linear growth. Also, the Flight Path scenarios in this thesis still grow after the Flight Path goals in 2050, as compared to a reduction in Figure 5.2. What can be seen is similar behavior between the Impulse and Continuous case, as in both cases they have a perceivable and large difference, which is breached when moving towards the end of the time frame. Upon further elaboration, it was found that this breaching of the gap was attributed to the increasing contrail-cirrus climate impact. It is clear that the baseline scenario and the BAU scenario only seem to differ primarily in the 2050-2100 region, and to equalize the trends the baseline scenario could be 'pulled down'. This difference can potentially be supported by the fact that the respective emission background schemes start to differ more significantly in this period. For example, when taking the end of the time frame, in the year 2100, the baseline scenario has an ITC of 212.77 mK and the BAU one of 155 mK, thus requiring a factorization of 0.73 to match. Factorizing the FP2050-Continuous scenario in 2100 with 0.73 would result in 72.64 mK of ITC, which matches the findings from Grewe et al. [2021]. Thus, although the different choices caused a difference in behavior for the latter part of the time frame, when applying adequate factorization or 'pulling down' of the modeled trends, the behavior of the results displays consistency.

Discussion of the Results: Composition of Climate Impact

Table 8.1 shows the resulting ITC in 2100 for the relevant scenarios. The baseline could result in up to 212.8 mK of ITC, which through the CORSIA+ plan is reduced by 29% to 151.2 mK. Although this constitutes a large reduction, it still amounts to about twice the allocated budget for the aviation sector under the assumption of 5% climate change caused by aviation. It is still a promising outcome given this only focuses on one aspect of the overall problem, reducing the CO_2 induced near-surface temperature change, still ignoring aspects such as net-NO_x-effects and contrail cirrus. To assess the broader impact, the baseline was iterated by using the IATA T4b storyline, which focuses on the change of fuel consumption as well as changes to the NO_x emissions through exploratory 'what if' EI_{NO_x} scenarios. These scenarios (IATA-T4a-High NO_x & IATA-T4b-FP2050 NO_x) caused a 25.8% and a 38.9% reduction in total ITC, yielding 157.8 mK and 130 mK respectively. The difference between the two cases is caused by how the NO_x emissions are dealt with, yielding a 38.3% reduction in the former and a 77.6% reduction in the latter. Appending findings from either case shows a clear trend, showing the effectiveness and necessity of carbon offsetting, but also the continuous need to keep on decreasing fuel consumption. Both for the direct effects of lowering more facets of the causes of aviation climate impact, besides the indirect effect of requiring fewer offsetting certificates resulting from lower fuel consumption. A fact that must certainly not be forgotten, given continued reliance on carbon offsetting, might work in the short-run, but will just shift the problem down a couple of generations. The balance between price and availability of offsets and practicing the act should be economically incentivized or discouraged by the market, it remains to be seen if this balance will be sufficient. Furthermore, the IATA T4b scenario shows that reducing fuel consumption will reduce the impact of contrail-cirrus. Through observing results such as seen for the extreme cases and the technology cases with the Flight Path 2050 equivalent EI_{NO_x} trends it was concluded that the contrail-cirrus behaves non-linearly. More specifically, the contrail-cirrus induced temperature change does not decrease linearly with the fuel consumption shown in Figure 5.13. Even in the 2025 Constant case in the extreme case figure, displaying constant fuel consumption from 2025 onwards results in a factor of 2.5 lower fuel consumption in 2100 however still, the contrail-cirrus ITC reduced by 38.4%. The contrail-cirrus ITC amounts to 35.8 mK in this case, near half the 75 mK Paris Agreement budget. In the case of the IATA T4b High NO_x scenario, which has a higher fuel consumption than the latter but still much less than the baseline, displays a contrail-cirrus ITC of 46 mK. The contrail-cirrus seems to move towards the baseline value, even though the fuel consumption is nearly half that of the baseline. The reduction of NO_x remains a topic of uncertainty. Standards exist, such as the ICAO CEAP NO_x limits, which require the NO_x mass during the landing and take-off test cycle, divided by the thrust to be below some regulatory maximum [1]. Also, electric propulsion could eliminate NO_x emissions but the ICAO CEAP conditions are not very stringent, and there is no monetization value to reducing NO_x because of which it does not have to be actively reduced currently. If new findings might direct a more stringent focus on NO_x emissions, technologies such as flameless combustion could potentially increase the thermal efficiency by 30% and reduce the NO_x emissions by more than 70% when waste heat of flue gases is regenerated [Xing et al., 2017].

After the scenarios which focus on one or the other aspect of the total picture comes the DoU-Future, which represents a loose implementation of multiple strategies, ultimately reducing all discussed parameters slightly. The scenario results in an ITC of 104.9 mK, which is driven by the contrail-cirrus impact remaining significant as the post-processing factorization is reduced. A host of questions exists concerning contrail-cirrus, and methods will have to be assessed congruently with furthering scientific knowledge to reduce the impact of the type of ITC. When turbofan-engines get more efficient and gain higher thermal efficiency, the exhaust air temperature congruently reduces, which improves the conditions for persistent contrail formation [Gierens et al., 2000]. Allowing a paradox of the decrease in fuel consumption but the increase in potentially

[1] EASA, URL: `https://www.easa.europa.eu/eaer/topics/technology-and-design/aircraft-engine-emissions`

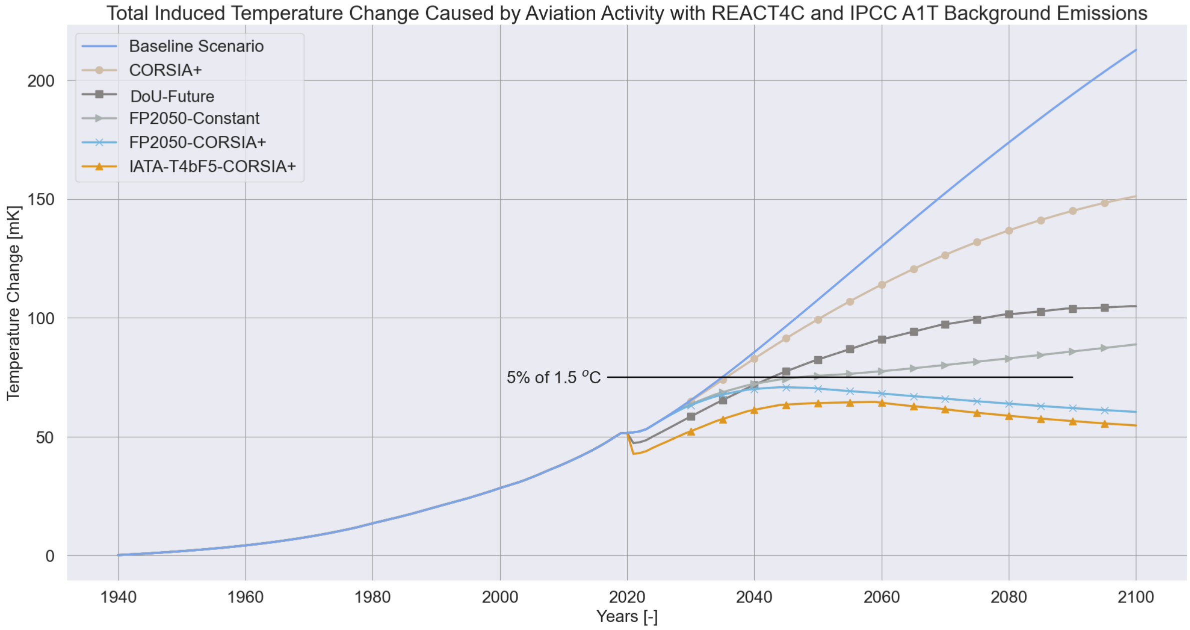

Figure 8.2: Temporal near-surface temperature change combining all relevant assessed scenarios combining findings from chapter 5 and chapter 6. Providing the temporal change in years on the horizontal axis and the temperature change in milikelvin (mK) on the vertical axis. The climate impact is modeled through using the REACT4C emission inventory and the IPCC A1T background emissions.

