Actions to Reduce the Climate Change Impact of the Aviation Sector

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Abstract

A sustainable aviation sector will require significant and strategic investment to mitigate its escalating impact on climate change. From a thorough review of international best practices, initiatives, and research programs, this report presents an organized set of actionable strategies to reduce aviation's impact on climate change. Recommended actions are divided into governmental, operational, and technological mitigation strategies. First, the impact of aviation on climate change is presented in the larger context of sustainable aviation. The various aviation emissions and their climate change effects are reviewed, highlighting their trade-offs and the current levels of scientific understanding, along with the need for a better understanding in specific areas. The business-as-usual projections demonstrate a continuous increase in the climate change impact of aviation as a result of the projected growth of the industry exceeding efficiency gains. Next, potential government actions are reviewed, including new regulations, incentives, and assistance. The necessary certification standards and market based measures will require significant global collaboration, with oversight from the International Civil Aviation Organization, in order to forge an international path forward. When combined with financial support, these actions will drive research and development toward the new technologies required to address climate change in an economically-driven industry. Subsequently, a number of operational strategies are reviewed with the goal of improving the gate to gate efficiency of flight operations. Strategies are considered in the areas of air traffic management, ramp and taxi operations, continuous decent, enroute cruise, and flight mission design. Finally, the advanced technologies representing the most promising investment opportunities are categorized and reviewed. These technologies have the greatest potential for climate change mitigation and aim to ensure the long-term sustainability of the industry. The advanced technologies are divided into six categories, including: (i) aerodynamics, (ii) advanced structures and materials, (iii) efficient and clean engine technologies, (iv) unconventional aircraft configurations, (v) electric aircraft technologies, and (vi) biofuels. Ultimately, the Canadian aviation sector (including government, industry, and academia) must take urgent and significant action to address its impact on climate change, while responsibly meeting the growing demands for air transport and, in turn, improving the quality of life of all Canadians for the foreseeable future.

Executive Summary

This report is submitted to the Secretariat of the Canadian Transportation Act Review. Its overarching objective is to inform the Secretariat of potential recommendations and actions to mitigate the escalating impact of aviation on climate change. The specific objectives of the research project are to (i) identify a business-as-usual scenario to project aviation emissions 20-30 years in the future, (ii) review and catalogue Canadian and international studies and initiatives that exist to reduce aviation's climate change impact, and (iii) review and recommend the best practices and investment opportunities to reduce the impact of Canada's aviation sector on climate change.

In the first section of the report, the current and forecasted (business-as-usual) climate change scenarios are reviewed in the context of sustainable aviation and current scientific understanding. The remaining sections of this report present an organized set of actions (best practices and recommended investment opportunities) for the Canadian government, industry, and academia. These actions have been divided into three categories: 1) government regulations, incentives, and assistance, 2) operational strategies, and 3) advanced technologies. Various Canadian and international initiatives in each category are described and reviewed throughout the report, but omitted from this executive summary for brevity. The urgent challenge facing the Canadian aviation sector is to invest, participate, and guide the research, development, and deployment of these solutions as soon as possible.

The Growth of Aviation and its Impact on Climate Change

In an attempt to ensure a sustainable aviation sector, the industry and its regulators must carefully balance and address their economic, environmental, and social concerns. The tremendous growth of the industry (which is forecast to continue in the coming decades) makes it one of the fastest growing contributors to greenhouse gas (GHG) emissions across all sectors. Currently, the aviation industry contributes between 2-3% of the world's anthropogenic GHG emissions, and upwards of 5% of anthropogenic climate change. Other non-GHG emissions from aircraft include NO_X, soot, aerosols, and sulphates, all of which interact with the upper troposphere and lower stratosphere to contribute further to the net radiative forcing from aviation. The formation of contrails and contrail-cirrus cloud may also be a significant contributor to aviation's impact on climate change. In the business-as-usual scenarios, it is clear that we can expect a significant increase in the climate change impact due to aviation emissions as a result of the projected growth of the industry exceeding efficiency gains.

Important interactions and trade-offs exist between the different aircraft emissions, as well as other environmental concerns, such as noise pollution. A better understanding of these trade-offs will require that we improve our scientific understanding of the climate change effects of all aircraft emissions, particularly non-CO_2 emissions. Focusing solely on CO_2 may lead to increases in NO_X, contrails, and contrail-cirrus formation, which may result in a net increase in the radiative forcing from aviation. Without an improved scientific understanding, it can be difficult to select, promote, prioritize, and actualize new policies, operational strategies and technology developments.

The Role of Government: Regulations, Incentives, and Assistance

Regulation through Certification Standards

Perhaps the most aggressive regulatory approach to limiting the environmental and climate change impact of aviation – without limiting the growth of the industry – is to enforce more stringent certification standards. Such standards create a direct link between quantifiable noise and emission reductions and the technology goals of manufacturers, in turn, driving advances in the state-of-the-art of sustainable and environmentally-responsible technologies.

Emissions from international aviation are specifically excluded from the climate change targets set under the Kyoto Protocol, which instead defers the responsibility to the International Civil Aviation Organization (ICAO). From a Canadian perspective, current climate change initiatives by Transport Canada will need to follow and actively participate in ICAO's developments.

ICAO's Committee on Aviation and Environmental Protection (CAEP) has focused primarily on ensuring sufficiently low levels of perceived noise and NO_X emissions. As an international path forward, CAEP approved (in 2013) the requirement for an official ICAO "Aircraft CO_2 Emissions Standard", and also agreed to deliver the full standard at the CAEP 10 meeting in 2016. As an environmentally-responsible member state, it is recommended that the Canadian government ratify this new aircraft emissions standard.

Incentivization through Market-Based Measures

At the 38th Session of the ICAO Assembly in 2013, more than 170 member states and international organizations pledged to develop a global Market-Based Measure (MBM) applicable to the aviation sector. A global MBM scheme is to be developed such that it puts a price on aviation emissions (focusing primarily on CO_2) with the goal of incentivizing significant reductions in climate change impact.

Two MBMs for putting a price on carbon are the cap-and-trade (or Emissions Trading System, ETS), and carbon tax. Note that some countries, such as the US and China, feel that such MBM schemes are in direct conflict with the ICAO Chicago Convention. For example, there was significant legal push back when the EU made its initial attempts to include international aviation in its ETS.

Canadian regulators and politicians must closely follow and actively participate in ICAO's development of such a strategy. ICAO's current vision is to implement an MBM by 2020. It is recommended that Canada take action to ratify the proposed MBM scheme, as it would be considered a significant step forward towards reducing the Canadian aviation sector's impact on climate change.

In both a carbon tax system and cap-and-trade system there is potential for significant revenue that would be generated by the paying polluters. It is recommended to reinvest such revenue in R&D toward technologies aimed at reducing aviation's climate change impact. Several promising technological avenues are discussed in this review. Researchers have also proposed and modeled an alternative approach that uses such revenue generation to subsidize airline fleet renewal.

It is important to emphasize that putting a price on emissions using MBMs alone will not sufficiently drive the necessary action. The additional cost of doing business does not guarantee that the aviation sector will take action to reduce emissions, but rather, that they will take action to address the added expense by whatever means they see fit, including passing the cost directly to the customer. Thus, government regulations, which can ensure specific reductions, should be combined with MBM measures. Furthermore, these combined strategies may place too large a burden on the direct users of aviation, while societal benefits are realized by a larger segment of the population. This may justify additional government assistance to provide funding for the development of green aviation technologies. Supporting R&D toward such technologies is in the national interest.

Assistance through Government Funding Strategies

Research conducted for the Canadian "Aerospace Review" in 2012 states that the aerospace industry is Canada's second-most research-intensive industry (based on R&D as a percentage of industry GDP). The research necessary to maintain a competitive aerospace industry requires financial investments totaling upwards of two billion dollars per year. This is made possible, in part, by the direct funding of government initiatives.

Indeed, the Canadian government and the Canadian aviation industry must invest heavily in the development of operational and technological mitigation strategies. It is recommended that the provincial and federal governments of Canada take the following action to fund and assist the aviation sector in reducing its impact on climate change:

1. Using existing funding mechanisms, shift the existing resources toward research programs that aim to reduce aviation's climate change impact, in turn prioritizing the industry's climate change concerns.
2. Find a means by which to generate additional revenue (potentially from within the industry itself) by putting a price on carbon through an MBM system. Redirect that revenue to invest in the development of green aviation initiatives and research programs.
3. The government of Canada should collaborate with ICAO in establishing a globally competitive research program aimed at reducing the climate change impact of aviation, with benefits that will be shared the world over. The goal of a globally competitive and collaborative research program would be to identify and accelerate the development of the most promising operations and technologies in order to address the aviation sector's climate change concerns more rapidly.

Operational and Technological Mitigation Strategies

In order to reduce the climate change impact of the aviation sector, we must ultimately seek improvements in flight efficiency and reductions in emissions per passenger-km through operational strategies and technological innovation. In this report we identify and briefly review the various best practices and investment opportunities from an international scan of ongoing initiatives and research programs.

Through the various operational and technological mitigation strategies, by the years 2030 and 2050, there is potential to reduce fleet carbon emissions from aviation by upwards of 29% and 60%, respectively. To achieve this, the Canadian government, industry, and academia must invest heavily and collaborate in domestic and international initiatives.

Note that all operational and technological strategies reviewed in the following sections are subject to rigorous testing and certification to ensure that they do not jeopardize flight safety.

Operational Strategies

Operational strategies offer great potential for significantly reducing the climate change impact of the aviation sector, up to 14% by 2050. Many of the operational strategies discussed have the advantage that they can be implemented with current technology. In some cases, the two lines of development (operations and technology) are independent; in others, they are inherently entwined.

The following is a list of the most promising operational strategies, beginning with those aimed at more efficient air traffic management, followed by those applicable to various phases of a flight, including: (i) ground operations, (ii) descent, and (iii) enroute cruise:

- **Air traffic management:**
  - Performance based navigation
  - Automatic dependent surveillance-broadcast
- **Ground operations:**
  - Strategies for ramp operations
  - Strategies for taxi operations
- **Descent operations:**
  - Tailored arrivals for continuous descent
- **Flight missions and enroute cruise:**
  - Reduced vertical separation minimum
  - Altitude and speed considerations
  - Contrail formation avoidance
  - Large aircraft for short range
  - Multi-stage long-distance travel
  - Air-to-air refuelling
  - Close formation flying

All of the above operational strategies require significant investment in research and development. Innovative solutions will be required to bring these strategies to fruition without compromising flight safety.

Advanced Technologies

Commercial aviation is an industry driven by technological innovation. Modern aircraft and engine technologies have matured significantly over the past decades. The conventional tube-and-wing technologies have become highly optimized and further step-changes will require the development and introduction of new and unconventional technologies. In order to reduce climate change impact, designers must seek out technologies that (i) reduce drag, (ii) reduce weight, (iii) reduce engine emissions, and (iv) reduce reliance on fossil fuels.

Given the necessary government incentivization and assistance, significant research efforts will lead to the revolutionary technological innovations necessary to reduce aviation emissions and its impact on climate change. By investing in the development of these technologies the Canadian government and the Canadian aviation industry can take a leadership role in guiding, assisting, and participating in the competitive (but often collaborative) global research effort toward green aviation. The following is a categorized list of some of the most promising investment and research opportunities in advanced technologies:

- **Aerodynamic technologies for reduced drag:**
  - Non-planar geometries for induced drag reduction
  - Natural laminar flow control
  - Discrete roughness elements for laminar flow control
  - Active flow control techniques
- **Advanced structures and materials for reduced weight:**
  - Advanced, hybrid and super-alloys
  - Advanced composites and the PRSEUS concept
  - Additive manufacturing
  - Active load alleviation
  - Morphing structures
- **Efficient and clean engine technologies for reduced emissions:**
  - High pressure ratio and turbine entry temperature engines
  - Ultra high-bypass ratio turbofans
  - Geared turbofans
  - Open rotor concept
  - Advanced combustor design for NO_X reduction
  - Distributed propulsion
- **Unconventional aircraft configurations – a multidisciplinary approach:**

  The need to improve fuel efficiency, while reducing noise and emissions, has led to the multidisciplinary design of several unconventional aircraft configurations, representing an important long-term investment opportunity. The following is a list of some of these configurations:

  - Blended wing-body
  - D8 or double bubble
  - Box-wing configuration
  - Strut-braced wing

- **Electric aircraft technologies for reduced emissions and reliance on fossil fuels:**
  - More electric aircraft
  - Electric auxiliary power units
  - Hybrid-electric propulsion
- **Biofuels for reduced emissions and reliance on fossil fuels:**

  Biofuels present a significant opportunity to reduce not only aviation's climate change impact, but also the industry's exclusive dependence on fossil fuels. Biofuels are a renewable source of energy derived from living (or very recently living) matter, such as crops, plants, animals, trees, and algae. The Sustainable Aviation Alliance in the UK estimates that the use of biofuels in aviation has the potential to reduce CO_2 emissions by upwards of 24% by the year 2050.

  Several challenges exist in the certification (combustion properties) and large-scale production (feedstock growth and processing) of aviation biofuels. Drop-in aviation biofuels must have chemical and combustion properties that closely mimic that of conventional kerosenes and are thus highly regulated.

  The net effect lifecycle metrics of biofuels are heavily dependent on the feedstocks employed. Significant investment is required in order to develop the necessary techniques to source and grow second and third generation feedstocks at large scales in locations worldwide, while providing more stable and affordable price points. On a longer term, likely beyond 2025, the alcohol to jet process based on bioethanol from algae may be a possibility for third generation aviation biofuels.

  In the near term, the ability of biofuels to replace conventional kerosenes is limited. As such, biofuels should not be regarded as a silver bullet solution to reducing aviation emissions. However, with significant effort and investment over the coming decades, it is expected that biofuels will play an important role in reducing aviation's climate change impact. Ultimately, the aviation industry must continue to investigate biofuels as an alternative energy source, while simultaneously developing strategies and technologies that reduce the overall energy requirements of air transportation.