Scenarios	ΔT_{total}	**% Diff**	ΔT_{CO_2}	**% Diff**	ΔT_{NO_x}	**% Diff**	ΔT_{Cont}	**% Diff**	ΔT_{H_2O}	**% Diff**
Baseline	212.771	-	82.082	-	66.136	-	58.025	-	6.528	-
Formation 5%	163.33	-23.24%	72.11	-12.15%	56.37	-14.76%	29.30	-49.50%	5.55	-15.01%
IATA T4b-High NO_x	157.845	-25.81%	67.394	-17.89%	40.166	-39.27%	46.138	-20.49%	4.146	-36.49%
Baseline-CORSIA+	151.173	-28.95%	20.484	-75.04%	66.136	-	58.025	-	6.528	-
IATA T4b-FP2050 NO_x	130.030	-38.89%	67.394	-17.89%	14.811	-77.61%	46.138	-20.49%	1.687	-74.16%
DoU-Future	104.898	-50.70%	30.914	-62.34%	30.519	-53.85%	40.185	-30.75%	3.281	-49.74%
FP2050-Constant	88.813	-58.26%	45.673	-44.36%	10.861	-83.58%	31.078	-46.44%	1.201	-81.60%
T40-CORSIA+	87.275	-58.98%	20.179	-75.42%	16.406	-75.19%	48.905	-15.72%	1.785	-72.66%
IATA-T4b-CORSIA+	83.138	-60.93%	20.503	-75.02%	14.811	-77.61%	46.138	-20.49%	1.687	-74.16%
FP2050-CORSIA+	60.409	-71.61%	19.743	-75.95%	8.577	-87.03%	31.078	-46.44%	1.011	-84.51%
T40F5-CORSIA+	56.664	-73.37%	19.984	-75.65%	10.765	-83.72%	24.663	-57.50%	1.251	-80.84%
IATA-T4bF5-CORSIA+	54.704	-74.29%	20.315	-75.25%	9.921	-85.00%	23.261	-59.91%	1.208	-81.50%

Table 8.1: Near-surface temperature breakdown for all relevant scenarios from chapter 5 and chapter 6. Induced temperature changes are provided in milikelvin (mK), obtained through the use of the REACT4C and IPCC A1T emission inventory, for the year 2100. Including the contributions of all CO_2 and non-CO_2 emissions, along with their percentage-based difference to the baseline value for varying trend factorization values.

significant climate impact resulting from contrail-cirrus. The contrail-cirrus has only been evaluated in these studies through post-processing based on literature, besides the in AirClim chemistry model dealing with the general formation, coverage, and radiative forcing calculations. Thus creating a direct relationship between fuel consumption and flown distance, which is bound through scaling assumptions to the 3D emission inventory. With current initialization conditions and chosen boundary conditions, the contribution is around 27% of the baseline climate impact, making it a relevant contribution. Contrail formation and subsequent climate impact are highly conditional, meaning that with adequate data, knowledge, and situational optimization, the related impact could be reduced when scientific consensus and economics agree. For example, one can compute the needed fuel to divert climate-sensitive regions, thereby potentially having to fly shortly at a lower altitude, which might then allow for more climate impact reductions as was touched upon.

The previous scenarios did not achieve to support the goals agreed upon by the Paris Agreement, within the limited scope of assuming an average contribution of the aviation sector at 5% of total anthropogenic warming. Some scenarios showed a desirable performance, which is turned to next. First, the exploratory quantitative scenario includes the 40% taxation with the CORSIA+ offsetting scheme and the Flight Path 2050 EI_{NO_x}-

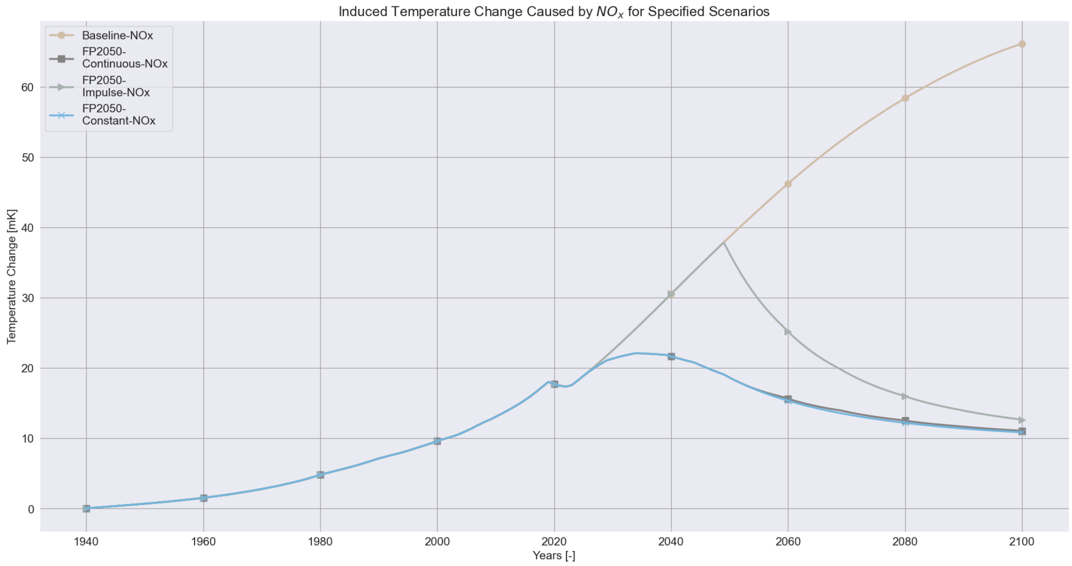

Figure 8.3: Change of the net-NO_x with years on the horizontal axis and temperature change in milikelvin (mK) on the vertical axis, representing the induced temperature change for the Flight Path 2050 scenarios

trend assumptions. This scenario assumes a full carbon offset realizing CNG, and the 40% does not rely on a complex underlying economical model. The T40-CORSIA+ scenario performs similar to the IATA-T4b-CORSIA+, where the climate impact is reduced by about 60%. Here, it remains true that the contrail-cirrus climate impact remains the bottleneck. Naturally, when adding modules that reduce the contrail-cirrus ITC, the scenarios' climate impact is reduced even further, such as for the T40F5-CORSIA+ and the ITATA-T4bF5-CORSIA+, which display a satisfactory outcome. This result logically flows from the previously set out tests and reduces the major climate impact groups: CO_2, net-NO_x-effects, and the contrail-cirrus. The only way to remain below the targets set is to start fast and not focus only on either CO_2- or non-CO_2-emissions. However, this current model assumes many aspects such as market module elasticity, fuel savings from formation flight, participating aircraft in formation flight, and much more as static, where they are dynamic. To present a counter-argument to the relatively optimistic results, the DoU-future was modeled to outline the impact of some assumptions made earlier for satisfactory models. The near-surface temperature ended up being around 105 mK, thus surpassing the goal but displaying a stabilizing climate impact in terms of growth. Taking into account emission inventory uncertainty or the potential of an A1B future over an A1T future, and the factorization with other work from literature discussed earlier, this scenario could still present a feasible scenario to achieve the goals of the Paris Agreement. The opposite could also remain true, the results obtained through the use of mean values for species RF could yield an underestimate of the total ITC.

The largest near-surface temperature-inducing entities, which are the primary argument of the implications made, are still a large uncertainty. Lee et al. [2021] states with displaying a 5-95% confidence that the mean values of 149.1 mW/m^2 between 1940 and 2018, can vary with about 80 mW/m^2. Both contrail-cirrus and net-NO_x-effects are sources of large uncertainty, with contrail-cirrus estimated at a mean of 111.4 mW/m^2 and uncertainty of around 78 mW/m^2. The net-NO_x-effect could even display cooling effects, which could imply that the net-NO_x-effect and contrail-cirrus expressed climate impact can be much lower or higher than expected. The highest certainty lies in reducing the CO_2 ITC, but this is a strategy that would rely upon a hopeful future as it constitutes 39% of the total climate impact, and displays the highest inertia due to the slow uptake of CO_2 emissions. This fact was already presented with Figure 6.4 and can be further elaborated with Figure 8.3, which shows that from 2050 on-wards the net-NO_x-effects ITC reduces significantly from about a difference of 20 mK between the FP2050-Continuous and FP2050-Constant case, to 5 mK in 2080 climbing converging steadily. Conversely, the CO_2-response is much slower, which could be vital when the aim is to remain below some threshold. The longer CO_2 reducing measures are postponed, there is a higher reliance on the reduction of shorter-life-time emissions, which could be either technologically impossible or economically unviable. Approaching this problem with too much optimism might diminish the focus on the more uncertain components and stimulate inaction, which sudden and rapid action can not set straight.

9

Aviation and Climate Goals; In Conclusion

This research aimed to search for the possibilities for the aviation sector of supporting the goals set in the Paris Agreement, which dictates a maximal temperature change of 2.0 ^oC but is more generally interpreted with a safety margin as 1.5 ^oC. The aviation industry is responsible for about 5% of the anthropogenic warming, which comes with an uncertainty of 2-14% [Grewe et al., 2019]. These aspects were synthesized into the research question:

Are the anticipated developments in the aviation sector in support of the goals agreed upon in the Paris Agreement, assessing performance through a scenario-based approach and the climate evaluation tool AirClim.

To answer the question research was required to scope this broad topic, which is approachable from many different points of view and design ideologies. The analysis was made possible through the use of the DLR-designed climate evaluation tool AirClim [Grewe and Stenke, 2008, Dahlmann et al., 2016a], furthermore AirClim was used in Grewe et al. [2021] serving as a pretext for this thesis. To create tangible storylines, scenarios were built based upon the three identified developmental spheres; the operational sphere, the technological sphere, and the political sphere. Each of these spheres is infinitely complex, where for example the political sphere is addressed qualitatively. Nonetheless, being fully aware of the qualitative/quantitative divide and the limited accuracy caused by uncertainties in modeling and calculating climate impact, conclusions can be drawn.

The ambitions set by the researchers for the Flight Path 2050 have resulted in the goals for 75% CO_2 and 90% NO_x emissions reduction per passenger kilometer. Modeling for these goals through assuming reductions in fuel consumption and NO_x emission performance has shown a favorable climate impact performance as shown in Figure 6.3. Neither case remained below the 75 mK threshold of the Paris Agreement, but they did stay below the 100 mK, which is the higher threshold of the Paris Agreement. Comparing this outcome to the work from Figure 5.2, adding the discussion from chapter 8 and applying the established factorization, the result would then remain below even the 75 mK threshold. The aviation sector is a slowly changing industry and will unlikely become green given the high energy demand for aviation and the extreme conditions experienced in general. Other branches, such as the automotive industry, could more easily transition to technology such as electric transport. Aviation will likely be a sector dependent on other more able sectors to transition and make up for the deficit aviation creates, which will initially allow for carbon offsetting via schemes such as the Carbon Offsetting Reduction Scheme for International Aviation and other relevant climate policy. Carbon offsetting will be an easy and vital aspect of the aviation sector transition to less climate impact, but it will not allow for carbon neutrality of the overall mechanism. The flow of assets to companies generating CO_2-certificates will have positive results but hopefully, the availability of the carbon offsetting option will not deprive technological advancement, for which a basis has been laid throughout this research. It remains the question if the market-based mechanism, built to allow for further growth of the aviation sector, will take relevant emissions other than CO_2 into account as time passes. Provided uncertainty exists, non-CO_2-emissions and their effects make up around 60% of the climate impact. If schemes predominantly focus on emissions containing only a small uncertainty due to high scientific consensus, such as CO_2-emissions, tangible action for non-CO_2 emissions might take too long. Current modeling setup has shown that if a pathway like FP2050 could be achieved, meaning that the sector would grow carbon neutrally, alongside the substantial reduction of fuel consumption and NO_x-emissions, the aviation induced climate impact has a chance of staying below the threshold for the Paris Agreement. This statement is made with the clear understanding that to make this scenario a reality, the aviation sector has to be radically overhauled by first a change in mindset, which focuses on climate impact, besides a radical overhaul of the current homogeneous infrastructure. More radical testing is needed on directly applicable operational strategies, and a better definition of priority through economic incentives e.g. for research and roll-out of low-NO_x technologies such as flameless combustion. One aspect is certain, the future of the aviation sector lies in the hand of a host of organizations and countries, to improve upon the current scenario is possible through the ability and willingness of these respective parties. Especially considering the delayed response of emission expression poses the largest problem given the political system is often short-term based these days, thus the question remains if the covered temporal trends can be realized even if they are technically speaking attainable.

Numerous tools were studied, from formation flight reducing the fuel consumption due to efficient wake surfing and the contrail-cirrus radiative forcing due to changing ice mass and extinction time, to more qualitative tools such as demand impulses due to taxation. Both the qualitative and the quantitative narratives were written and studied through the climate evaluation tool, for it is hardly possible to give a quantitative model regarding the whole. This thesis shows what a reduction in fuel consumption could yield, and attaches a reason to this reduction, but the interpretation of it can be varied through logical qualitative operations. For example, the IATA roadmap to 2050 provided a framework through the CO_2-intensity of the technological future of the aviation sector, focusing on the reduction of fuel consumption. But that reduction in fuel consumption can also be achieved by a patchwork of policies and technological advances. Instead of a top-down approach to study the impact of the whole sector, bottom-up studies should be performed to allow for tangible actions needed by individual components of the overall system. There needs to be an interplay between global top-down studies, which generates specialized bottom-up assessments to get a more detailed idea of what can be achieved.

The general fact is, that the baseline scenario displays three components that have to be reduced, regardless of their radiative forcing confidence interval. The reduction of CO_2-emission can be tackled through general fuel consumption reductions and carbon offsetting, which is still in its infancy. Schemes to reduce NO_x-emissions currently rest on the requirements set by the ICAO CEAP, and the reduction potential of NO_x is uncertain both in terms of how much can be reduced by technology, besides the actual impact of the net-NO_x-effects. Some options could be hopeful, such as electric propulsion, which will likely initially only be for smaller seat-classes aircraft and potentially for bigger aircraft later. One could switch to hydrogen propulsion, which could remove the NO_x but inversely would increase the water vapor content, which could change the impact of the contrail-formation tremendously if not assessed properly. Necessity might allow a higher acceptance for reverting to propeller-based propulsion, but it seems doubtful that slower aviation will become an acceptable norm again. Methods such as RQL and the current still uncertain developments of flameless combustion could drive down the NO_x-emissions of the currently used engine types. Improvements such as novel aircraft designs, which would lower the fuel consumption even when using the current engines, could also assist this effort to reduce the NO_x per passenger kilometer and thus the absolute NO_x-emissions. The options of mixing and matching strategies for operations, human psychology, and technological advancement are limitless. Similarly, as was mentioned about relying too much on policy-based strategies such as carbon offsetting, it would be dangerous to rely solely upon technology. Approaching the problem through a combination of human psychology, through understanding why people travel by aircraft and what would influence the behavior, besides improving the handling and technology in the aircraft itself.

Some scenarios contained unrealistic or qualitative expectations at best, regarding taxation, carbon offsetting, and e.g. formation flight, for which the primary purpose was to show what the addition of supplementary conceptual models could yield. To offset this too optimistic view, the Degree of Uncertainty-Future seen in Figure 6.10 was generated. The DoU-Future combined a qualitative RPK reduction represented as a 20% taxation increase, with reductions of CO_2 emissions through a light offsetting scheme, appended with the assumption of 50% of the aircraft performing formation flight and a EI_{NO_x} trend less ambitious but still reducing the NO_x emissions per kilogram of fuel by 60%. This scenario does not end up meeting the Paris Agreement goal causing 104.9 mK of warming, with the blend of sustainable aviation fuel used potentially allowing for CO_2 savings, which could conversely cause a decrease in climate performance of the scenario. However, it is still a hopeful outcome, reducing the climate impact as opposed to a future where the climate impact is not kept in check by 51%. If future efforts to meet the Paris Agreement goals will only focus on the CO_2-emissions, it is certain the aviation sector, using the current mean values for radiative forcing for non-CO_2-effects, will not pass the test of time. Refer to Figure 6.6 or the fact which every segment of this thesis has outlined, showing that the only manner to systematically reduce all impact groups is by reducing the fuel consumption. Be it through a pandemic or gains in efficiency. All sorts of strategies should be tried, even if the application is inefficient highlighting the importance and stimulating further research. Even the pandemic, which reduced air traffic to almost nothing but cargo-related traffic, only created a minor relief that did not seem to have much effect on the continuation of climate impact after recovery but a slight deprivation.

The aviation sector may develop that it can support the goals set in the Paris Agreement, where the word 'support' implies moving the aviation sector to the 75 mK goal, but it should also be read in a more general sense. The 75 mK goals, which corresponds to the lower 1.5 ^oC Paris Agreement goals of near-surface temperature increase compared to pre-industrial levels, is also already a figure based upon assumptions. It could be that aviation becomes a relatively larger or smaller contributor to the overall anthropogenic warming in the future. The aviation sector is one of the more extreme sectors to renovate, due to the high investment cost of purchasing an aircraft and the long development process of new technology. It remains to be seen if this fact might disallow the aviation sector to continue to grow and meet climate goals, in which case it is uncertain what will happen then. Potentially, the aviation sector can be assisted by external sectors through offsetting, for which also adequate studies are required to assess if this would be adequate, and what the potential impact shift could be. The aviation market might fail to produce results, in which external policy and behavior changes will be needed. Individual adjustments are already observed through flight shaming as a psychological tool, for which it is uncertain if this will impact the macro-growth of aviation activity or not. Repeating findings from Gössling and Humpe [2020], the top 10% of emitters account for around 45% of CO_2-equivalent emissions. Gössling et al. [2019] underlined the fact that the oft-mentioned contribution of aviation to the GDP and employment by advocates, the increased dependence on air travel goes in against SDGs such as Production and Consumption and Climate Action, which contradicts the dedications of the Paris Agreement. Reducing the climate impact to the intended goals will be extremely difficult, however, it is the obligation of policymakers and especially global and economical powers to live up to their obligations. These obligations will have to be fulfilled either through the removal of the fallacies and unfair power distribution currently possessed by the aviation sector, by re-assessing things such as tax exemptions, or through nudging the aircraft manufacturers to take more risks by presenting adequate monetary rewards. The current world is far from stabilizing, let alone solving the climate crisis. This thesis has illuminated several important aspects through assessing the problem with a global scope, displaying both more certain and uncertain aspects of the problem. It generates a reasonable answer to the macro-problem but does not support or properly outlines all the micro-problems, which will still require tireless efforts from researchers in the future. To not pro-actively respond to these findings would be to set the next generations up for an unpredictable world on which plenty of scientific and speculative literature has been based. It was conventional thinking and a lack of understanding which got us into the current conundrum of growth versus climate, where unconventional thinking and continued scientific pursuit of the issue might allow us to get out of it.

Bibliography

AerSale. Aircraft Life Cycle Management: A Breakdown of Your Aircraft Life Cycle, 2019. URL https://www.aersale.com/media-center/aircraft-life-cycle-management.

Air Transport Bureau. Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis. *International Civil Aviation Organization (ICAO), Montréal, Canada*, (February):178, 2020.