> Significant challenges remain in the development, certification and deployment of the advanced technologies discussed herein. The Canadian aviation sector must take action to invest in such technologies with the vision of responsibly addressing the climate change concerns of the industry, while meeting the growing demands for air travel, in turn improving the quality of life of all Canadians for the foreseeable future.

Contents

List of Symbols and Abbreviations

List of Symbols:

CH_4	Methane
CO_2	Carbon dioxide
NO_X	Nitrogen oxides
NO	Nitric oxide
NO_2	Nitrogen dioxide
O_3	Ozone
SO_X	Sulfur oxides
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide

List of Abbreviations:

ABSU	Aviation System Block Upgrades
ADS-B	Automatic Dependent Surveillance-Broadcast
ACARE	Advisory Council for Aeronautics Research in Europe
ANS	Air Navigation System
APU	Auxiliary Power Unit
ASTM	American Society of Testing and Materials
ATAG	Air Transportation Action Group
ATC	Air Traffic Control
ATJ	Alcohol To Jet
ATJ-A	Alcohol To Jet with Aromatics
ATM	Air Traffic Management
BC	British Columbia
BWB	Blended Wing-Body
CAEP	Committee on Aviation and Environmental Protection
CARAC	Canadian Aviation Regulation Advisory Council
CESTOL	Cruise Efficient Short Take-Off and Landing
CPDLC	Controller-Pilot Data-link Communication
CREATE	Collaborative Research And Training Experience
CRSA	Centre for Research in Sustainable Aviation
ERA	Environmentally-Responsible Aviation
ETS	Emissions Trading System
EU	European Union
FAA	Federal Aviation Administration
FMS	Flight Management System
FTK	Freight-Tonne-Kilometers

GARDN	Green Aviation Research and Development Network
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GPU	Ground Power Unit
GTL	Gas To Liquid
HEFA	Hydroprocessed Esters and Fatty Acids
HRJ	Hydrotreated Renewable Jet
IATA	International Air Transport Association
IASL	Institute for Air & Space Law
ICAO	International Civil Aviation Organization
ILUC	Indirect Land Use Change
IPCC	Inter-governmental Panel on Climate Change
LASR	Large Aircraft for Short Range
MBM	Market Based Measure
MCAM	Monash Centre for Additive Manufacturing
NASA	National Aeronautics and Space Administration
NSERC	Natural Sciences and Engineering Research Council
OPR	Overall Pressure Ratio
PBN	Performance-Based Navigation
PCA	Pre-Conditioned Air
PM	Particulate Matter
PRSEUS	Pultruded Rod Stitched Efficient Unitized Structure
R&D	Research & Development
RF	Radiative Forcing
RPK	Revenue-Passenger-Kilometers
RVSM	Reduced Vertical Separation Minimum
SAFE	Sustainable Alternative Fuels Evaluation
SARPs	Standards And Recommended Practices
SESAR	Single European Sky Air Traffic Management Research
SOFC–GT	Solid-Oxide Fuel Cell – Gas Turbine
SUGAR	Subsonic Ultra Green Aircraft Research
SPK	Synthetic Paraffinic Kerosene
TET	Turbine Entry Temperature
UK	United Kingdom
US	United States
UTIAS	University of Toronto Institute for Aerospace Studies
UTLS	Upper Troposphere and Lower Stratosphere

1 Introduction

1.1 Overview

In the first section of this report, the current challenges faced by the aviation sector are reviewed in the context of sustainable and environmentally-responsible aviation. We then present the historical and forecasted growth in the demand for air travel. Next, we review the various aviation emissions and their resulting impact on the atmosphere. Future trends in aviation emissions and climate change are then extrapolated based on several business-as-usual scenarios and, finally, this section presents a review of the current mitigation initiatives that are currently underway, both in Canada and around the world.

The remaining sections of this report discuss a series of specific actions that can be taken to reduce the sector's impact on climate change. These actions have been divided into three categories: 1) government regulations, incentives, and assistance, 2) operational strategies, and 3) advanced technologies. Each will be discussed in detail in Sections 2 to 4. The overarching goal of these sections is to demonstrate clearly that there are many actions that can be taken by the industry and its regulators to significantly reduce aviation's climate change impact. The hope is that these actions will allow the industry to safely meet its increasing demands, while responsibly addressing its climate change impact and improving the quality of life of all Canadians for the foreseeable future.

1.2 Towards Sustainable Aviation

Aviation is essential to serving the needs of all Canadians. From the dawn of commercial aviation, our dependence on the domestic and international air transport of passengers and goods has grown tremendously. In just over a century, aviation has progressed from the revolutionary, yet clumsy, Wright-Flyer of 1903, to the impressive transonic aircraft of modern day civil aviation, for example, the recent double-deck Airbus 380 capable of routinely and safely transporting some 500 passengers across distances greater than 13,000 km and at speeds greater than 900 km/h. Indeed, in a matter of hours modern aviation readily connects goods and people from all corners of the world. Compared to an average of 120 transatlantic flights per week in 1948, there are now more than 1,200 flights every single day that safely cross the North Atlantic airspace alone [5].

This rapid technological revolution has, in turn, led to the huge growth of the aviation industry and has contributed significantly to the world's Gross Domestic Product (GDP) [106]. Unfortunately, this growth has been accompanied by an increasingly negative impact on the global atmosphere and climate change. This impact must be reduced in the larger context of ensuring the long-term sustainability of the aviation industry.

In an attempt to ensure a sustainable aviation sector, the industry and its regulators must carefully balance and address their economic, environmental, and social concerns. From an economic perspective, the industry must maintain high levels of growth and employment while accounting for unit development costs, operational costs, growing infrastructure, and the relative affordability and competitiveness of air travel [106]. From an environmental perspective, the industry must seek to mitigate the negative environmental effects of its technology, including greenhouse gas (GHG) emissions, aerosols, noise, the

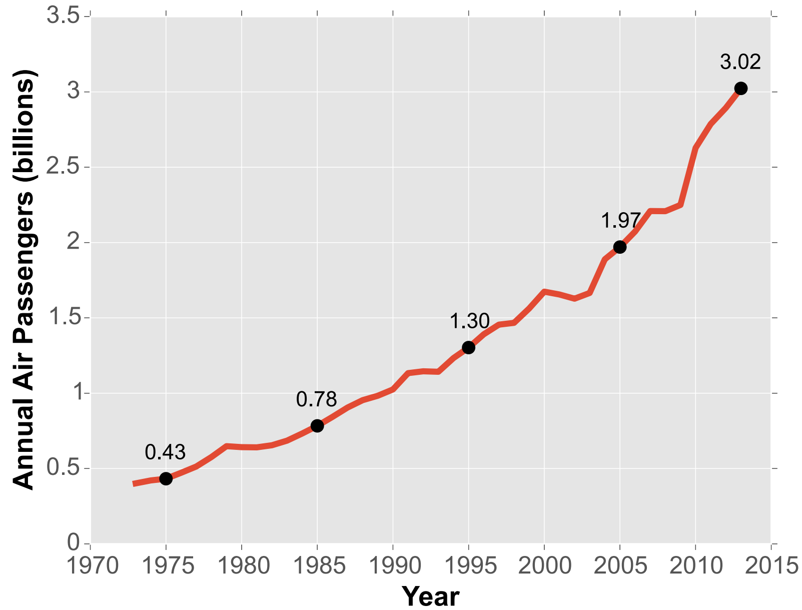


Figure 1: Historical growth of global annual air passengers, data from World Bank [98]

consumption of natural resources, and end-of-life disposal [89]. Finally, from a social perspective, the industry is first-and-foremost responsible for public safety, but also public accessibility across Canada, passenger comfort, travel times, and public opinion when informing decisions on policy and infrastructure [106]. While the scope of this report focuses specifically on climate change impact, the review will touch on all perspectives and concerns throughout.

1.3 Growth in Demand for Air Transport

The commercial aviation industry has seen tremendous growth since the World War II era. Here we present various metrics to demonstrate this growth. The first metric uses data available over the longest period and is simply the total number of annual passengers flown by commercial airlines; Figure 1 shows the growth in the annual number of revenue generating passengers over the past forty years (data from World Bank [98]). The world's average year-on-year growth rate over this period was 5.25%, averaging 6% over the past decade alone.

Other popular metrics for assessing the growth of aviation are those that can account for the total distance flown by both passengers and freight. Revenue-Passenger-Kilometers (RPK) is a metric that multiplies the total number of revenue generating passengers by the distance travelled by each passenger. An analogous metric, called Freight-Tonne-Kilometers (FTK), is the total freight (measured in tonnes) multiplied by the distance each unit of freight has travelled. Figure 2 shows the RPK data over the past decade (from ICAO [55]). Note from these figures that the growth in the demand for air transport has been generally resilient and quick to rebound from global events, such as 9/11 and the 2008 global financial crisis.

Figure 2: Recent annual growth of Revenue-Passenger-Kilometers (RPK), source: [55]

Future projections by Boeing predict a 5.0% annual increase in RPK up to 2032, with a 5.8% annual increase in FTK [14]. Almost identical numbers have have been projected by Airbus [43]. Furthermore, Boeing's market outlook projects that by the year 2032, the total number of commercial transport aircraft in operation will double to 41,240 aircraft, as compared to 20,310 in operation as of 2013 [14]. In fact, airlines are expected to invest more than 1 trillion USD in fleet renewal over the next 20 years [72].

From an economic standpoint this rapid growth directly contributes to increased revenue, job creation, and the world (including Canada's) GDP. However, from an environmental standpoint, it implies that the total and relative impact of aviation on climate change and natural resources will continue to increase for the foreseeable future. Not only is aviation's impact on climate change growing, but it is growing relatively faster than other industries. Gossling and Upham have suggested that there is no other human activity pushing *individual* emission levels as fast and as high as air travel [43].

As a final note, there are some critics, such as George Monbiot [76], that strongly condemn the rapid growth of aviation due to its projected climate change impact. Monbiot recommends that regulations be put in place to limit its growth and halt the construction of any new airport infrastructure [76]. However, it should first be recognized that aviation's absolute contribution to climate change remains, at least for now, relatively small (as quantified in the next section). Furthermore, there are many other highly effective regulatory, operational, and technological strategies (many of which are reviewed in this report) that can be enacted to significantly mitigate aviation emissions and climate change while enabling the sector to continue to meet the growth in demand. If, however, aggressive voices such as Monbiot's cause political considerations to limit the growth of the industry, then it would be prudent to first consider limiting non-urgent freight transportation, before limiting passenger travel. This would require a public acknowledgement that certain goods need not arrive at our doorstep so quickly [43], and might rather be deferred to longer duration transport by sea.

1.4 Aviation and the Atmosphere

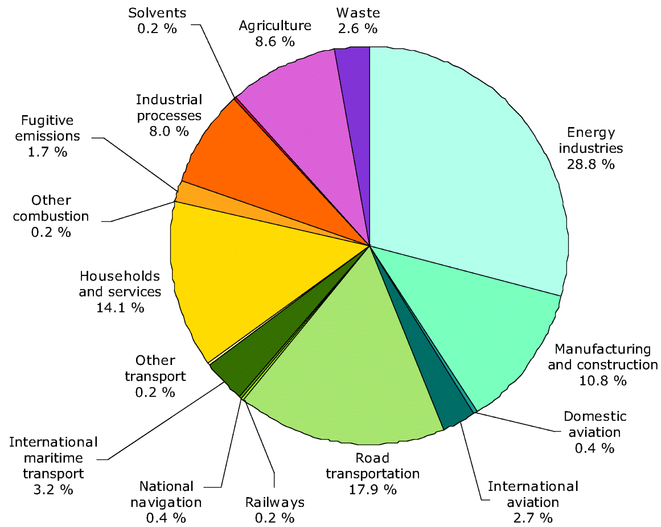
Through the combustion of fossil fuels, the gas turbine engines used to propel transport aircraft emit gases and particles that alter the composition of the atmosphere. This, in turn, has a net warming effect that contributes to climate change. In this section we review how and to what extent these emissions effect climate change, highlighting the level of scientific understanding along the way. Much of this overview draws upon the landmark IPCC report of 1999, titled "Aviation and the Global Atmosphere" [89], along with more recent publications, such as the comprehensive 400 page review titled "Climate Change and Aviation", edited by Stefan Gossling and Paul Upham [43] in 2009.

To what extent does aviation contribute to anthropogenic GHG emissions? In Figure 3(a), a sector-by-sector breakdown of the GHG emissions in the European Union is presented, with international and domestic aviation combining for 3.1% of the total. Similar contributions are seen at a global level, with the aviation sector contributing between 2-3% of the total global GHG emissions [43]. Looking specifically at domestic aviation in Canada, we see a greater contribution then in most other countries or jurisdictions. For example, in Figure 3(b), it can be seen that Canada's domestic aviation accounts for 5% of Canada's transportation sector emissions, or approximately 1% of Canada's total GHG emissions (as compared to 0.4% in the European Union). Interestingly, GHG emissions from international flights operating in and out of a given nation are often omitted from national GHG emission totals. This is likely due to the fact that national emissions targets set under the Kyoto Protocol are required to account for domestic aviation only [23]. The critical establishment of targets for international aviation emissions is an ongoing work-in-progress, with the responsibility placed largely on ICAO (as discussed in Section 2). In general, Suzuki [23] suggests that the resulting climate change impact of aviation is disproportionately large considering the relative economic size of the industry.