Airbus. European laminar flow research takes a new step with airbus' blade flight lab. https://www.airbus.com/newsroom/news/en/2017/09/european-laminar-flow-research-takes-a-new-step-with-airbus-blad.html, 2017. [Online; accessed 15 December 2020].

Airbus. Global Market Forecast; Cities, Airports & Aircraft 2018-2038. 2019.

Airbus. How a fello'fly flight will actually work, 2020. URL https://www.airbus.com/newsroom/stories/how-a-fello-fly-flight-will-actually-work.html.

H. Appleman. The Formation of Exhaust Condensation Trails by Jet Aircraft. *Bulletin of the American Meteorological Society*, 34(1):14–20, 1953. ISSN 0003-0007. doi: 10.1175/1520-0477-34.1.14.

Aviation Week Intelligence Network. Airbus Seeks Up To 10% Fuel Burn Savings By Aircraft Flying Together. 2019. URL https://aviationweek.com/shownews/airbus-seeks-10-fuel-burn-savings-aircraft-flying-together.

Susanne Becken and Brendan Mackey. What role for offsetting aviation greenhouse gas emissions in a deep-cut carbon world? *Journal of Air Transport Management*, 63:71–83, 2017. ISSN 09696997. doi: 10.1016/j.jairtraman.2017.05.009.

Paolo Bertoldi. *Overview of the European Union policies to promote more sustainable behaviours in energy end-users*. Elsevier Inc., 2019. ISBN 9780128185674. doi: 10.1016/B978-0-12-818567-4.00018-1. URL https://doi.org/10.1016/B978-0-12-818567-4.00018-1.

H.D. Betz, Ulrich Schumann, and Pierre Laroche. *Lightning: Principles, Instruments and Applications: Review of Modern Lightning Research*. 01 2009. ISBN 978-1-4020-9078-3. doi: 10.1007/978-1-4020-9079-0.

Simon Blakey, Lucas Rye, and Christopher Willam Wilson. Aviation gas turbine alternative fuels: A review. *Proceedings of the Combustion Institute*, 33(2):2863–2885, 2011. ISSN 15407489. doi: 10.1016/j.proci.2010.09.011. URL http://dx.doi.org/10.1016/j.proci.2010.09.011.

Boeing. Commercial market outlook 2019-2038, 2019. URL https://www.boeing.com/commercial/market/commercial-market-outlook/.

Marty K Bradley. How sweet the future of aviation - An informal brainstorm turns into potential climate-saving flight technologies., 2017. URL https://www.boeing.com/features/innovation-quarterly/aug2017/feature-technical-sugar.page.

Marty K Bradley and Christopher K Droney. Subsonic Ultra Green Aircraft ResearchPhaseII: N+4 Advanced Concept Development. 2012.

Marty K Bradley, Timothy J. Allen, and Christopher K Droney. Subsonic Ultra Green Aircraft Research: Phase II - Volume III - Truss Braced Wing Design Exploration. *NASA Technical Report*, CR–2015-21:76, 2015.

David Brain and Marylin Bastin. The Benefits Of CCO / CDO Operations-European Task Force Findings. pages 145–152, 2019. URL https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019{_}pg145-152.pdf.

Martijn Brons, Eric Pels, Peter Nijkamp, and Piet Rietveld. Price. *Print and Paper Europe*, 13(7):37, 2001. ISSN 14713063. doi: 10.4324/9781315850177-4.

Ulrike Burkhardt and Bernd Kärcher. Global radiative forcing from contrail cirrus. *Nature Climate Change*, 1: 54–58, 4 2011. ISSN 1758678X. doi: 10.1038/nclimate1068.

CAN & ICSA. Contribution of the Global Aviation Sector To Achieving Paris Agreement Climate Objectives. *Climate Action Network (CAN) and International Coalition for Sustainable Aviation(ICSA) Joint input to the Talanoa Dialogue*, pages 1–7, 2018.

Stuart Bryce Capstick and Alan Lewis. Effects of personal carbon allowances on decisionmaking: Evidence from an experimental simulation. *Climate Policy*, 10(4):369–384, 2010. ISSN 17527457. doi: 10.3763/cpol.2009.0034.

Richard Carmichael. Behaviour change, public engagement and Net Zero, a report for the Committee on Climate Change. (October), 2019. URL https://www.theccc.org.uk/publication/behaviour-change-public-engagement-and-net-zero-imperial-college-london/.

CE Delft. *Taxes in the Field of Aviation and their impact - Final report*. Number June. 2019. ISBN 978-92-76-08132-6. URL https://publications.europa.eu/en/publication-detail/-/publication/0b1c6cdd-88d3-11e9-9369-01aa75ed71a1.

NASA Ames Research Center. Variable camber aerodynamic control surfaces and active wing shaping control. https://www.nasa.gov/sites/default/files/atoms/files/arc-16644-1_variable_camber_aerodynamic_control_surfaces_and_active_wing_shaping_control.pdf, 2014. [Online; accessed 15 December 2020].

Lucas Chancel, Thomas Piketty, Branko Milanovic, Christopher Lakner, Paul Segal, Sudhir Anand, Glenn Peters, and Robbie Andrews. Carbon and inequality: From Kyoto to Paris Trends in the global inequality of carbon emissions (1998-2013). (November), 2015. URL https://wid.world/document/chancel-l-piketty-t-carbon-and-inequality-from-kyoto-to-paris-wid-world-working-paper-2015-7/.

K. Dahlmann, V. Grewe, M. Ponater, and S. Matthes. Quantifying the contributions of individual NOx sources to the trend in ozone radiative forcing. *Atmospheric Environment*, 45(17):2860–2868, 2011. ISSN 13522310. doi: 10.1016/j.atmosenv.2011.02.071. URL http://dx.doi.org/10.1016/j.atmosenv.2011.02.071.

K. Dahlmann, V. Grewe, C. Frömming, and U. Burkhardt. Can we reliably assess climate mitigation options for air traffic scenarios despite large uncertainties in atmospheric processes? *Transportation Research Part D: Transport and Environment*, 46(2):40–55, 2016a. ISSN 13619209. doi: 10.1016/j.trd.2016.03.006. URL http://dx.doi.org/10.1016/j.trd.2016.03.006.

Katrin Dahlmann, Alexander Koch, Florian Linke, Benjamin Lührs, Volker Grewe, Tom Otten, Doreen Seider, Volker Gollnick, and Ulrich Schumann. Climate-compatible air transport system-Climate impact mitigation potential for actual and future aircraft. *Aerospace*, 3(4):1–25, 2016b. ISSN 22264310. doi: 10.3390/aerospace3040038.

Katrin Dahlmann, Sigrun Matthes, Hiroshi Yamashita, Simon Unterstrasser, Volker Grewe, and Tobias Marks. Assessing the climate impact of formation flights. *Aerospace*, 7(12):1–12, 2020. ISSN 22264310. doi: 10.3390/aerospace7120172.

Sierk De Jong, Kay Antonissen, Ric Hoefnagels, Laura Lonza, Michael Wang, André Faaij, and Martin Junginger. Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnology for Biofuels*, 10(1):1–18, 2017. ISSN 17546834. doi: 10.1186/s13068-017-0739-7.

Eurocontrol. Fuel Tankering: economic benefits and environmental impact. *Aviation Intelligence Unit - Think Paper*, (June), 2019.

European Federation for Transport and Environment. Taxing aviation fuel in Europe. (February): 1–2, 2019. URL https://www.transportenvironment.org/sites/te/files/publications/2019{_}02{_}Taxing{_}kerosene{_}intra{_}EU.pdf.

European Parliament. Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003 87 EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community. *Official Journal of the European Union*, L(8/3):3–21, 2008. ISSN 1098-6596. doi: ISSN1725-2555. URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008L0101.

European Parliament and the Council of the European Union. Directive 2009/29/EC of the European Parliament and of the council of 23 april 2009 ammending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. *Official Journal of the European Union*, 140:63–87, 2009.

Jasper Faber and Thomas Huigen. A study on aviation ticket taxes. *CE Delft*, pages 5–10, 2018. URL www.cedelft.eu.

David W Fahey and David S Lee. Aviation and Climate Change: A Scientific Perspective. *Carbon & Climate Law Review*, 10(2):97–104, 2016.

Martin Falk and Eva Hagsten. Short-run impact of the flight departure tax on air travel. *International Journal of Tourism Research*, 21(1):37–44, 2019. ISSN 15221970. doi: 10.1002/jtr.2239.

General Electric. Gex9 commercial aircraft engine. https://www.rolls-royce.com/media/our-stories/innovation/2016/advance-and-ultrafan.aspx#solution, 2018. [Online; accessed 15 December 2020].

Klaus Gierens, Ulrich Schumann, Manfred Helten, Herman Smit, and Pi Huan Wang. Ice-supersaturated regions and subvisible cirrus in the northern midlatitude upper troposphere. *Journal of Geophysical Research Atmospheres*, 105(D18):22743–22753, 2000. ISSN 01480227. doi: 10.1029/2000JD900341.