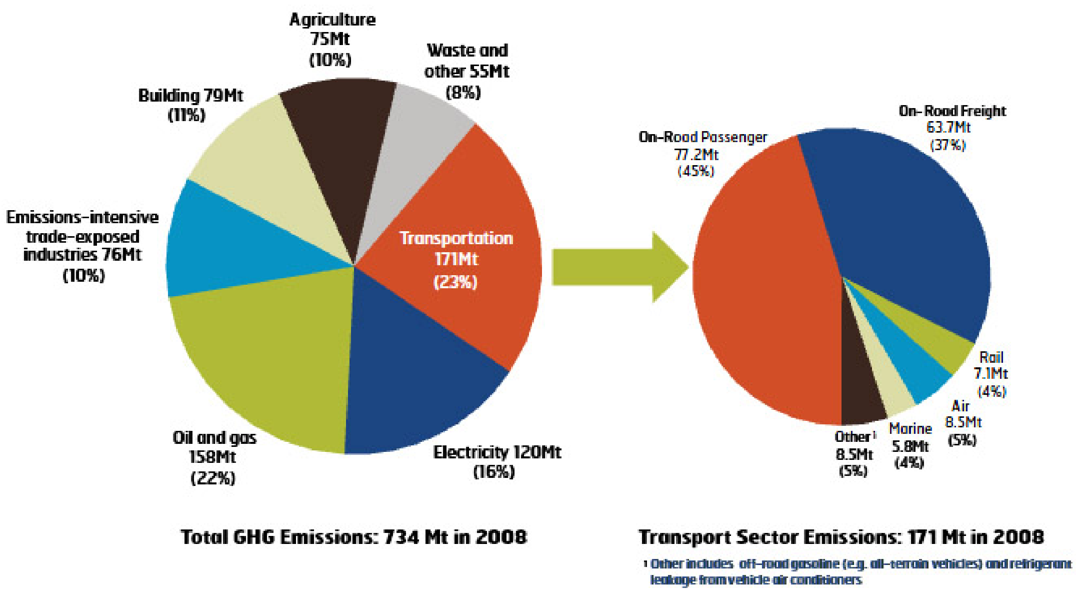
As previously mentioned, measures such as limiting or halting the growth of the aviation industry are likely not warranted (at least not for the time being) considering aviation's relatively small contribution to anthropogenic GHG emissions. However, Gossling and Upham [43] emphasize that aviation's contributions should be taken seriously, and considered with regard to (i) the rapid growth of the aviation industry, (ii) the target GHG reductions required by the IPCC, and the fact that (iii) the highest density of aviation activity is still concentrated in industrialized countries with high per capita emissions (in turn, aviation may represent a larger share of emissions in those countries). Furthermore, climate change considerations must account for non-GHG emissions deposited at high altitude which then interact with the properties of the Upper Troposphere and Lower Stratosphere (UTLS). Indeed, when considering the total climate change impact of all human activity (including non-GHGs), aviation may contribute upwards of 5% [68].

The direct GHG emissions from gas turbine engines are carbon dioxide (CO_2) and water vapour [89]. In addition, gas turbines emit other gases and particles that affect the composition of the atmosphere, including: nitrogen oxides (NO_X), sulfur oxides (SO_X), and soot. Under the right conditions, gas turbine engines are also responsible for the formation of condensation trails (or contrails) and may also contribute to cirrus cloud formation. The following is a brief description of the various aircraft emissions and their contributions to climate change; more detailed descriptions may be found in the literature [43, 89]:

Carbon dioxide (CO_2): Carbon dioxide is a GHG and a direct result of the combustion of fossil fuels. When aviation kerosene (jet fuel) is burned, the carbon released bonds with the oxygen in the atmosphere (O_2) creating CO_2 [23]. The quantity of CO_2 emitted is thus directly related to the quantity of fuel burned. Its impact on the atmosphere and on climate change are perhaps the most well understood of any of the compounds emitted by aircraft. It has a direct warming effect by absorbing and



(a) GHG emissions in the European Union (including international and domestic aviation), source: [38]



(b) GHG emissions in Canada (not including international aviation), source: [101]

Figure 3: Breakdown of GHG emissions on a sector-by-sector basis in Europe and Canada

retaining heat in the atmosphere. The residence times of CO_2 are the longest of any of the aircraft emissions, lasting between 50-200 years [89].

Water Vapour: Water vapour is also a GHG and retains heat in the atmosphere. However, since it is emitted in the UTLS, it is typically removed by rainfall in a very short period, on the order of 1 or 2 weeks. Thus, the direct radiative climate change effect of water vapour from aviation is comparatively small [89]. On the other hand, water vapour can be involved in the formation of contrails and contrail-cirrus cloud formation, which will be discussed below.

Nitrogen Oxides (NO_X): Nitrogen Oxides is a term used to simultaneously refer to nitric oxide (NO) and nitrogen dioxide (NO_2). The formation of NO_X can result from a large number of chemical reactions, as reviewed by Lee [43]. While CO_2 emissions can be directly related to the specific fuel consumption of an engine, NO_X emissions depend on several additional factors, including: the stoichiometric (air-to-fuel) ratio, the flame temperature in the combustor, and the resident times at the flame temperature.

NO_X emissions have two primary impacts in the UTLS. The first is the enhancement of ozone (O_3), a powerful GHG, which results in a warming effect. The second is the depletion of methane (CH_4), also a GHG, which results in a cooling effect. The net effect of NO_X emissions is ultimately a warming effect, as illustrated in Figure 4, discussed below. As we shall see in Section 4.4, the design of advanced combustors for NO_X reduction continues to be an important and challenging area of research.

Particulate Matter (PM): Sulphates and soot (or black-carbon particles) form the majority of aerosols emitted by modern gas turbine engines. Sulphates are the result of the relatively low sulphur content in aviation kerosene, which reacts to form sulphur dioxide (SO_2) and sulphur trioxide (SO_3) [43]. Soot, which can appear as black smoke, is the result of the incomplete combustion of kerosene in the combustor [43]. Increases in sulphates tend to have a cooling effect, while increases in soot have a warming effect. While the accumulation of these aerosols is predicted to increase with aviation fuel use, their effect on climate change is considered to be significantly lower than other aircraft emissions [89]. However, similar to water vapour, these aerosols can be involved in the formation of contrails and contrail-cirrus cloud [43].

Contrails and Contrail-Cirrus Cloud: Contrails are formed when the water vapor emitted by gas turbine engines in the UTLS condenses to form trailing lines of cloud-like structures. On a clear day, they are easily observable from the ground by the naked eye. This condensation occurs when the water pressure in the exhaust plume exceeds the liquid's supersaturation point as it mixes with the colder and less moist surrounding atmosphere [87]. The condensation of water occurs on the particulate matter in the exhaust plume (sulphates and soot). Given the right temperature and humidity, freezing can occur shortly after condensation [87]. The residence time of the contrail depends on the level of ice saturation in the surrounding air. If the air is already ice-saturated, the contrails persist and they have a net warming effect on the local atmosphere.

Furthermore, the local atmospheric conditions may provoke an evolution of the linear contrails into contrail-cirrus cloud formation [87], which may have a further warming effect. Contrails and contrail-cirrus are recognized as the most poorly understood of aviation's contributions to climate change. While some studies have suggested that they may contribute upwards of 20% of the total climate change impact resulting from aircraft emissions [87], other studies suggest significantly less impact. Further scientific research is required.

To compare the climate change impact of the above sources, we employ the Radiative Forcing (RF) metric [43, 87, 89, 106]. The RF metric can be very informative since its value (for a unit increase in a given pollutant) is directly proportional to the expected steady-state climate response in terms of global

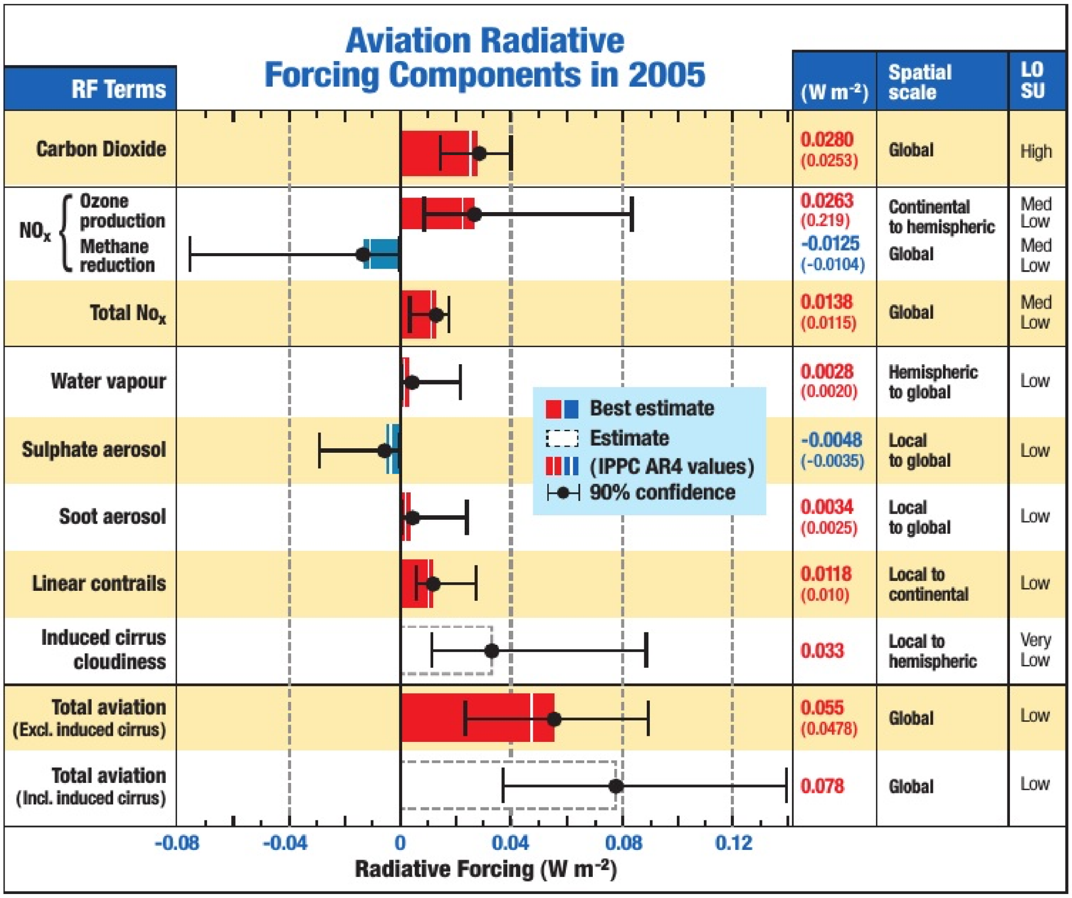


Figure 4: Radiative Forcing (RF) from aircraft, source: [60]

mean surface temperature [87]. A formal definition may be found in the 1999 IPCC report [89]. Figure 4 provides a comparative assessment of the climate change impact of aviation's pollutants. Note that a positive RF value is indicative of an increase in the global mean surface temperature. The horizontal bars are representative of the scientific uncertainty for each case, which was derived using expert scientific judgment and combines the uncertainty of calculating the atmospheric change due to emissions with that of calculating the radiative forcing itself [89]. On the topic of cirrus-cloud formation, in particular, it is evident that its RF is potentially significant, but the uncertainty and lack of scientific understanding is very large.

Despite progress in our scientific understanding, more research is required. Indeed, in a review by Gossling and Upham [43], they state that "a well-defined and scientifically sound metric for the overall contribution of a single flight to radiative forcing has not yet been agreed upon, as this poses some fundamental theoretical difficulties".

1.4.1 The Need for Additional Scientific Research

In an excellent chapter titled "Aviation and Climate Change: The Science" [43], Lee presents a detailed review of past scientific research regarding aviation emissions and climate change. In the mid-1990s initiatives such as AERONOX and the Subsonic Assessment Program led to the landmark IPCC report in 1999, titled "Aviation and the Global Atmosphere" [89], which is often still used as a benchmark today [43]. Lee also points out that more recently, Europe has taken the lead in the research effort to better understand, quantify, and reduce the uncertainties associated with the effects of aviation on climate change. Progress in the United States slowed due to the demise of NASA's aviation-dedicated atmospheric effects research programs [43]. However, recent research in North America has been taken up by both academia and the US Federal Aviation Administration (FAA). Research questions have more recently shifted focus from determining the magnitude of the effects on climate change to questions regarding the mitigation and reduction opportunities. However, such questions "frequently run up against a lack of basic scientific knowledge in some areas" [43]. There is a clear need for significant research in environmental and atmospheric sciences, and in particular, in our understanding of how aviation emissions impact climate change.

In a review for ICAO, Maurice and Lee [74] published a comprehensive assessment of our scientific knowledge, along with the uncertainties and gaps in quantifying aviation's impact on climate change, noise and air quality. Ultimately, their recommendation was to form, through ICAO, an international (virtual) working group of the top scientific experts in the world in order to further our scientific understanding in the context of informing policy decisions.

Without an improved scientific understanding, it can be difficult to select, promote, prioritize, and actualize new policies, operational strategies and technology developments. In order to create new regulations they must be based on a sound understanding and on accurately quantified metrics for the various climate change effects. As an international path forward, ICAO is currently taking steps to establish the necessary metrics and performance requirements to deliver an aircraft level CO_2 certification standard by 2016 (discussed further in Section 2.3). However, as discussed in the next section, there are important trade-offs to consider between the different aircraft emissions that effect the overall RF from an aircraft. A better understanding of these trade-offs will require that we improve our scientific understanding of the climate change effects of the other aircraft emissions. For example, if additional research into contrails and contrail-cirrus cloud formation should quantify their radiative forcing with a higher degree of certainty, then it may be prudent to adopt operational strategies that avoid contrail and contrail-cirrus cloud formation, potentially at the expense of additional CO_2 emissions (such strategies are presented in Section 3). Finally, from a technological standpoint, the uncertainty can complicate and misinform the design space presented to engineers, potentially resulting in sub-optimal technology. This becomes particularly evident when engineers and manufacturers attempt to understand and ultimately weigh the various design trade-offs at play.

1.4.2 Trade-offs and Additional Considerations

Environmental design trade-offs between aviation's various pollutants are still very much an active area of research [72]. One of the most important considerations that has yet to be discussed (since it does not directly impact climate change) is that of aircraft and engine noise generation. Noise has become a prominent issue in aircraft and engine design as regulators try to reduce the number of people negatively impacted by the increasing air traffic and growing infrastructure. Due to more stringent noise regulations, engines have become much quieter than they used to be, and attention has begun to shift towards reducing the noise generated by the airframe itself [50], particularly from the landing gear and high-lift devices.

Noise can indirectly impact climate change due to the design trade-offs involved. A good example of this can be found in the design of the Airbus 380. Since the aircraft was required to fly in and out of Heathrow airport, and Heathrow was imposing a strict noise requirement, the manufacturer was required to modify their design to meet the noise requirement. The result was an increase in fuel burn that effects all Airbus 380s in service around the world (regardless of their proximity to Heathrow). Dray [30] also points out that designs aimed at producing lower noise levels can increase airport-area NO_X emissions. Another example is provided by Manzoor [72], who points out that the new TALON IITM designed to reduce NO_X by over 25% resulted in approximately three times the amount of smoke production. Clearly, there are difficult trade-offs that must be carefully considered and appropriately weighted when making policy and design decisions.

Focusing solely on CO_2 may lead to increases in NO_X, contrails, and contrail-cirrus formation, which may result in an increase in net RF from aviation (discussed further in Sections 3 and 4). Manzoor describes the optimization of the trade-offs as a system level issue that could have significant impact on our ability to develop and introduce new technologies in a timely and cost-effective manner [72]. Ultimately, future technologies will depend on the motivation of manufacturers and the demands of the industry. Incentivizing the industry to take action based more heavily on environmental and climate change considerations is reviewed in Section 2. Finally, in our discussion of operational strategies and advanced technologies (in Sections 3 and 4) various additional trade-offs will be highlighted throughout.

1.5 Business As Usual Scenario

Historically, the aviation industry has seen an average of about 1 to 1.5% annual improvement in technological efficiency. Airbus states that, over a 40-year period, the aviation industry has improved fuel burn and CO_2 emissions by 70%, NO_X emissions by 90% and noise by 75% [6]. While impressive, it can be argued that engineers are capable of far more significant reductions. Gossling and Upham criticize the industry of "presenting itself frequently as an environmental champion" [43], often neglecting to mention that the absolute emissions of the aviation sector continue to rapidly increase.

If the status quo continues, we can expect a significant increase in the climate change impact due to aviation emissions as a result of the projected growth exceeding efficiency improvements. Studies conducted by the IPCC in 1999 presented a series of six projections to the year 2050 based on different plausible scenarios and assumptions [89]. In Figure 5, Lee *et al.* [69] collected research data from seven different sources (including the IPCC) to plot and compare the growth of the past and projected CO_2 emissions (in millions of tonnes per year) from the aviation sector from 1990 through to 2050. In the business-as-usual scenarios, it is clear that as aviation grows, its negative impact on climate change will continue to increase. The above scenarios are formed on the basis of a GDP-driven industry, while estimating technological improvements to 2050 [43].

Nevertheless, as we will discuss, there exist many means by which the climate change challenge can be addressed. Figure 6 provides a roadmap toward achieving a reduction in aviation CO_2 emissions of 50% by the year 2050 (relative to the 2005 baseline). The roadmap illustrates that in order to meet this

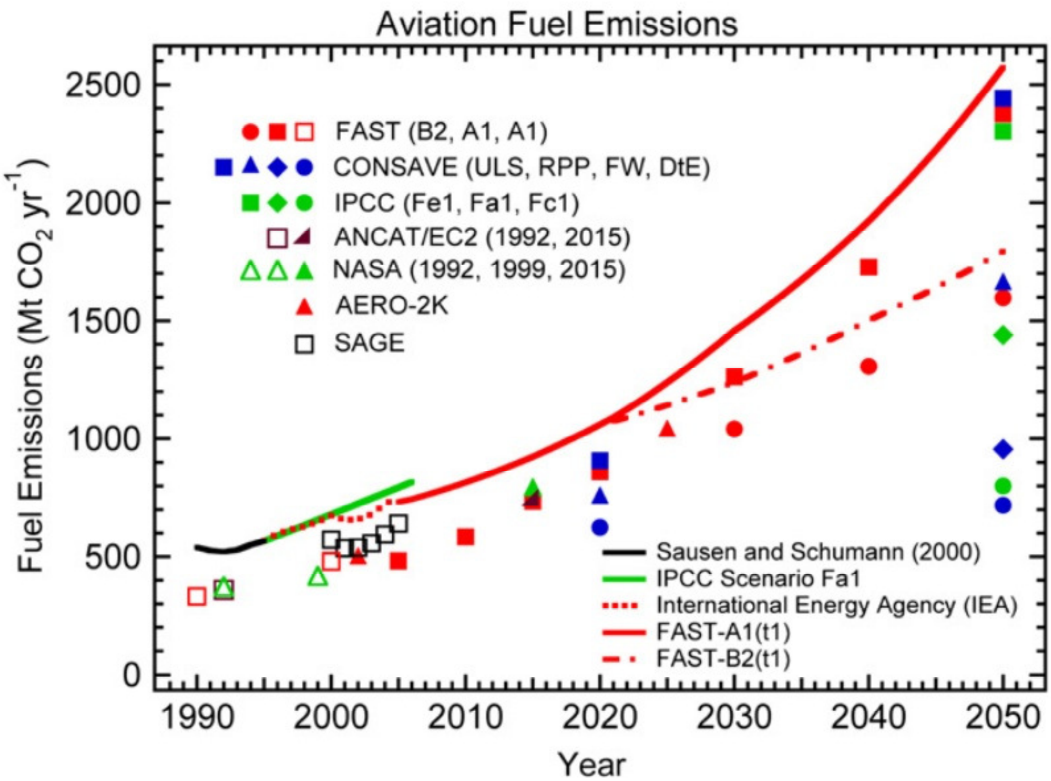


Figure 5: Past and future CO_2 emissions from the aviation section, source: [68]

target, we must seek improvements through fleet renewal, operational strategies, technology advancements and low carbon fuels, all of which are discussed in detail in this report. Finally, it should be emphasized that the reduction in aviation's climate change impact, and the achievement of the CO_2 emissions target by 2050, will only be possible with the support and incentivization of governments around the world, including Canada's (as discussed in Section 2).

1.6 Review of Existing Initiatives

As recently as the early 2000's, the number of initiatives that existed for the purpose of addressing the environmental concerns and sustainability of the aviation industry were few and far between. Over the past decade, the number of such initiatives has grown tremendously; these are now incorporated into various levels of government, industry and academia around the world. The following is a selected list (by no means comprehensive) of some of the most prominent initiatives and developments from different regions of the world, with special attention given to the Canadian initiatives. The following serves only as a high-level summary; many of the best practices and ideas from the following initiatives are presented in subsequent sections of this report.

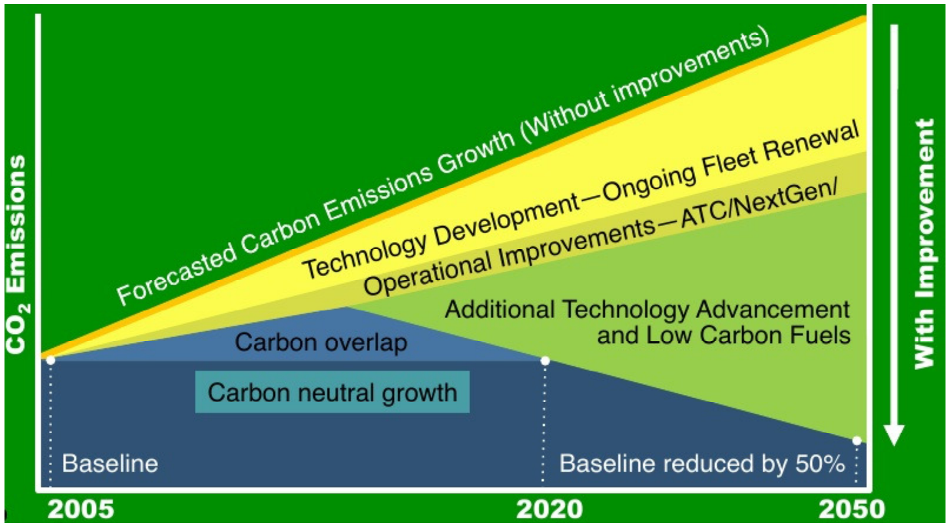


Figure 6: Emissions reduction roadmap, source: [25]

1.6.1 Selected Canadian Initiatives

- In 2012, Transport Canada initiated a voluntary action plan titled "Canada's Action Plan to Reduce Greenhouse Gas Emissions from Aviation" [101]. The action plan focuses on three areas: 1) fleet renewal and upgrades, 2) more efficient air operations, and 3) improved capabilities in air traffic management. Since its inception there have been two annual reviews highlighting progress to date [102, 103]. Transport Canada has also formed a joint government-industry Working Group on Aviation Emissions. The working group was established in 2010 to develop a plan to address GHG emissions from the domestic aviation sector [101]. In the future, it is recommended that this working group also include academia in order to foster a more collaborative and coordinated research and development effort.
- In 2009, the Green Aviation Research and Development Network (GARDN) was founded. Its mandate is "to increase the competitiveness of Canada's aerospace industry by reducing the environmental footprint of the next generation of aircraft, engines and avionics developed in Canada" [46]. GARDN is now in its second phase (GARDN II), beginning in 2014, and includes over 270 industrial and academic researchers, including over 100 students. A review of the various research projects may be found in [46].
- In 2013, The University of Toronto Institute for Aerospace Studies (UTIAS) established the Centre for Research in Sustainable Aviation (CRSA). The CRSA brings together professors, scientists, and industry researchers to conduct research and provide students with the interdisciplinary skills required to develop future generations of environmentally sustainable aircraft [105]. Supported in part by an NSERC CREATE grant, the CRSA offers a unique program in sustainable aviation to graduate level students that includes strategic professional training opportunities, a student research symposium, a research project management workshop, and industrial internships. The CRSA annually alternates between hosting the biannual UTIAS International Workshop on Aviation and Climate Change, and the biannual UTIAS National Colloquium on Sustainable Aviation, and also hosts an

annual Summer School on Sustainable Aviation.

- McGill University's Institute for Air & Space law (IASL) and Centre for Research in Air and Space Law regularly hold workshops, seminars, and conferences bringing together industry, academia, and ICAO representatives to discuss matters on international aviation policy and air navigation. For example, in 2012, the IASL held an Emissions Trading & International Civil Aviation Symposium, in which many of the benefits and challenges of including aviation in global and local cap-and-trade systems were presented.

1.6.2 Selected American Initiatives

- The National Aeronautics and Space Administration (NASA) has a well-established Environmentally-Responsible Aviation (ERA) project that began in 2009 under the Integrated Systems Research Program. The ERA project "explores and documents the feasibility, benefits and technical risk of vehicle concepts and enabling technologies to reduce aviation's impact on the environment" [79].
- The NASA Fundamental Aeronautics Subsonic Fixed Wing project aims to address and develop revolutionary long-term technologies to significantly improve the energy efficiency of subsonic aircraft, with dramatic reductions in emissions and noise. The Subsonic Fixed Wing project focuses heavily on the multidisciplinary advancement of unconventional aircraft technologies requiring mature technology solutions in the 2025-2030 time frame. The hope is that these new technologies will "enable the national vision of significant growth in airspace system throughput in coming decades while reducing overall environmental impact" [41].
- The FAA's Office of Environmental Impacts and Mitigation has established a five-pillar initiative to reduce aviation's impact on the environment [73]. The objectives are to: 1) advance scientific understanding and improve analysis capabilities, 2) accelerate operational changes, 3) mature new aircraft technology, 4) develop alternative fuels, and 5) employ policies and market based measures. All of these topics are discussed further in this report (with alternative fuels included in Section 4).

1.6.3 Selected European Initiatives

- In 2008, the European Commission launched the Clean Sky Joint Technology Initiative with a budget of €1.6 billion [20], equally shared between the Commission and industry. The program's mission is to "develop breakthrough technologies to significantly increase the environmental performances of airplanes and air transport, resulting in less noisy and more fuel efficient aircraft" [20]. The project aims to meet the objectives set out by ACARE - the Advisory Council for Aeronautics Research in Europe. The ACARE objectives are divided into three main areas: 1) reduced fuel consumption (CO_2 and NO_X reduction), 2) external noise reduction, and 3) aircraft life cycle.
- In collaboration with the Clean Sky initiative, the Aeronautics and Air Transport Research Programme [37] oversees a large number of technological and operational research projects in the European Union. A review of the individual projects, including recent progress and expected results may be found in [37].

- The European Union (EU) Horizon 2020 program is the biggest research and innovation program ever established in the EU, with over €80 billion of funding available over 7 years from 2014-2020 [36]. As part of Horizon 2020, funding is provided for the development of resource-efficient transportation aimed at making aircraft cleaner and quieter to minimize aviation's impact on climate and the environment [36]. Projects are aimed at more efficient air traffic management systems, new aircraft technologies, and alternative fuels.
- In the United Kingdom (UK), the Greener by Design initiative is led by the Royal Aeronautics Society's Environmental Specialist Group. Their mandate is to provide "an independent source of information and advice regarding the environmental issues and potential solutions facing civil aviation and communicating with stakeholders and the general public alike." [12]. Also in the UK is the Sustainable Aviation Alliance [95], which brings together UK's airlines, airports, aerospace manufacturers and air navigation service providers. Both the Sustainable Aviation Alliance and Greener by Design group report regularly on operational and technological progress in reducing aviation's environmental impact.
- Finally, the EU has established an Emissions Trading System (ETS) which is the first in the world that has attempted to include international aviation in its regulatory framework, in effect placing a price on all aircraft CO_2 emissions in the EU. This initiative will be discussed in more detail in Section 2.