Stefan Gössling and Andreas Humpe. The global scale , distribution and growth of aviation : Implications for climate change. 65(May), 2020. doi: 10.1016/j.gloenvcha.2020.102194.

Stefan Gössling, Paul Hanna, James Higham, Scott Cohen, and Debbie Hopkins. Can we fly less? Evaluating the 'necessity' of air travel. *Journal of Air Transport Management*, 81(September), 2019. ISSN 09696997. doi: 10.1016/j.jairtraman.2019.101722.

Brandon Graver and Daniel Rutherford. Transpacific Airline Fuel Efficiency Ranking. (January):6–17, 2016.

Brandon Graver, D Ph, Daniel Rutherford, and D Ph. TRANSATLANTIC AIRLINE FUEL EFFICIENCY RANKING , 2017. (September), 2018.

J. E. Green. Air Travel - Greener by Design mitigating the environmental impact of aviation: Opportunities and priorities. *Aeronautical Journal*, 109(1099), 2005. ISSN 00019240. doi: 10.1017/s0001924000000841.

V. Grewe and A. Stenke. AirClim: An efficient tool for climate evaluation of aircraft technology. *Atmospheric Chemistry and Physics*, 8(16):4621–4639, 2008. ISSN 16807324. doi: 10.5194/acp-8-4621-2008.

Volker Grewe, Sigrun Matthes, Christine Frömming, Sabine Brinkop, Patrick Jöckel, Klaus Gierens, Thierry Champougny, Jan Fuglestvedt, Amund Haslerud, Emma Irvine, and Keith Shine. Feasibility of climate-optimized air traffic routing for trans-Atlantic flights. *Environmental Research Letters*, 12(3), 2017. ISSN 17489326. doi: 10.1088/1748-9326/aa5ba0.

Volker Grewe, Sigrun Matthes, and Katrin Dahlmann. The contribution of aviation NO x emissions to climate change: are we ignoring methodological flaws? *Environmental Research Letters*, 14(12):14–18, 2019. ISSN 17489326. doi: 10.1088/1748-9326/ab5dd7.

Volker Grewe, Arvind Gangoli Rao, Tomas Grönstedt, Carlos Xisto, Florian Linke, Joris Melkert, Jan Middel, Barbara Ohlenforst, Simon Blakey, Simon Christie, Sigrun Matthes, and Katrin Dahlmann. Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nature Communications*, 12(1):1–10, 2021. ISSN 20411723. doi: 10.1038/s41467-021-24091-y. URL http://dx.doi.org/10.1038/s41467-021-24091-y.

John F. Gundlach IV, Philippe André Tétrault, Frank H. Gern, Amir H. Nagshineh-Pour, Andy Ko, Joseph A. Schetz, William H. Mason, Rakesh K. Kapania, Bernard Grossman, and Raphael T. Haftka. Conceptual design studies of a strut-braced wing transonic transport. *Journal of Aircraft*, 37(6):976–983, 2000. ISSN 00218669. doi: 10.2514/2.2724.

Laura E. Hombach, Larissa Doré, Katrin Heidgen, Heiko Maas, Timothy J. Wallington, and Grit Walther. Economic and environmental assessment of current (2015) and future (2030) use of E-fuels in light-duty vehicles in Germany. *Journal of Cleaner Production*, 207:153–162, 2019. ISSN 09596526. doi: 10.1016/j.jclepro.2018.09.261.

D. Hummel and M. Beukenberg. Aerodynamics, performance and control of airplanes in formation flight, 1990.

IATA. Healthy Passenger Demand Continues in 2018 with Another Record Load Factor, 2019a. URL https://www.iata.org/en/pressroom/pr/2019-02-07-01/.

IATA. Air Passenger Market Analysis –December 2019. Below-trend but still solid air passenger growth in 2019. Technical report, 2019b. URL https://www.iata.org/en/iata-repository/publications/economic-reports/air-passenger-monthly---dec-2019/.

IATA. Air Passenger Market Analysis. (December):2019–2022, 2020a.

IATA. Air Passenger Market Analysis. (November), 2020b.

IATA. 2020 Worst Year in History for Air Travel Demand, 2021a. URL https://www.iata.org/en/pressroom/pr/2021-02-03-02/.

IATA. Passenger volumes did not improve in December. (January), 2021b.

ICAO. ICAO Environmental Report 2016, aviation and climate change. *Environmental report 2016*, pages 205–207, 2016a. ISSN 1098-6596.

ICAO. 2016–2030 Global Air Navigation Plan. *International Civil Aviation Organization Published in Montréal, Canada*, 2016b.

ICAO. The World of Air Transport in 2018, 2018a. URL https://www.icao.int/annual-report-2018/Pages/the-world-of-air-transport-in-2018.aspx.

ICAO. Solid passenger traffic growth and moderate air cargo demand in 2018, 2018b. URL https://www.icao.int/Newsroom/Pages/Solid-passenger-traffic-growth-and-moderate-air-cargo-demand-in-2018.aspx.

ICAO. The World of Air Transport in 2019, 2019. URL https://www.icao.int/annual-report-2019/Pages/the-world-of-air-transport-in-2019.aspx.

ICAO. FEB 2020 : Air Transport Monthly Monitor FEB 2020 : Air Transport Monthly Monitor. pages 2019–2020, 2020. URL https://www.icao.int/about-icao/Pages/default.aspx.

Intergovernmental Panel on Climate Change. *Climate Change 2014 Mitigation of Climate Change*. 2014. ISBN 9781107654815. doi: 10.1017/cbo9781107415416.

International Air Transport Association (IATA). Aircraft Technology Roadmap to 2050. pages 1–51, 2019. URL https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf.

International Air Transport Association (IATA). Air Passenger Market Analysis –September2020. 2020. ISSN 0363-5465.

IPCC. *CLIMATE CHANGE 2013 Climate Change 2013*. 2013. ISBN 9781107661820. URL https://www.researchgate.net/profile/Abha_Chhabra2/publication/271702872_Carbon_and_Other_Biogeochemical_Cycles/links/54cf9ce80cf24601c094a45e/Carbon-and-Other-Biogeochemical-Cycles.pdf.

IPCC. *Technical Summary. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 2021. ISBN 9789291691586.

Irene Kwan and Daniel Rutherford. U . S . Domestic Airline Fuel Efficiency Ranking , 2011 – 2012. (April):2011–2012, 2014. URL `http://theicct.org/sites/default/files/publications/ICCT{_}USairline-ranking{_}2013.pdf`.

Sverker C. Jagers, Åsa Löfgren, and Johannes Stripple. Attitudes to personal carbon allowances: Political trust, fairness and ideology. *Climate Policy*, 10(4):410–431, 2010. ISSN 17527457. doi: 10.3763/cpol.2009.0673.

Helen Jiang. Key Findings on Airplane Economic Life. (March):9, 2013.

Martin Kaltschmitt. *No Title*. 2018. ISBN 9783662530634.

Thomas E. Kent and Arthur G. Richards. Potential of Formation Flight for Commercial Aviation: Three Case Studies. *Journal of Aircraft*, pages 1–14, 2020. doi: 10.2514/1.c035954.

Alexander Koch. Climate Impact Mitigation Potential given by Flight Profile and Aircraft Optimization Climate Impact Mitigation Potential given by Flight Profile and Aircraft Optimization Vom Promotionsausschuss der. (November 2013), 2015. doi: 10.13140/RG.2.1.4896.9047.

André Koloschin and Nicolas Fezans. Flight physics of fuel-saving formation flight. *AIAA Scitech 2020 Forum*, 1 PartF(January):1–12, 2020. doi: 10.2514/6.2020-1002.

Irene Kwan and Daniel Rutherford. Transatlantic Airline Fuel Efficiency Ranking, 2014. *Icct*, (November), 2015.

Konstantinos G. Kyprianidis and Erik Dahlquist. On the trade-off between aviation nox and energy efficiency. *Applied Energy*, 185:1506–1516, 1 2017. ISSN 03062619. doi: 10.1016/j.apenergy.2015.12.055.

Eric F. Lambin and Patrick Meyfroidt. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, 108(9):3465–3472, 2011. ISSN 00278424. doi: 10.1073/pnas.1100480108.

Mareike Lange. The GHG balance of biofuels taking into account land use change. *Energy Policy*, 39(5):2373–2385, 2011. ISSN 03014215. doi: 10.1016/j.enpol.2011.01.057. URL `http://dx.doi.org/10.1016/j.enpol.2011.01.057`.

Stephan Langhans, Florian Linke, Peter Nolte, and Volker Gollnick. System analysis for an intermediate stop operations concept on long range routes. *Journal of Aircraft*, 50(1):29–37, 2013. ISSN 15333868. doi: 10.2514/1.C031446.

Jörgen Larsson, Anna Elofsson, Thomas Sterner, and Jonas Åkerman. International and national climate policies for aviation: a review. *Climate Policy*, 19(6):787–799, 2019. ISSN 17527457. doi: 10.1080/14693062.2018.1562871.

D. S. Lee, G. Pitari, V. Grewe, K. Gierens, J. E. Penner, A. Petzold, M. J. Prather, U. Schumann, A. Bais, T. Berntsen, D. Iachetti, L. L. Lim, and R. Sausen. Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment*, 44(37):4678–4734, 2010. ISSN 13522310. doi: 10.1016/j.atmosenv.2009.06.005. URL `http://dx.doi.org/10.1016/j.atmosenv.2009.06.005`.