1.6.4 Selected Global Initiatives

- The International Civil Aviation Organization (ICAO) is widely considered the regulatory entity of international civil aviation under the mandate of the United Nations. ICAO's member states participate in setting out the regulatory rules of the industry. As an integral part of the ICAO council, the Committee on Aviation and Environmental Protection (CAEP), established in 1983, is responsible for "formulating new policies and adopting new Standards And Recommended Practices (SARPs) related to aircraft noise and emissions, and more generally to aviation environmental impact" [54]. In 2004, ICAO (and hence CAEP) adopted three environmental goals in conjunction with the Kyoto Protocols mandate as follows [54]:

  1. To limit or reduce the number of people affected by significant aircraft noise.
  2. To limit or reduce the impact of aviation emissions on local air quality.
  3. To limit or reduce the impact of aviation greenhouse gas emissions on the global climate.

- The International Air Transport Association (IATA) has set up several programs with the goal of assisting and standardizing techniques for airlines and passengers to improve their environmental performance in the areas of: 1) alternative fuels, 2) carbon offset programs (for individual and corporate footprints), and 3) environmental assessments [53].
- The Inter-governmental Panel on Climate Change (IPCC) has been responsible for some of the most comprehensive research and documentation on the impact of aviation on the environment [89]. They have also recommended various climate change targets based on current levels of scientific understanding. Many of their findings are used throughout this report.

- The Air Transportation Action Group (ATAG) has brought together a coalition of airlines and aircraft and engine manufacturers. In 2008, the various members signed a declaration committing themselves to action on climate change. ATAG aims to “demonstrate environmental leadership by delivering on our goal to cap net aircraft carbon emissions from 2020 and work to achieve our ambitious goal of a 50% reduction in net carbon emissions by 2050 compared to 2005 levels [4].

2 Government Regulations, Incentives, and Assistance

2.1 Overview

The aviation sector is supported by an elaborate framework of government regulations, incentives, and assistance that is critical to its success [34]. Despite this supporting framework, the industry's decision-making process regarding operational strategies and technological development has been largely guided by economics, and less influenced by climate change concerns. The competition and market forces that exist have (thus far) failed to initiate sufficient action with regards to aviation's climate change impact. If this burden is left to the private sector alone, sufficient reductions in emissions to meet the IPCC targets will likely not occur. In declaration 5 (b) of the Canadian Transportation Act, it states that "regulation and strategic public intervention are (to be) used to achieve economic, safety, security, environmental or social outcomes that cannot be achieved satisfactorily by competition and market forces" [75]. This suggests that government regulations, incentives, and assistance should be considered as a means to ensure that the targeted environmental outcomes are met.

In this section we review various actions that the government can take to directly and indirectly reduce the climate change impact of the aviation sector. As it is central to the discussions that follow, we begin by reviewing the role of ICAO to which Canada is a member state. Next we review various government regulations in the form of certification standards for environmental protection, followed by the possible government actions for incentivizing the industry by including it in an emissions trading or carbon taxation scheme. Finally, we will discuss the importance of continuing and strengthening various forms of government assistance in the context of reducing aviation's climate change impact.

2.2 The Chicago Convention and the Role of ICAO

ICAO is the widely recognized governing body of the international civil aviation industry. With headquarters located in Montreal, Quebec, it consists of 191 member states, including Canada. ICAO was established in 1944 when the initial member states signed a multilateral binding agreement known as the Convention on International Aviation (more commonly referred to as the Chicago Convention) [56]. The Chicago Convention solidified the role of ICAO and provides a platform and governing body through which the member states may amend and update their multilateral agreements.

The importance of the Chicago Convention and ICAO to aviation's impact on climate change should not be underestimated. Emissions from international aviation are specifically excluded from the climate change targets set under the Kyoto Protocol, which instead defers the responsibility to ICAO. The Chicago Convention – signed long before aviation's impact on climate change was of concern – prevents the taxation of commercial aviation jet fuel, which has recently presented some regulatory and legal issues [56].

For example, in 2008, the European Union's plans to include local and international aviation in their emissions trading system (as described in Section 2.5.3) was labelled an illegal tax and threatened with sanctions by countries including the USA and China, who cited the Chicago Convention [43]. In December of 2011, the EU's actions were deemed compatible with international law by the European Court of Justice in a legal case brought by some US airlines and their trade association against the inclusion of aviation in the EU ETS [35]. At least until 2016, only flights that remain within the European Economic Area are included in the EU ETS [35].

While the Chicago Convention allows for amendments and additions, ICAO has yet to take any such action on the issue of fuel taxation. It is also important to recognize that, while the original Chicago Convention is binding, any new recommendations (or SARPs) are binding only to the states that choose to implement them; member states can opt-out of SARPs by registering their differences with ICAO [26].

Over the years, ICAO has generally been a successful initiative of the United Nations. However, the more recent concerns regarding aviation's impact on climate change present a significant challenge to the organization. Indeed, the burden on ICAO is daunting, as it must consider the interest of both developed and developing states [1]. ICAO has faced strong criticism from environmental and policy experts for the pace at which they are taking action on climate change; see, for example, the scathing reviews of Gossling and Upham [43] and Abeyratne [1]. Nonetheless, the intentions of ICAO are to take more significant action towards addressing aviation's climate change impact.

From a Canadian perspective, current climate change initiatives by Transport Canada and more specifically, the Canadian Aviation Regulation Advisory Council (CARAC) [101, 102, 103] will need to follow and actively participate in ICAO's developments. Ultimately, the Canadian government should consider ratifying new certification standards and the carbon pricing system recommended by ICAO for the purpose of environmental protection.

2.3 Certification Standards

Any new aircraft or engine design entering the fleet must first be certified through the local regulatory authorities, and each new aircraft must receive and maintain a Certificate of Airworthiness in order to operate. Perhaps the most aggressive regulatory approach to limiting the environmental and climate change impact of aviation – without limiting the growth of the industry – is to enforce more stringent certification standards. Such standards create a direct link between quantifiable noise and emission reductions and the technology goals of manufacturers, in turn, driving advances in the state-of-the-art of sustainable and environmentally-responsible technologies.

Over the past 40 years, ICAO and CAEP have continuously developed certification standards and related regulations and procedures to protect the environment [57]. These certification standards are presented as recommendations to the member states who then implement and enforce them by law under their local jurisdictions. In Canada, manufacturers such as Pratt & Whitney Canada, Bombardier Aerospace, and others, have continuously adapted to ensure that their new technologies meet any newly adopted standards by Transport Canada. The new standards are typically applied to new aircraft and engines entering the fleet no earlier than five years from the time the standard is announced. The aim is to give manufacturers sufficient time to design and implement any new technologies required without significantly affecting their short-term product development plans.

Every three years, CAEP formally convenes to present studies and develop environmental recommendations that include: 1) GHG emissions, 2) noise levels, and 3) local air quality emissions [54]. Almost all standards recommended by CAEP thus far have been applied to aircraft and engines for noise and local air quality. The first ever certification standards adopted by ICAO and its member states were related to controlling smoke and fuel venting from gas turbine engines in the early 1980s. Focus then shifted to ensuring sufficiently low levels of perceived noise (with updates to standards in 1978 and 2006) and NO_X emissions (with updates to standards in 1998, 2004, and 2010). The typical approach taken thus far by CAEP has been to balance what is technologically feasible with the health impacts of people living in the vicinity of airports [109]. The specific details of these standards, and the aircraft to which they apply, can be found in the various chapters of ICAO Annex 16 Volume 1 (Noise), and Volume 2 (Aircraft Engine Emissions) [57].

Although CAEP has yet to implement an aircraft level fuel efficiency (and hence CO_2 emissions) standard, it is currently under review. In 2010, as a results of Resolution A37-19, CAEP began the development of new certification standards for particulate matter and CO_2 emissions (see Section 1.4 for a review of their climate change impact). In 2012, a metric for CO_2 was agreed upon. In 2013, CAEP approved the requirement for an official ICAO "Aircraft CO_2 Emissions Standard" and also agreed to deliver the full standard at the CAEP 10 meeting in 2016 [61]. As an environmentally-responsible member state, it is critical that Canada and its regulator, namely Transport Canada, seriously consider taking action to adopt this new aircraft emissions standard.

While new certification requirements are typically enforced only on new state-of-the-art technologies that have yet to be certified, we must also consider the possibility of enforcing emissions and efficiency requirements on the existing fleet. This may result in forcing fleet renewal and/or retrofits if more efficient alternative technologies are available. There are two reasons for this: first, the urgent nature of the climate change crisis calls for urgent action, and second, aircraft and engine technology typically remain in the fleet for multiple decades, implying that new certification standards will not have a major impact for many years to come. It has been estimated by Dray *et al.* [30] that if all aircraft in the current fleet were (hypothetically) replaced with the present state-of-the-art, an immediate 10% reduction in CO_2 emissions from aviation would result.

Thus, it may be prudent to subject the aging members of the fleet to periodic emissions and efficiency control tests. The implication of failing a test would be similar to an airworthiness directive in that if corrective action is not taken in a timely fashion, the Certificate of Airworthiness of the given aircraft is revoked. This approach would require significant economic and environmental research prior to implementation, particularly in establishing the performance standards that justify replacement, economic ramifications, and associated penalties, a job well-suited for ICAO. A simpler, but more aggressive alternative would be to establish regulations for aircraft and engine retirement. This could be achieved by setting an upper limit on the age (or maximum number of cycles) of the aircraft and engines in the fleet, directly imposing a fleet renewal/upgrade timeline on the operators. As discussed in Section 2.5.5, it may be possible for the government to subsidize fleet renewal through a carbon pricing system.

2.4 Aviation Safety and Certification of New Operations and Systems

In order to meet the increased certification standards discussed in the previous section, airframe and engine manufacturers will propose innovative and unconventional technologies, many of which are discussed later in this review. Historically, the aviation industry has been slow to implement radical design changes; a good example is the use of carbon fiber materials in place of metals, which took decades to gain sufficient confidence and know-how prior to full scale deployment on aircraft. As far as climate change is concerned, time is not on our side, and the need to accelerate the development and deployment of technology requires an acceleration of the certification and testing process.

Any attempt, however, to accelerate the certification of new operations and systems must be uncompromising in ensuring the safety and reliability of the new technology. Any increase in the number of incidents would be completely unacceptable, and may ultimately slow the progress of the industry.

2.5 Putting a Price on Carbon: Market Based Measures

At the 38th Session of the ICAO Assembly in 2013, more than 170 member states and international organizations pledged to develop a global Market Based Measure (MBM) applicable to the aviation sector [1]. A global MBM scheme is to be developed such that it puts a price on aviation emissions (focusing primarily on CO_2) with the goal of incentivizing significant reductions in climate change impact. The objective is to assign an economic value to our environment and to send a signal to the aviation industry to focus on its climate change impact. Ideally, MBMs will spur growth in clean technology development. In this section we will discuss two MBMs for putting a price on carbon in the context of the aviation industry. The first is the carbon taxation approach and the second is the cap-and-trade (or Emissions Trading System, ETS). Before discussing the two approaches, we first review the motivation and the current state of MBMs in aviation.

One of the motivations of employing MBM approaches, as opposed to non-MBM approaches (such as the certification standards presented in the previous section) is that they provide a more flexible and cost-effective means for reducing aviation's impact on climate change. They give companies the flexibility to reduce emissions in a way that best suits them, as opposed to strict certification requirements which dictate either the amount of emissions to be reduced or, potentially, the technology to be used. They run the risk, however, that companies may choose not to reduce their emissions at all, but rather resort to other means of compensating for the additional cost of doing business (such as passing the cost on to the customer). Ultimately, both non-MBM and MBM approaches must be combined to drive the action necessary for reducing aviation's climate change impact.

While some parts of Canada have yet to implement any form of carbon pricing, a few provinces and many other jurisdictions around the world have started taking significant action: as of May 2014, 39 national and 23 sub-national jurisdictions had implemented or were scheduled to implement a carbon pricing scheme [77]. However, it is important to note that, with the exception of the EU ETS, international aviation has been entirely exempt from all existing initiatives.

2.5.1 Existing Initiatives in Canada

The following presents a brief summary of some of the provincial carbon pricing initiatives underway in Canada:

- The government of British Columbia has had a carbon tax in place for the past seven years that has shown impressive results, including reductions in CO_2 emissions in the province without evidence of economic slowdown [33]. However, jet fuel used for flights departing and arriving from outside of the province (which accounts for the bulk of aviation's consumption) are not taxed [33].

- The government of Alberta has a system in place that focuses on emission-intensity reductions, offsets, trading in market instruments, and technology innovation. A review by Taylor [96] suggests that Alberta has positioned itself to achieve dramatic GHG emission reductions over the next years and decades.
- The government of Quebec established a cap-and-trade system in 2013. The program currently applies to large electricity generators and industrial facilities; however there are plans to include transportation and heating fuels in the near future [77].
- Ontario joined Quebec and British Columbia (at the United Nations Framework Convention on Climate Change in December 2014) by committing to collaborate on reducing mid-term GHG emissions. In early 2015, the Ontario government made it clear that putting a price on carbon will be part of their new climate change strategy [77].

2.5.2 The ICAO Strategy

In a recent book authored by Abeyratne [1], titled "Aviation and Climate Change: In Search of a Global Market Based Measure", he addresses the complexities, sensibilities and possibilities of developing a global MBM for aviation, with focus on ICAO's development strategy. Abeyratne's message is that ICAO's MBM scheme should be "coercive, enforceable and within the philosophy and meaning of the Chicago Convention" [1]. Insofar as Canada is concerned, regulators and politicians should closely follow and participate in ICAO's development of such a strategy. Information to date includes the following list that will guide the development of ICAO's global MBM strategy. According to ICAO Resolution A38-18 [59] (repeated verbatim) the new global MBM will:

- support sustainable development of the international aviation sector;
- support the mitigation of GHG emissions from international aviation;
- contribute towards achieving global aspirational goals;
- be transparent and administratively simple;
- be cost-effective;
- not be duplicative and international aviation CO_2 emissions should be accounted for only once;
- minimize carbon leakage and market distortions;
- ensure the fair treatment of the international aviation sector in relation to other sectors;
- recognize past and future achievements and investments in aviation fuel efficiency and in other measures to reduce aviation emissions;
- not impose inappropriate economic burden on international aviation;
- facilitate appropriate access to all carbon markets;
- be assessed in relation to various measures on the basis of performance in terms of CO_2 emissions reductions or avoidance, where appropriate;

- include *de minimis* provisions;
- where revenues are generated from MBMs, it is strongly recommended that they should be applied in the first instance to mitigating the environmental impact of aircraft engine emissions, including mitigation and adaptation, as well as assistance to and support for developing States;
- where emissions reductions are achieved through MBMs, they should be identified in States' emissions reporting; and
- take into account the principle of common but differentiated responsibilities and respective capabilities, the special circumstances and respective capabilities, and the principle of non-discrimination and equal and fair opportunities.

ICAO's current vision is to implement the resulting scheme (which will include either an ETS or a taxation strategy [1]) by 2020. With regard to its implementation, ICAO recommends three types of legal mechanisms, including: 1) international treaties, 2) assembly resolutions, and 3) standards contained in the annexes to the Chicago Convention [1]. Any member state that ratifies the global MBM scheme would then be legally bound to it. If Canada takes such action when the time comes, it would be considered a significant step forward towards reducing the Canadian aviation sector's impact on climate change.

2.5.3 The Cap-and-Trade Approach: an Emissions Trading System

The cap-and-trade (or ETS) approach provides a means by which to limit (or cap) the total quantity of anthropogenic emissions. The metric thus far in most cap-and-trade systems is based on tonnes of CO_2. At the core of a cap-and-trade system, a polluter (typically large scale businesses) must obtain permits in order to legally pollute. The permits are obtained from a governing body which typically provides a certain number of free permits to the polluters on an annual basis (based on some selected level of emissions deemed appropriate for the given polluter). When a polluter runs out of their allocated permits, it must either cease polluting, or purchase additional permits. For example, in the EU ETS there are two methods by which a polluter may purchase additional permits. The first method is through a carbon trading market in which the buying and selling of permits between polluters can occur across industries and jurisdictions. The second is through an auctioning system in which the polluter purchases permits directly from the governing body, who then uses the revenue for a given purpose (Section 2.5.5). The world's carbon market is estimated at over 60 billion USD [18].

As mentioned, the only governing body to incorporate aviation into a cap-and-trade system has been the EU through its ETS system. If, for any reason, ICAO fails to produce a viable global MBM in a timely fashion, then the EU ETS could be used by Canada as a model for the incorporation of aviation into its own MBM system. The EU ETS attempts to have the following general characteristics [104]:

1. The key objective of the policy is to limit emissions, not to raise revenues.
2. Allowances (or permits) are allocated for free or through an auctioning system, with the auctioning system now being the preferred method. As of 2013, more than 40% of all allowances were obtained via the auctioning system, with this share rising progressively each year [35].
3. In 2012, the aviation sector was allocated 97% of the average CO_2 emissions from the 2004-2006 period, reduced to 95% for the period from 2013-2020.

4. All of the revenue raised by the EU ETS is to be spent by EU Member States on climate change mitigation and adaptation.

The cap-and-trade approach has several advantages. First-and-foremost, unlike a taxation system (described in the next section) the cap-and-trade system guarantees that total emissions will not exceed the specified cap. This, in turn, requires monitoring, reporting, and enforcing through legal action if and when member parties do not obtain the required permits. Over time, the cap is expected to decrease in order to further reduce climate change impact. The cap-and-trade system affords the aviation industry with the greatest flexibility and is considered to be the most cost-effective way to pay for carbon emissions. Arguably, it may be too flexible, and the cap-and-trade system may result in having no effect on aviation's emissions (see below). However, by setting a global (or jurisdictional) cap on total emissions, reductions must come from somewhere (such as other industries), and insofar as the atmosphere is concerned, it does not matter from which industries the reductions are achieved.

This leads to the likely scenario in which the aviation industry is put at a relative disadvantage in relation to other industries. This is because it is inherently more difficult and expensive to reduce emissions from the aviation sector (ultimately through new operational strategies and technologies) then it is from other industries, particularly in the transportation sector. One can therefore expect that money will flow more readily from the aviation industry to the governing body (through an auctioning system), or to other industries that find cheaper and faster ways of reducing emissions (through an open carbon market). In essence, the aviation industry is not a low-hanging fruit, and will likely take a back seat while other industries reap the benefits (at least initially). Aviation's relatively high growth rate, as discussed in Section 1.3, also presents a challenge to its incorporation into a cap-and-trade system, which selects a cap level for each industry in a somewhat arbitrary fashion.

Perhaps one of the greatest disadvantages of the cap-and-trade system is in its legal and administrative complexities. The carbon market and auctioning system require significant resources and legislature for their operation, as does enforcing compliance. To establish a global system would require widespread agreement on many policies and legalities, and may significantly slow or even prohibit its implementation.

A cap-and-trade system that uses an open carbon market is inherently political, in that the carbon market opens itself up to potential bilateral and multilateral agreements between non-competing industries and/or nations. For example, the locomotive industry may strategically choose not to sell their extra permits to the aviation industry (its competitor in regional transportation services).

The current cap-and-trade systems around the world are still in their infancy, and with time, as the systems are updated and revised to improve their efficacy, they will mature and ultimately become ingrained in the business strategies of the industries which fall under their legislation. Time will tell if the aviation industry will remain under the EU ETS and whether ICAO chooses to recommend a cap-and-trade system as its global MBM strategy.

2.5.4 Carbon Taxes on Jet Fuel

The principle of an environmental tax on jet fuel is to charge polluters (the airlines whose aircraft consume the jet fuel) in order to compensate for their environmental damage [43]. At its core, when an airline consumes a unit of kerosene, the airline must pay a prescribed amount set by a governing body in order to counteract the societal costs of burning the kerosene.

This immediately highlights one of the difficulties of the carbon taxation approach: how much should regulators charge? If the tax is too high, the concern is economic slowdown, and if it is too low, airlines are not likely to take any additional action to reduce their carbon emissions (beyond the business-as-usual efficiency gains). However, it has been shown that an effective balance can be achieved.

In BC's carbon tax system, for example, the tax was initially set at \$10 per tonne of CO_2, subsequently raised by \$5 per year thereafter until it reached \$30 per tonne (roughly 7 cents per litre of gas) in 2012 [33]. The result was that BC's per capita consumption of fuels subject to the tax declined by 19% compared to the rest of Canada. At the same time, its economy kept pace with the rest of Canada's [33]. Note that most carbon tax systems include a plan to increase the tax over time, in order to promote further reductions in emissions. While this also increases the cost to airlines over time, the fixed schedule provides a far more predictable economic structure for the airlines, particularly when compared to the cap-and-trade systems that involves the potentially volatile trading or auctioning of permits.

Furthermore, whereas the complexity of a cap-and-trade systems can take years to sort out and implement, the relatively simple carbon tax can potentially be implemented in a much shorter time frame. It does not require the same level of complex negotiations that are required to determine the number of permits to allocate and distribute. It is easy for the general public to comprehend, and it is easy to apply in a fair and consistent manner across all industries. Noncompliance is also much less of an issue, particularly in the aviation sector, where in order to burn the fuel, the tax will have already been paid at the time of its purchase.

Carbon tax is often seen as good policy by environmental advocates, but as bad politics on parliament hill. Many expert environmentalists and law makers highly recommend the carbon tax approach and consider it to be excellent policy [43, 1]. From a political standpoint, it is often argued by politicians that a carbon tax would be a job-killing initiative that would immediately slow the economy. However, there is little evidence to support that claim, and some studies have shown that little to no negative effects are observed [33, 92]. For further discussion on the various advantages and myths surrounding carbon taxes, see a review by Rivers [92].

Perhaps the greatest obstacle to the widespread application of a carbon tax, particularly as applied to the aviation sector, is that it is labelled a "tax" in the first place, particularly since a tax on jet fuel is prohibited under the Chicago Convention. To circumvent the issue, Abeyratne [1] recommends a government permit approach, somewhat similar to the cap-and-trade approach, but without the cap. The government would sell permits for each unit of fuel consumed, which must be purchased at a given dollar value by the consumer (and could be traded amongst consumers as well). Abeyratne argues that a charge could be designed such that it acts the same way as a tax, but remains in accordance with ICAO policies [1].

One of the primary disadvantages to the carbon tax system is that, without a cap, it is virtually impossible to predict the degree to which emissions will decline. While it provides more certainty to airlines as to their annual expenditures, it provides less certainty regarding the industry's reductions in climate change impact. The same is true of cap-and-trade system in which aviation is one of several consumers. It may, however, be possible to alleviate such uncertainty by reinvesting the revenue generated from a carbon tax back into the aviation industry to be used for climate change mitigation programs.

2.5.5 Allocation of Revenues

In both a carbon tax system and a cap-and-trade system that employs an auctioning platform, significant revenue would be generated by the paying polluters. In the case of airlines worldwide, the value would likely be on the order of billions of dollars. The question is then: how should the governing bodies distribute or allocate the revenue stream that results? A few approaches are reviewed in this section, with varying influences on climate change impact.

The first approach could involve distributing the carbon revenue generated by air travel back to the citizens of the given member states. For example, the federal government of Canada could issue equal annual payouts to all Canadians. This approach is not recommended as it would provide no additional benefit to climate change. While it is likely a strong political move, it creates a situation in which the airlines effectively pay twice: they must pay the carbon tax, and also fund its abatement [43].

A more effective approach would be to use carbon tax revenue to directly finance technology and operational R&D projects aimed at reducing aviation's climate change impact. Several promising technological avenues are discussed in the remainder of this review. Ideally, the revenue would be invested in a balanced portfolio of short, medium, and long-term R&D projects that span the technology readiness levels. Ultimately, this revenue would help the airlines, by assisting in the development and actualization of more efficient operations and technologies that burn less CO_2 and hence reduce their expenses. The importance of such funding in the aerospace industry is discussed further in the next section.

Finally, Dray *et al.* [30] have proposed and modelled an interesting approach that uses carbon tax revenue to subsidize fleet renewal. The idea is to assist the airlines in upgrading their aircraft and engine technologies more frequently, in turn increasing the efficiency of the overall fleet. This has the added advantage of spurring more business and revenue for manufacturers who can use the additional revenue for the purpose of R&D. While not discussed in [30], this approach would work best in conjunction with government regulations for fleet renewal timelines and certification standards for emissions and fuel efficiency. Regulations for fleet renewal may be based on the age (or number of cycles) of the aircraft and engines, or perhaps on standardized emissions and efficiency tests. Any aircraft in the fleet that fails to pass such tests would be either forced to retire, or be repaired and/or retrofitted such that it passes the tests.

As a final note, it is worth reiterating that putting a price on carbon using MBMs alone will not sufficiently drive the necessary action. The additional cost of carbon does not guarantee that the aviation sector will take action to reduce emissions, but rather, that they will take action to address the added expense by whatever means they see fit, including passing the cost directly to the customer, or leveraging any available financial avenue to purchase and trade additional permits. Thus, government regulations, which can ensure specific reductions, should be combined with MBM measures. Furthermore, these combined strategies may place too large a burden on the direct users of aviation, while societal benefits are realized by a larger segment of the population. This may justify additional government assistance to provide funding for the development of green aviation technologies, as discussed in the next section. Supporting R&D toward such technologies is in the national interest.

2.6 Government Funding for Research and Development

In 2012, the Government of Canada conducted an independent national "Aerospace Review" that was tasked with examining how federal policies and programs can maximize the performance of the Canadian aerospace industry [34]. The review states that the aerospace industry is Canada's second-most research-intensive industry (based on R&D as a percentage of industry GDP). The research necessary to maintain a competitive aerospace industry requires financial investments totalling upwards of two billion dollars per year [99]. This is made possible, in part, by the direct funding of government initiatives. In a submission to the Aerospace Review, Theckedath [99] reviews the various government initiatives and mechanisms employed to fund the aerospace, including:

- Green Aviation Research and Development Network (GARDN)
- Sustainable Development Technology Canada
- Industrial Research Chairs Initiative and Collaborative Research and Development Grants
- National Research Council Aerospace
- Natural Sciences and Engineering Research Council (NSERC)
- Canadian Foundation for Innovation
- Scientific Research and Experimental Development Tax Credit Program
- Canadian Space Agency
- Government Procurement
- Strategic Aerospace and Defence Initiative
- Defence Research and Development Canada

According to Theckedath [99] the federal government's recent investments in the aerospace industry amount to several hundreds of millions of dollars per year. From the above initiatives, the two that are specifically concerned with the development of clean technologies are the GARDN project and the Sustainable Development Technology Initiative. The former was previously discussed in Section 1.6, and the latter includes, but is not restricted to, the aviation sector. It should be noted, however, that mitigation programs may also be funded through the other initiatives, such as Collaborative Research and Development Grants. Significant funding is also provided to private and academic sectors outside of the above initiatives. In essence, these programs establish a framework by which the federal government can provide the necessary funding to aerospace R&D.

Many of the operational and technological ideas worthy of such funding are outlined in Sections 3 and 4 of this report, respectively. These ambitious programs required to mitigate climate change impact will involve advanced and unconventional strategies that require significant financial investment. The federal government must continue to strengthen its assistance to the industry by directly funding initiatives such as GARDN, as well as independent research programs in academia and the private sector. Ideally, future investments in R&D programs will span the range of technology readiness levels and aim to bring conceptual ideas to fruition by connecting the academic and private sectors. Finally, as mentioned in Section 2.5.5, it may be possible for the government to provide this financial support indirectly through an established revenue-generating MBM system which, in turn, may be devised to fund the research from within the industry itself.