D. S. Lee, D. W. Fahey, A. Skowron, M. R. Allen, U. Burkhardt, Q. Chen, S. J. Doherty, S. Freeman, P. M. Forster, J. Fuglestvedt, A. Gettelman, R. R. De León, L. L. Lim, M. T. Lund, R. J. Millar, B. Owen, J. E. Penner, G. Pitari, M. J. Prather, R. Sausen, and L. J. Wilcox. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244(July 2020), 2021. ISSN 18732844. doi: 10.1016/j.atmosenv.2020.117834.

David S. Lee, David W. Fahey, Piers M. Forster, Peter J. Newton, Ron C.N. Wit, Ling L. Lim, Bethan Owen, and Robert Sausen. Aviation and global climate change in the 21st century. *Atmospheric Environment*, 43(22-23):3520–3537, 2009. ISSN 13522310. doi: 10.1016/j.atmosenv.2009.04.024. URL `http://dx.doi.org/10.1016/j.atmosenv.2009.04.024`.

Florian Linke. The global fuel saving potential of intermediate stop operations considering meteorological and operational influences. *31st Congress of the International Council of the Aeronautical Sciences, ICAS 2018*, pages 1–10, 2018.

Florian Linke, Volker Grewe, and Volker Gollnick. The implications of Intermediate Stop Operations on aviation emissions and climate. *Meteorologische Zeitschrift*, 26(6):697–709, 2017. ISSN 16101227. doi: 10.1127/metz/2017/0763.

Tobias Marks, Katrin Dahlmann, Volker Grewe, Volker Gollnick, Florian Linke, Sigrun Matthes, Eike Stumpf, Majed Swaid, Simon Unterstrasser, Hiroshi Yamashita, and Clemens Zumegen. Climate impact mitigation potential of formation flight. *Aerospace*, 8(1):1–18, 2021. ISSN 22264310. doi: 10.3390/aerospace8010014.

Sigrun Matthes, Ling Lim, Ulrike Burkhardt, Katrin Dahlmann, Simone Dietmüller, Volker Grewe, Amund S. Haslerud, Johannes Hendricks, Bethan Owen, Giovanni Pitari, Mattia Righi, and Agnieszka Skowron. Mitigation of non-CO2 aviation's climate impact by changing cruise altitudes. *Aerospace*, 8(2):1–20, 2021. ISSN 22264310. doi: 10.3390/aerospace8020036.

Karen Mayor and Richard S.J. Tol. The impact of the UK aviation tax on carbon dioxide emissions and visitor numbers. *Transport Policy*, 14(6):507–513, 2007. ISSN 0967070X. doi: 10.1016/j.tranpol.2007.07.002.

Sofia Pinheiro Melo, Alexander Barke, Felipe Cerdas, Christian Thies, Mark Mennenga, Thomas S. Spengler, and Christoph Herrmann. Sustainability assessment and engineering of emerging aircraft technologies-challenges, methods and tools. *Sustainability (Switzerland)*, 12(14), 2020. ISSN 20711050. doi: 10.3390/su12145663.

Sophie Michot, Nicu Stancioi, Colin Mcmullan, Serge Peeters, and Sandrine Carlier. ii aero2k flight movement inventory project report.

Raj Nangia, Nelson Brown, Donald Erbschloe, and Dennis Carter. Formation flying (Air-wake-surfing) for efficient operations. *AIAA Scitech 2020 Forum*, 1 PartF(January), 2020. doi: 10.2514/6.2020-1001.

Craig L. Nickol and William J. Haller. Assessment of the performance potential of advanced subsonic transport concepts for NASA's environmentally responsible aviation project. *54th AIAA Aerospace Sciences Meeting*, 0(January 2016):1–21, 2016. doi: 10.2514/6.2016-1030.

Malte Niklaß, Benjamin Lührs, Volker Grewe, and Volker Gollnick. Implementation of eco-efficient procedures to mitigate the climate impact of non-CO 2 effects. *31st Congress of the International Council of the Aeronautical Sciences, ICAS 2018*, (September), 2018.

Adrian O'Connell, Marina Kousoulidou, Laura Lonza, and Werner Weindorf. Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. *Renewable and Sustainable Energy Reviews*, 101(November 2017):504–515, 2019. ISSN 18790690. doi: 10.1016/j.rser.2018.11.033. URL `https://doi.org/10.1016/j.rser.2018.11.033`.

Yael Parag and Tina Fawcett. Personal carbon trading: a review of research evidence and real-world experience of a radical idea. *Energy and Emission Control Technologies*, (October):23, 2014. ISSN 2253-2218. doi: 10.2147/eect.s56173.

Matthew Paterson and Johannes Stripple. My space: Governing individuals' carbon emissions. *Environment and Planning D: Society and Space*, 28(2):341–362, 2010. ISSN 02637758. doi: 10.1068/d4109.

Jan Pechstein, Nils Bullerdiek, and Martin Kaltschmitt. A "book and Claim"-Approach to account for sustainable aviation fuels in the EU-ETS – Development of a basic concept. *Energy Policy*, 136(August 2019): 111014, 2020. ISSN 03014215. doi: 10.1016/j.enpol.2019.111014. URL `https://doi.org/10.1016/j.enpol.2019.111014`.

Paul Peeters. *Tourism's impact on climate change and its mitigation challenges: How can tourism become 'climatically sustainable'?* 2017. ISBN 9789055841745.

Paul Peeters, James Higham, Diana Kutzner, Scott Cohen, and Stefan Gössling. Are technology myths stalling aviation climate policy? *Transportation Research Part D: Transport and Environment*, 44:30–42, 2016. ISSN 13619209. doi: 10.1016/j.trd.2016.02.004. URL `http://dx.doi.org/10.1016/j.trd.2016.02.004`.

T. Planès, S. Delbecq, V. Pommier-Budinger, and E. Bénard. Simulation and evaluation of sustainable climate trajectories for aviation. *Journal of Environmental Management*, 295, 2021. ISSN 10958630. doi: 10.1016/j.jenvman.2021.113079.

D. I.A. Poll. On the effect of stage length on the efficiency of air transport. *Aeronautical Journal*, 115(1167): 273–283, 2011. ISSN 00019240. doi: 10.1017/S0001924000005741.

Plenty Road. Benefits of the Blended Wing Body Aircraft Compared to Current Airliners. 2015.

Rolls-Royce. The advance turbofan. https://www.rolls-royce.com/media/our-stories/innovation/2016/advance-and-ultrafan.aspx#solution, 2018. [Online; accessed 15 December 2020].

Rolls-Royce. Rolls-royce starts manufacture of world's largest fan blades – made of composite material – for next-generation ultrafan® demonstrator. https://www.rolls-royce.com/media/press-releases/2020/11-02-2020-intelligentengine-rr-starts-manufacture-of-world-largest-fan-blades.aspx, 2020. [Online; accessed 15 December 2020].

Dan Rutherford. Standards to promote airline fuel efficiency. (May), 2020.

Safran. Safran aircraft engines - innovation | research innovation. https://www.safran-aircraft-engines.com/innovation-0, 2017a. [Online; accessed 15 December 2020].

Safran. Fuel cells: green energy on board. https://www.safran-group.com/media/fuel-cells-green-energy-board-20170405, 2017b. [Online; accessed 15 December 2020].

Robert Sausen and Ulrich Schumann. Estimates of the climate response to aircraft CO2 and NO(x) emissions scenarios. *Climatic Change*, 44(1-2):27–58, 2000. ISSN 01650009. doi: 10.1023/a:1005579306109.

Robert Sausen, Ivar Isaksen, Volker Grewe, Didier Hauglustaine, David S. Lee, Gunnar Myhre, Marcus O. Köhler, Giovanni Pitari, Ulrich Schumann, Frode Stordal, and Christos Zerefos. Aviation radiative forcing in 2000: An update on IPCC (1999). *Meteorologische Zeitschrift*, 14(4):555–561, 2005. ISSN 09412948. doi: 10.1127/0941-2948/2005/0049.

Janina Scheelhaase, Sven Maertens, Wolfgang Grimme, and Martin Jung. EU ETS versus CORSIA – A critical assessment of two approaches to limit air transport's CO2 emissions by market-based measures. *Journal of Air Transport Management*, 67(November 2017):55–62, 2018. ISSN 09696997. doi: 10.1016/j.jairtraman.2017.11.007. URL https://doi.org/10.1016/j.jairtraman.2017.11.007.

Janina D. Scheelhaase. How to regulate aviation's full climate impact as intended by the EU council from 2020 onwards. *Journal of Air Transport Management*, 75(August 2018):68–74, 2019. ISSN 09696997. doi: 10.1016/j.jairtraman.2018.11.007. URL https://doi.org/10.1016/j.jairtraman.2018.11.007.

David S. Stevenson, Ruth M. Doherty, Michael G. Sanderson, William J. Collins, Colin E. Johnson, and Richard G. Derwent. Radiative forcing from aircraft NOx emissions: Mechanisms and seasonal dependence. *Journal of Geophysical Research D: Atmospheres*, 109(17), 2004. ISSN 01480227. doi: 10.1029/2004JD004759.