The Canadian government and the Canadian aviation industry can take a leadership role in guiding, assisting, and participating in the competitive (but often collaborative) global research effort toward green aviation. The provincial and federal governments of Canada can take the following actions to fund and assist the development of operational and technological mitigation strategies to reduce aviation's impact on climate change:

1. Using existing funding mechanisms (such as NSERC and the others listed earlier in this section), shift the existing resources toward research programs that aim to reduce aviation's climate change impact, in turn prioritizing the industry's climate change concerns.
2. Find a means by which to generate additional revenue (potentially from within the industry itself) by putting a price on carbon through an MBM system. Redirect that revenue to invest in the development of green aviation initiatives and research programs.
3. The government of Canada should collaborate with ICAO in establishing a globally competitive research program aimed at reducing the climate change impact of aviation, with benefits shared the world over. The goal of a globally competitive and collaborative research program would be to identify and accelerate the development of the most promising operations and technologies in order to address the aviation sector's climate change concerns more rapidly.

3 Operational Strategies

3.1 Overview

In this section we review the operational strategies which offer the greatest potential for significantly reducing the climate change impact of the aviation sector. The section begins with a review of air traffic management and the related initiatives and technologies aimed at improving its efficiency. Next we proceed through the various ground and in-flight operational strategies that the industry should consider to reduce its climate change impact, including: various ramp and taxi operations, tailored arrivals for continuous descent, efficient enroute cruise strategies, and novel flight missions. As we shall see, new ground and in-flight operations are inherently linked with air traffic management systems.

Many of the operational strategies that we discuss in this section have the advantage that they can be implemented with today's technology. While advanced technologies and biofuels (which are the subject of Section 4) typically have a higher potential to reduce aviation's climate change impact, they also take considerable time to develop, certify and disseminate into the fleet. In some cases, the two lines of development (operations and technology) are independent; in others, they are inherently entwined. In the discussions that follow, we shall highlight the operational actions for which technological design changes are required.

Studies performed by the Sustainable Aviation Alliance in the UK [95] have attempted to quantify the potential benefit of the various mitigation strategies. Table 1 compares the potential impact of operational strategies, as well as advanced technologies and biofuels on carbon emissions by the years 2030 and 2050. Their assessment estimates that by the year 2050 an overall 13.5% reduction in carbon emissions is possible by increasing the efficiency of air traffic management and flight operations [95].

As a final note, all operational strategies suggested in the following sub-sections are subject to rigorous testing and certification to ensure that they do not jeopardize flight safety.

Table 1: Impact of measures to improve carbon efficiency of UK aviation, by 2030 and 2050, data from [95]. Note that the total is not the arithmetic sum (for example, a 50% reduction on top of a 50% reduction would equal a 75% reduction)

Measure	Fleet Carbon Efficiency Benefit (%)	
	2030	2050
ATM and Operations	7	13.5
Imminent Aircraft	13	17
Future Aircraft	1.5	26
Sustainable Fuels	10.5	24
TOTAL	28.5	59.5

3.2 Air Traffic Management and Related Technologies

Air Traffic Management (ATM) is an important component of modern air transportation. ATM systems are responsible for the safe and efficient gate to gate movement of aircraft around the world. These systems are supported by technologies and procedures for navigation, weather monitoring, communication and flight tracking, as well as air traffic controllers and flight service operators. ATM systems are designed to direct and coordinate the increasingly complex network of flights that criss-cross our planet every hour of every day, through all types of weather systems.

It is widely recognized that there are several opportunities for global harmonization and efficiency gains in ATM, as well as an urgent need to address the rapid growth in air traffic. Note that ATM applies to aircraft traffic in the air and on the ground. Ultimately, the more efficiently the flights can safely move from gate to gate under the instructions of air traffic control, the less fuel they will burn, resulting in reduced emissions and climate change impact. In this sub-section we will review some of the existing initiatives and technological opportunities related to ATM efficiency.

3.2.1 Existing Initiatives

Various initiatives to improve and upgrade ATM systems are underway around the world. It is an inherently international operation, and once again, ICAO plays a vital role. The following presents a brief review of the ICAO, Canadian, American, and European initiatives underway:

- ICAO has published a detailed (128 page) "Global Air Navigation Plan" for the period from 2013-2028 with the following five strategic objectives [58]:

  1. Safety: Enhance global civil aviation safety.
  2. Air Navigation Capacity and Efficiency: Increase capacity and improve efficiency of the global civil aviation system.
  3. Security and Facilitation: Enhance global civil aviation security and facilitation.
  4. Economic Development of Air Transport: Foster the development of a sound and economically-viable civil aviation system.
  5. Environmental Protection: Minimize the adverse environmental effects of civil aviation activities.

  As part of their global plan, ICAO has launched the Aviation System Block Upgrades (ASBU) initiative in an attempt to harmonize, support, and roadmap the communication, navigation, and surveillance technology upgrades around the world. Canada is a strong supporter and advocate of the ASBU framework [102].

- NAV CANADA is the private company that owns and operates Canada's civil Air Navigation System (ANS). NAV CANADA's development plans are "inextricably linked" [24] to ICAO's global harmonization activities. The ANS plan described in [24] provides a detailed year-by-year schedule of technological upgrades from 2013 to 2019.

- Transport Canada's Working Group on Aviation Emissions (which includes NAV CANADA) has recently focused on aspects related to performance-based navigation and surveillance coverage (both will be discussed further below).
- In 2007, the European Commission launched the Single European Sky ATM Research (SESAR) program, which is an ambitious program to upgrade ATM infrastructure and modernize its technologies across Europe [3].
- It is expected that by the year 2025, all aircraft and airports in US airspace will be connected through the US NextGen system [3]. The NextGen system is aimed at sharing information between aircraft and ATM systems in real time with the goal of improving efficiency and safety, as well as absorbing the predicted growth in air transportation [2].

3.2.2 ATM Related Technologies

In Canada, there are two promising technologies that are being considered by NAV CANADA and Transport Canada's Working Group to improve the efficiency of ATM. The first is referred to as Performance-Based Navigation (PBN), which has the potential to revolutionize air traffic management. The basic idea behind PBN is to transition away from the traditional flight navigation techniques that rely on ground-based beacons and towards more reliance on airborne technologies such as global navigation satellite systems [85]. The airborne technologies are more precise and contain altitude information in addition to directional information. Within PBN there are navigation strategies, procedures, and specifications that facilitate more efficient flight navigation by allowing aircraft to follow a precise three-dimensional path. PBN is particularly beneficial for optimizing the enroute climb and descent profiles of departing and arriving aircraft, as well as managing traffic separation through airborne technologies.

As described by the FAA [39], PBN has three advantages to ATM and operations: (i) time and fuel savings with a direct impact on reducing emissions, (ii) more efficient use of the airspace, and (iii) reduced dependence on Air Traffic Control (ATC) for vectoring, altitude, and speed assignment. According to NAV CANADA, the implementation of PBN will result in less variability in the actual path flown by aircraft, which will result in less fuel burn and lower GHG emissions [85]. Ultimately, a PBN approach provides the airspace designer with a powerful tool that facilitates the precise positioning of routes and more efficient instrument flight procedures.

The second technology upgrade considered by Transport Canada and NAV CANADA is related to the surveillance of aircraft. An increased area of surveillance coverage presents the opportunity for more efficient air operations through ATM and will result in reduced fuel burn and GHG emissions [102]. In fact, a majority of the world's airspace is not covered by any real time surveillance [100]. As a supplement to radar surveillance, the Automatic Dependent Surveillance-Broadcast (ADS-B) system is a technology in which an aircraft first determines its own position (using satellite navigation) and then broadcasts that information to ground stations and other aircraft [39]. Current initiatives [102] include increasing the existing volume of airspace covered by the ground-based ADS-B receivers and, more ambitiously, plans to upgrade to the use of space-based ADS-B. The space-based ADS-B initiative is a $3 billion USD collaborative project between the US, Canada, and Europe in which satellites are currently being launched into space with the ability to receive ADS-B broadcasts from aircraft [100]. This, in turn, has the potential to provide global ADS-B coverage while potentially eliminating the need for ground-based ADS-B infrastructure [100].

3.3 Ground Operations

3.3.1 Ramp Operations

Commercial transport aircraft require power while on the ground, both when parked at the gate and taxiing to and from the runway. Electrical power at the gate is required for the purposes of powering environmental systems (heating and cooling), and providing power for the crew as they perform their cabin, kitchen galley, and preflight tasks. Traditionally, the necessary power is generated by an Auxiliary Power Unit (APU), which is a small gas turbine engine located in the tail section. Furthermore, larger aircraft require pneumatic power (bleed air) from the APU in order to start their main gas turbine engines. All the while the APU is burning jet fuel, which it obtains from the fuel tanks on board the aircraft, and producing unwanted aviation emissions, noise, and reduced local air quality.

As such, Canadian airlines and Transport Canada's Working Group [101] are taking action to reduce their dependence on APUs by providing a means of connecting directly to ground power sources. The advantage to using ground sources is that they can supply power that has been generated by more efficient and cleaner technologies. This power link may be achieved either by mobile Ground Power Units (GPUs) or sources built into the terminal itself. For example, at Tokyo-Haneda airport, ground power feeds are built right into the surface of the apron for direct connection to parked aircraft [94]. In addition, at an increasing number of airports, large yellow tubes can be seen connected to the fuselage of parked aircraft; these are filled with Pre-Conditioned Air (PCA) and are used to provide the environmental control required inside the cabin without reliance on the aircraft's APU [103]. PCA equipment is currently being deployed at various airports across Canada [103]. Finally, for initial engine start-up, it is also possible to avoid the use of the APU via Ground Support Equipment used to spool up the first gas turbine engine (of a multi-engine aircraft). Subsequent engines are then started by cross-feeding bleed air from the engine that was ground-started. As a final note, in Section 4.6, we will discuss the development of electric fuel-cell APU technology.

3.3.2 Taxi Operations

The taxiing of aircraft to and from runways has a significant contribution to the fuel burn and emissions at airports. The quantity of fuel burned is dependent upon a number of factors, including: how many engines are running, throttle settings, and pilot/airline decision making regarding engine shutdown during delays [10]. A study at MIT [10] found that it is becoming increasingly common for flights to have lengthy taxi-out times (greater than 40 minutes) particularly at busy airports. For flights within Europe, aircraft spend between 10-30% of their flight time taxiing, with the short-to-medium range Airbus 320 consuming 5-10% of its fuel on the ground. To alleviate the fuel burned due to taxi operations one mitigation strategy underway is looking at improving the ground-based ATM strategy and surveillance technologies to better prioritize, schedule, and direct ground traffic, in turn reducing the taxi-out times and departure queues [101].

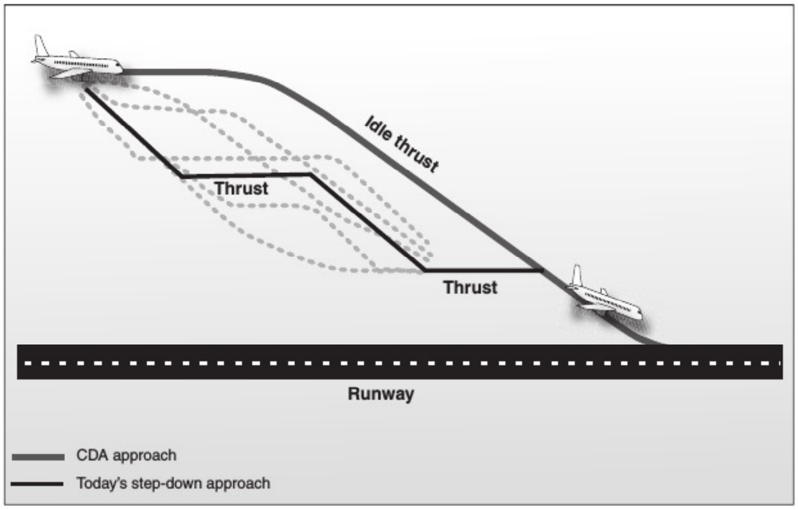


Figure 7: Continuous vs step-down approach profiles, source: [28]

A second mitigation strategy is the so-called "taxibot" approach which stands to revolutionize taxi operations at airports around the world. A taxibot is a pilot-controlled ground vehicle that tows the aircraft by the aircraft's nose-wheel to and from the runway (including push-back from the gate), thereby keeping the engines of the aircraft shut-down for the entire duration. Pilots steer the taxibot using their aircraft's nose wheel tiller (as they normally would) and the taxibot then translates nose-gear deflections into directional changes through a turret upon which the nose wheel sits; no modifications are required to the aircraft in order to employ a taxibot. Reductions in emissions are achieved, since the engines of the taxibot (which can be diesel-electric) burn considerably less fuel than the aircraft's gas turbine engines. A Canadian taxibot initiative has begun through WestJet at Vancouver International Airport [102].

3.4 Tailored Arrivals for Continuous Descent

Continuous descent operations allow aircraft to descend uninterrupted at very low engine power, in turn promising significant fuel burn and emissions reduction during that phase of the flight mission. During the descent phase, an aircraft must reduce engine power and begin bleeding off its airspeed as it transitions from cruise to a final approach configuration. Traditionally aircraft fly a step-ladder descent profile (depicted in Figure 7) as the pilots receive incremental altitude, speed, and heading instructions from the terminal and arrival air traffic controllers. Whenever the aircraft levels off (at each new step), additional engine power must be applied in order to maintain a constant altitude and speed. Current ATM systems and procedures, particularly in heavily congested airspace, require this type of approach for traffic separation. Unfortunately, the constant application of power results in relatively high fuel burn as compared to a continuous descent approach.