Susanne Stoll-Kleemann. From Denial to Moral Disengagement : How integrating fundamental insights from psychology can help us better understand ongoing inaction in the light of an exacerbating climate cris ... (June), 2020.

Majed Swaid, Tobias Marks, Benjamin Lührs, and Volker Gollnick. Quantification of formation flight benefits under consideration of uncertainties on fuel planning. *31st Congress of the International Council of the Aeronautical Sciences, ICAS 2018*, 2018.

Laurent Tabernier, Esther Calvo Fernández, Andreas Tautz, Robin Deransy, and Peter Martin. Fuel tankering: Economic benefits and environmental impact for flights up to 1500 nm (full tankering) and 2500 nm (partial tankering). *Aerospace*, 8(2):1–16, 2021. ISSN 22264310. doi: 10.3390/aerospace8020037.

ThalesGroup. The more electric aircraft pushes back. https://onboard.thalesgroup.com/electric-aircraft-pushes-back/, 2017. [Online; accessed 15 December 2020].

Transport & Environment. Making aviation fuel mandates sustainable. pages 1–13, 2020.

United Nations. KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. *Prispevki za Novejso Zgodovino*, 58(2), 1998. ISSN 24637807.

United Nations. Paris Agreement. 2015. ISSN 05134870.

United Nations. Department of Economic and Social Affairs, Population Division: World Population Prospects 2019, Volume II: Demographic Profiles. II:1–5, 2019. URL `https://population.un.org/wpp/Graphs/1{_}DemographicProfiles/World.pdf`.

United Nations. CORSIA SUPPORTING DOCUMENT CORSIA Eligible Fuels – Life Cycle Assessment Methodology. (March), 2021.

S. Unterstrasser and A. Stephan. Far field wake vortex evolution of two aircraft formation flight and implications on young contrails. *Aeronautical Journal*, 124(1275):667–702, 2020. ISSN 00019240. doi: 10.1017/aer.2020.3.

Simon Unterstrasser. The contrail mitigation potential of aircraft formation flight derived from high-resolution simulations. *Aerospace*, 7(12):1–22, 2020. ISSN 22264310. doi: 10.3390/aerospace7120170.

Detlef P. van Vuuren, Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C. Hurtt, Tom Kram, Volker Krey, Jean Francois Lamarque, Toshihiko Masui, Malte Meinshausen, Nebojsa Nakicenovic, Steven J. Smith, and Steven K. Rose. The representative concentration pathways: An overview. *Climatic Change*, 109(1):5–31, 2011. ISSN 01650009. doi: 10.1007/s10584-011-0148-z.

Bojun Wang, Aidan O'Sullivan, Lynnette Dray, and Andreas W. Schäfer. Modeling Airline Cost Pass-Through within Regional Aviation Markets. *Transportation Research Record*, 2672(23):146–157, 2018. ISSN 21694052. doi: 10.1177/0361198118792337.

Birka Wicke, Pita Verweij, Hans Van Meijl, Detlef P. Van Vuuren, and Andre P.C. Faaij. Indirect land use change: Review of existing models and strategies for mitigation. *Biofuels*, 3(1):87–100, 2012. ISSN 17597269. doi: 10.4155/bfs.11.154.

H. W. Wong and R. C. Miake-Lye. Parametric studies of contrail ice particle formation in jet regime using microphysical parcel modeling. *Atmospheric Chemistry and Physics*, 10(7):3261–3272, 2010. ISSN 16807324. doi: 10.5194/acp-10-3261-2010.

George Wright, Ron Bradfield, and George Cairns. Does the intuitive logics method - and its recent enhancements - produce "effective" scenarios? *Technological Forecasting and Social Change*, 80(4):631–642, 2013. ISSN 00401625. doi: 10.1016/j.techfore.2012.09.003.

Fei Xing, Arvind Kumar, Yue Huang, Shining Chan, Can Ruan, Sai Gu, and Xiaolei Fan. Flameless combustion with liquid fuel: A review focusing on fundamentals and gas turbine application. *Applied Energy*, 193:28–51, 2017. ISSN 03062619. doi: 10.1016/j.apenergy.2017.02.010. URL `http://dx.doi.org/10.1016/j.apenergy.2017.02.010`.

Xinyi Sola Zheng and and Daniel Rutherford. U.S.–LATIN AMERICA AIRLINE FUEL EFFICIENCY RANKING, 2017–2018. (Nevember), 2019. URL `http://theicct.org/sites/default/files/publications/ICCT{_}USairline-ranking{_}2013.pdf`.

Xinyi Sola Zheng, Brandon Graver, and Dan Rutherford. U . S . Domestic Airline Fuel Efficiency Ranking , 2017 – 2018. (September):1–14, 2019.

A

Appendix A: Literature Review

Representation of Aircraft Type Fuel Performance per Revenue Passenger Kilometer

Condensed representation of the relevant aircraft types and their fuel efficiency, outlining the difficulty of creating a uniform framework of efficiency due to large discrepancies between airliner fleets.

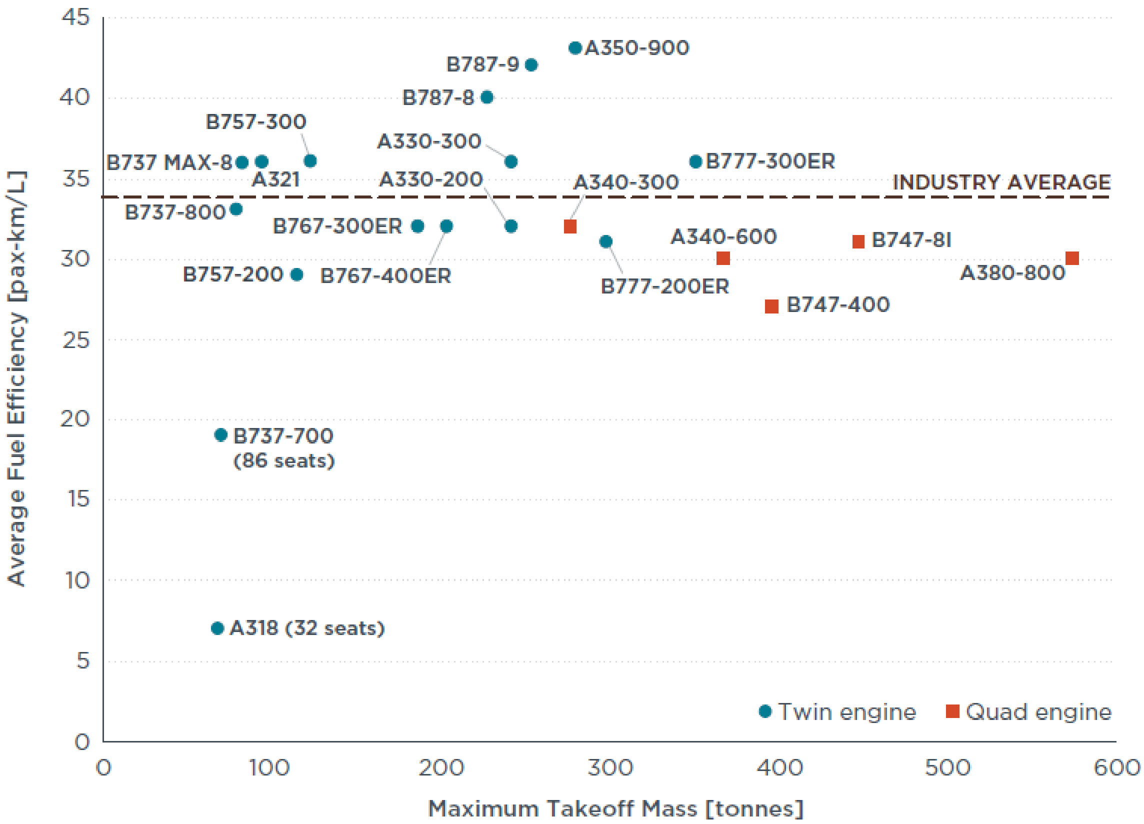

Figure A.1: Fuel efficiency per aircraft from ITCC studies in units of RPK/L on the vertical axis and maximum take off weight on the horizontal axis for both quad and twin engine aircraft. Results present a performance of a specific aircraft type with respect to an industry average, where it can be seen that all quad engine aircraft perform below the industry average and newer twin engine aircraft such as the Boeing 777 and 787 perform above industry average Graver et al. [2018]

General Breakdown of Formation Flights Test

This represents the overview of tests done regarding formation flight, showing that numerous combinations have been tried. Often these combinations contain fighter-jets and not commercial airliners, which still requires the necessary testing.

Project	Year	Results	Aircraft Type	Conditions
***NASA AFLP*[1]**	1998-2001	up to 18% fuel burn reduction flying nose-to-tail	2 x F/A-18	Type: Fighter-Jet Mach: 0.56 Alt.: 7620 m
USAFTPS*[2] *TALON GAGGLE	2001	Savings ranging from 5% fuel burn increase to 18% savings for flights with 2 T-38s. Flights with 3 T-38s were inconclusive. High pilot workload with 3 crafts	2&3 x T-38	Type: Fighter-Jet Mach: 0.47 Alt.: 3048 m
NASA's SURF	2003	29% fuel savings due to wake-energy. Sufficient bandwidth for control. Milder than expected vortex effects	F/A-18 and DC-8	Type: Fighter-Jet + Large Transporter Mach: - Alt.: 7620 m
USAF F-16 Dollar Draft	2004	13.1% +/- 7% fuel savings. Maintaining stable position in vortex was described as a high workload.	2 x F-16	Type: Fighter-Jet Speed: 210/270/ 300 knots CAS Alt: -
NASA/USAF CAPFIRE	2010	Mostly manually flown at 305 m and 914 m separation. Maximum reduction in fuel burn was around 6.8-7.8% which varied per wing. Maximum avg. thrust reduction was 9.2%	2 x C-17	Type: Military-Transport-Aircraft Mach: 0.46 Alt.: 7620 m
***DARPA/USAF/ Boeing $AVE*[3]**	2012-2013	At 1220 or 2440 m aft the leading aircraft. Further distance makes it harder to harvest the core energy. 10-15% fuel savings were obtained. $AVE also led to better automated software.	2 x C-17	Type: Military-Transport-Aircraft Mach: 0.73-0.75 Alt.: 9144 m
Boeing C-17/ 777 Programs (Part of Eco-Demonstrator Project)	2018	The collaboration with $AVE was cancelled in July 2018. Boeing flew its own two 777F models working hard with its TCAS[4] suppliers to assure safe flight. Good aircraft data should provide sufficient for formation flight. The ecoDemonstrator showed 4-6% fuel burn savings for a more civil-aircraft like application.	Boeing 777F + C-17	Type: Freigther Mach: 0.46 Alt.: 7620 m
NASA C-20A/ G-III*[5] *Cooperative Trajectory	2016-2017	Tests performed at 1220 meters apart. Maximum sustained peak measured fuel flow reduction was 8%. Increased cabin noise of 1-2 dB was observed and vibrations were no worse than light turbulence.	G-III + C-20A	Type: Business-Jet Mach: 0.7 Alt.: 9144 m
Airbus AFFP	2020-2021	Not performed yet. Estimated fuel savings between 5-10% [Airbus, 2020].	A350-1000 + A350-900	Type: Civil-Jet Mach: 0.73-0.76 Alt.: 9144 m

Table A.1: Performed and future large research schemes for formation flight indicating the project, year of testing, general results from the test, aircraft types involved in the formation and the conditions of the flights [Nangia et al., 2020]. 1: AFLP: Autonomous Formation Flight Project. 2: USAFTPS: US Air Force Test Pilot School. 3: $AVE: Surfing Aircraft Vortices for Energy. 4: TCAS: Traffic Collision Avoidance System. 5: G-III: Gulfstream-III.

Aircraft's Retrofits and Potential Savings

This section shows a breakdown taken from the IATA roadmap to 2050 report and re-made in latex, regarding the technology retrofitting possibilities along with the savings each retrofit could yield in Table A.2. Table A.3 and Table A.4 provide an accessible breakdown for relevant strut-braced-wing concepts and blended wing body concepts respectively.

Group	Concept	Concept Research Institution or Group	TLR	Expected Fuel Efficiency Increase
New Engine Architecture	Advance Turbofan [Rolls-Royce, 2018]	Rolls-Royce	8	20% (Compared to Trent 700)
	Ultrafan [Rolls-Royce, 2018]	Rolls-Royce	7	25% (Compared to Trent 700)
	GE9X [General Electric, 2018]	General Electric	8	10% (Compared to GE90-115B)
	Counter Rotating Fan [Safran, 2017a]	Safran	3	15 - 20%
	Ultra-High Bypass Ratio Engine [Safran, 2017a]	Safran	5	20 to 25%
Advanced Engine Concepts	Zero Hub Fan [Rolls-Royce, 2020]	Rolls-Royce	7	2 to 4%
Engine Cycle	Adaptive/Active Flow Control	Research Topic	2	10 to 20%
	Ubiquitous Composites (Gen 2)	Research Topic	3	10 to 15%
Aerodynamics	Natural Laminar Flow (NLF) [Airbus, 2017]	BLADE	8	5 to 10%
	Hybrid Laminar Flow Control (HLFC) [ICAO, 2016a]	NASA - ERA Scheme	7	10 to 15%
	Variable Camber with New Control Surface [Center, 2014]	NASA - Ames Research Center	5	5 to 10%
	Spiroid Wingtip	APB WINGLETS COMPANY LLC (Expired Patent)	7	2 to 6%
Systems	Electric taxiing system with Auto Transformer Rectifier Unit [ThalesGroup, 2017]	ThalesGroup	8	3%
	Fuel Cells [Safran, 2017b]	Safran	8	1 to 5%

Table A.2: Summary of aircraft retrofits per defined group of retrofitting, outlining the concept, research institution working on it, the technology readiness level and the expected savings. Many retrofits are nearly ready for roll-out but retrofits such as active flow control are only in the academic stages of research. Source: IATA Aircraft Technology Roadmap to 2050

Concept	Concept	EIS	Projected Fuel Savings	Market Segment
SUGAR Free	Current Tech. - Similar to Boeing 737	N/A	Baseline	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
Refined SUGAR (N+3 Tech)	Conventional Cofig + N+3 Tech, + NEXTGEN ATC + GE gFan	After 2035	44% to 54% fuel burn Reduction using gFan and large wing span	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
SUGAR High (N+3 Tech)	High span SBW + N+3 Technology + GE gFan+ and open fan	After 2035	39% up to 58% reduced fuel burn if wing weight reduction and aerodynamic improvements	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
SUGAR Volt	SUGAR HIGH Config + battery gas turbine hybrid propulsion (GE hFan)	After 2035	63% up to 90% fuel burn reduction	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
SUGAR Ray (BWB)	Hybrid Wing Body + SUGAR High Tech. + (Reduced Noise Focus)	After 2035	43% reduced fuel burn	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
N+4 (2040-2045) SUGAR High	High Wing Span High Aspect Ratio High Lift over Drag + GE 2045 Engines (gFan++)	2040-2045	53.3% reduced fuel burn	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
SUGAR Freeze	N+4 Technology+ Liquified Nitrogen Gas+ GE 2045 Engines (gFan++)	After 2045	57.2% reduced fuel burn	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
SUGAR Freeze UDF	SUGAR Freeze + Unducted Fans	After 2045	62.1% reduced fuel burn	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
SUGAR Freeze HYBRID BLI	SUGAR Freeze + Hybrid BLI	After 2045	60.8% reduced fuel burn	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154
SUGAR Freeze HYBRID UDF	SUGAR Freeze + Hybrid Unducted Fans	After 2045	64.1% reduced fuel burn	Range: Medium Max: 3500 NM Designed: 900 NM Pax: +/- 154

Table A.3: Boeing SUGAR initiative breakdown of all relevant concepts including the name, general lay-out, entry into service (EIS) year, expected fuel savings and the market it will be used for. A variety of concepts exist with the fuel savings percentages relating to the SUGAR Free, which is a strut-braced-wing concept with similar technology to the Boeing 737[Bradley and Droney, 2012, Bradley et al., 2015, International Air Transport Association (IATA), 2019].

Concept	Concept	EIS	Projected Fuel Savings	Market Segment
DZYNE BizJet	BWB + Semi-Buried Nacelles + Pivot-Piston Landing Gear	After 2025	39% fuel burn (compared to G650ER)	Range: Diverse Design: 8200 NM Pax: 18
DZYNE BWB-112	BWB + Semi-Buried Nacelles + Pivot-Piston Landing Gear + T-Plug	After Bizjet	43% fuel burn (compared to Bombardier CS-100)	Range: Long-Haul Design: 3200 NM Pax: 112
DZYNE BWB-165	BWB + Semi-Buried Nacelles + Pivot-Piston Landing Gear + T-Plug	After Bizjet	39% fuel burn (compared to 737 MAX 8)	Range: Long-Haul Design: 3500 NM Pax: 165
DZYNE BWB-210	BWB + Semi-Buried Nacelles + Pivot-Piston Landing Gear + T-Plug	After Bizjet	40% fuel burn (compared to 737 MAX 9)	Range: Long-Haul Design: 3800 NM Pax: 210
Flying-V	V-Shaped BWB + 2019 Most Advanced Gas Turbines + A350 Wingspan + A350 Capacity	N/A	20% fuel burn (compared to best-in-class 2019 A350)	Range: A350 Similar Design: A350 Similar Pax: 314
D8 (NASA, Aurora, P&W and MIT)	Composite Double Bubble Concept + BLI Engines OR Wing Mounted Engines	Different Models for 2025-2030 and 2035+	56% with 2035 Tech. 29% fuel burn with wing mounted engines for 2025 (Compared to Boeing 737-800/ A320)	Range: Short-Medium Design: 3000 NM Pax: 314

Table A.4: NASA X-Plane BWB and Double Bubble concepts with relevant information regarding EIS and projected fuel savings