Tailored arrivals is a concept that enables the actualization of continuous descent under constrained airspace conditions [22]. In fact, one of the objectives of the US NextGen ATM system is to accommodate the more efficient trajectory-based arrivals under all traffic conditions [22]. This may be accomplished through what is known as Controller-Pilot Data-link Communication (CPDLC), which provides a more direct link between ATC and the aircraft's Flight Management System (FMS). CPDLC allows for the controller's waypoint, altitude and speed restrictions to be sent directly to the flight deck, where it is approved by the pilots, and directly fed into the aircraft's FMS, all in real time. Over 1700 trials have been conducted to demonstrate the feasibility of tailored arrivals for continuous descent using Boeing 777 and 747 aircraft at San Francisco airport [22, 3]. The trials, reported on by Coppenbarger *et al.* [22], included dynamic continuous descent trajectory solutions in the presence of complex airspace constraints. Significant fuel burn savings of up to 40% for the arrival portion of the flight missions have been demonstrated [3], in turn resulting in significant reductions in aviation emissions. Finally, an additional motivation to pursue the use of continuous descent approaches is that the resulting profiles tend to keep aircraft at higher altitudes as they overfly populated areas enroute to the airport, as shown in Figure 7, resulting in potentially significant noise reduction.

3.5 Flight Missions and Enroute Cruise

3.5.1 Reduced Vertical Separation Minimum

Improved operational efficiency has been made possible by reducing the vertical spacing between aircraft during enroute cruise. Prior to 2005, the air laws specified a minimum vertical separation of aircraft equal to 2,000 ft for cruise flight levels between 29,000 and 41,000 ft (which is typical for medium and long range transport aircraft). Since 2005, as endorsed by ICAO, a new Reduced Vertical Separation Minimum (RVSM) equal to 1,000 ft was implemented simultaneously across North America. The new RVSM allows for more efficient flight trajectories and has the effect of doubling the available airspace at cruise flight levels. Recent research by Malwitz *et al.* [71] modelled the effects of employing RVSM and quantified its benefit on climate change. They predicted that (over the domestic US) the resulting fuel burn reduction amounts to 1.8% ($\pm$0.5%), with a NO_X reduction equal to 3.1% ($\pm$1.2%). RVSM is an excellent example of improving the efficiency of in-flight operations with a direct benefit to aviation's climate change impact.

3.5.2 Altitude and Speed Considerations

There is considerable discussion in the aircraft design literature concerning the benefit of flying at lower altitudes and speeds [109]. This operational strategy would typically require a redesign of the aircraft for slower speeds. By cruising at lower altitudes the negative climate change impact of NO_X, contrails, and cirrus-cloud formation are all greatly reduced. Moreover, the reduced speed can lead to reduced fuel burn. The trade-offs involved with this approach are quite complex, particularly when aircraft redesign is at play. Design optimization studies carried out by Antoine and Kroo demonstrate the interdependencies [9]. For example, the reduction in climate change impact achieved through NO_X, contrail, and contrail-cirrus may be counteracted by an increase in CO_2 emissions [9]. It may be possible, however, to achieve a reduction in CO_2 emissions through the redesign of the aircraft. Design changes such as lower sweep-back of the wings, reduced structural weight, and natural laminar flow will be discussed further in Section 4. Flying at slower speeds has two additional consequences. The first is airspace congestion and flight planning which must be coordinated with the ATM systems, and the second is of a more social nature, in that the flying public may not be supportive of longer flight times or the potential for more in-flight turbulence.

Ultimately, further research and trade-off studies are required to determine the net climate change effect that results when redesigning aircraft to fly lower and slower. While flying lower primarily helps with NO_X, contrails, and contrail-cirrus formation, the degree to which it effects CO_2 must be fully accounted for. Moreover, it is critical that we invest in increasing our scientific understanding of the climate change impact of aviation emissions, particularly contrails and contrail-cirrus, in order to make informed decisions regarding such operational strategies.

3.5.3 Contrail Formation Avoidance

In the same vein as the previous mitigation strategy, flight path modifications to avoid the formation of contrails (and hence contrail-cirrus cloud) can be employed with a potential net reduction to aviation's impact on climate change [45]. The idea is to first detect the atmospheric conditions in which an aircraft would generate persistent contrails (as discussed in Section 1.4) and then proceed to dynamically alter the aircraft's flight path to avoid (or escape) such regions. This presents a design trade-off in that additional fuel burn (and hence emissions) are required to perform such diversions. As mentioned in Section 1.4.1, if additional research into contrails and contrail-cirrus cloud formation should quantify their radiative forcing with a higher degree of certainty, then it may be determined that a contrail avoidance strategy is worth implementing. This may pose potential air traffic issues, or at least a higher demand on ATC, particularly with the reduced vertical separation between aircraft. However, it is not unlike the common request made by pilots to maneuver out of a particularly turbulent region of the atmosphere.

3.5.4 Large Aircraft for Short Range

The larger transport aircraft in the fleet today have been optimized for long-range flight and are capable of travelling distances in excess of 10,000 km. A study by Kenway *et al.* [63] has considered reducing aviation's environmental impact by designing and operating large aircraft on shorter-range flights. As background for this research, they found that more than 90% of high-traffic routes flown by airlines cover distances less than 3,000 km. As such, Kenway *et al.* [63] considered the design optimization of a Large Aircraft for Short Range (LASR) capable of transporting 300 passengers. The LASR was designed for a range of about 5,500 km; an Airbus 330 with a passenger capacity of 293 has a maximum range of about 13,000 km. When the aircraft is redesigned for shorter range, significant efficiency gains were found. Since the large aircraft is not required to cover a long distance, it can be redesigned such that it does not need to carry as much fuel, which itself represents a significant portion of the take-off weight.

Figure 8 compares the resulting LASR aircraft configuration to an Airbus A330 and the Airbus A320. The A320 would be more commonly used for the 5,500 km flight range. The resulting LASR aircraft was found to provide a reduction in GHG emissions per passenger-km of flight of 5% compared to the A320 and 13% compared to the A330 [63]. An advantage to this operational strategy is that no new advanced technologies are required. The aircraft manufacturers would need to resize various components of existing aircraft technology (such as the wings, which no longer need to store as much fuel). Thus, this approach provides a mitigation strategy that is realizable in the near-term. Finally, the LASR strategy has the potential added benefit of reducing the total number of aircraft in the sky for the same passenger

Figure 8: Planform view of LASR (left), A330 (center) and A320 (right), source: [63]

demand, in turn reducing airspace congestion and alleviating some pressure on ATM systems.

3.5.5 Multi-Stage Long-Distance Travel

Another environmentally responsible operational strategy is that of using medium range aircraft for multi-stage long-distance travel [3]. The principal advantage of breaking up the long distance flights into multiple shorter flights is that the aircraft need not carry the entire weight of fuel required for the whole journey. Instead, at each stop, the aircraft may refuel for the next stage. The resulting reduction in take-off weight significantly reduces the overall fuel burn and emissions of the long-distance trip, even when accounting for the fuel required for multiple take-offs, enroute climbs, and descents. For example, when a 15,000 km trip is broken up into three 5,000 km stages, it was found by Hahn [49] that the overall fuel burn may be reduced by up to 29%. In contrast to the LASR project, this mitigation strategy might add significant workload to the ATM systems.

3.5.6 Air-to-Air Refuelling

In order to eliminate the multiple stops required in multi-stage long-distance travel, one approach that has been proposed by several researchers [78, 2, 51], is to employ air-to-air refueling of commercial aircraft. Figure 9 depicts the air-to-air refueling operation in which a tanker aircraft is connected to a transport aircraft (in this case, a Boeing 747). A study by Nangia [78] compared various commercial aircraft designed for four different ranges (from 5,000 km to 22,000 km), all with the same passenger capacity of 300 passengers, with and without air-to-air refueling. The study found that short-to-medium range aircraft operating with air-to-air refueling observe a 30-40% benefit in fuel savings (which also accounts for the fuel required by the tanker aircraft). Heesbeen *et al.* [51] are investigating the feasibility and safety of such operations using human-in-the-loop simulations; further R&D is required. Nangia [78] also proposes that air-to-air refueling can be used in combination with a close formation flying strategy.

Figure 9: Air-to-air refueling operation, source: [97]

3.5.7 Close Formation Flying

Canadian geese will fly in V-type formations in order to reduce their energy requirements. This same principle is being proposed as a means to reduce the energy required for commercial air transport. The reduction in energy is achieved by staggering the aircraft such that the position of each aircraft is in the up-wash field generated by the neighbouring aircraft immediately ahead [78]. The idea would be for aircraft on similar flight paths to rendezvous and fly in formation during their cruise segment, subsequently separating as they approach their destinations. The arrival and destination airports of the aircraft in formation need not be the same. Formations with as few as two or three aircraft can result in substantial drag reductions, which translates directly into reductions in fuel burn and emissions [86]. Formation flying feasibility studies have been conducted by Bower *et al.* [16] employing five FedEx flights flying from the Pacific Northwest to Memphis, TN. It was found that average fuel savings of 4% to 12% can be achieved depending on the spacing between wingtips.

Significant R&D is required to bring this mitigation strategy to fruition. The use of close formation flying will require new ATM procedures, air laws, and on-board technologies to achieve a sufficient level of safety, reliability, and automation, without over-tasking the pilots. However, no new airframe or engine technology is needed.

4 Advanced Technologies

4.1 Overview

Commercial aviation is an industry driven by technological innovation. Meanwhile, modern aircraft and engine technologies have matured significantly over the past decades. The conventional tube-and-wing technologies have become highly optimized and further step-changes will require the development and introduction of new and unconventional technologies [109]. The energy required to sustain steady cruise flight depends on the basic forces acting on an aircraft, including: its weight due to gravity, the lift force acting perpendicular to the fight direction, the drag force acting opposite to the flight direction, and the thrust produced by the engines. Thus, in order to reduce climate change impact, designers must seek out technologies that (i) reduce drag, (ii) reduce weight, (iii) reduce engine emissions, and (iv) reduce reliance on fossil fuels.

In this section we review some of the technological opportunities that have the greatest potential for reducing aviation's impact on climate change. Recall from Section 2 that the aviation industry is Canada's second-most research intensive industry. Given the necessary government incentivization and assistance, these significant research efforts will lead to the revolutionary technological innovations necessary to reduce aviation emissions and its impact on climate change. By investing in the development of these technologies, as discussed in Section 2.6, the Canadian government and the Canadian aviation industry can take a leadership role in guiding, assisting, and participating in the competitive (but often collaborative) global research effort toward green aviation. Indeed, many of the technologies presented in this section will combine to play a vital role in allowing the aviation sector to meet its climate change targets, all the while meeting the growing demand for air travel. The technologies reviewed in this section have been divided into the following categories:

- Aerodynamic technologies for reduced drag
- Advanced structures and materials for reduced weight
- Efficient and clean engine technologies for reduced emissions
- Unconventional aircraft configurations – a multidisciplinary approach
- Electric aircraft technologies for reduced emissions and reliance on fossil fuels
- Biofuels for reduced emissions and reliance on fossil fuels

Finally, it must be emphasized that aircraft and engine design are inherently multidisciplinary. Important trade-offs exist between the disciplines that must be understood and accounted for in order to assess the net efficiency gains. Throughout our discussion, we attempt to highlight the various design trade-offs involved with each new technology.

4.2 Aerodynamics

Developing advanced technologies that significantly reduce aerodynamic drag is one of the most important actions that the industry can take to reduce aviation's impact on climate change. By reducing the drag force on an aircraft, we can directly reduce the thrust requirement on its engines, in turn reducing fuel burn and emissions. Moreover, the reduced fuel burn means that less total fuel is needed, which makes the aircraft lighter, and allows us to design a lighter-weight structure. Thus, there is an important cumulative reduction to aviation's climate change impact that is realized by reducing aerodynamic drag.

The two main contributors to the total drag on an aircraft are its induced drag (accounting for approximately 30-40%) and its viscous drag (accounting for more than 50%). The former is associated with the vortices shed primarily from the wing tips as a result of the production of lift. The latter is associated with the viscosity of the air and the frictional effects in a thin layer of the flow near the surface of an aircraft, known as the boundary layer. In this section we will review non-planar geometries for minimizing induced drag, as well as passive and active flow control techniques for reducing viscous drag.

4.2.1 Non-Planar Geometries for Induced Drag Reduction

Non-planar wing geometries present one the most promising approaches to reducing induced drag. The idea is to move away from the planar (or flat) wing designs and toward more non-planar shapes capable of displacing the wing-tip vortices and reducing the air flow interaction that occurs between the lower and upper surfaces of the wing [109]. Some non-planar wing geometries already exist in the current fleet, taking the form of angled, blended, or split-tip winglets that can be seen at an aircraft's wing-tips. It is estimated that winglets can lead to induced drag reductions between 2-5% [64]. However, more research is required to fully understand the design trade-offs involved, as winglets increase the viscous drag and weight of the wing. Other, more unconventional, non-planar geometries have been proposed with the potential to reduce induced drag upwards of 40%. These unconventional geometries, which represent more long-term mitigation strategies, will be reviewed in Section 4.5.

4.2.2 Natural Laminar Flow Control

Natural laminar flow control is a means of designing an aircraft with significantly lower viscous drag than current airframe technologies in the fleet. As mentioned, viscous drag is associated with the boundary layer. The boundary layer on a given surface of an aircraft (such as the wings) begins as a smooth, organized, *laminar flow* and somewhere along the way it transitions to an apparently chaotic, random, three-dimensional *turbulent flow*. The laminar portion of the boundary layer exhibits significantly less viscous drag than does the turbulent portion. Thus, delaying laminar-turbulent transition to a location further downstream on the given surface offers the potential to significantly reduce viscous drag.

Natural laminar flow control is a technique that involves shaping the geometry of wings and aircraft such that they are characterized by extended regions of favourable pressure gradients, giving rise to extended regions of laminar flow. It has the advantage that it can be implemented on present technologies; however, it is typically most effective on short-range aircraft flying at relatively low Reynolds numbers and Mach numbers, with low wing-sweep angles [44]. Nonetheless, for these aircraft, there is potential to reduce the total viscous drag upwards of 40%. In order to realize such benefits, further research in aircraft design must consider ways to smooth, or altogether remove, the protruding geometries that exist on wings (such as control surface hinges and the large flap tracks that sit underneath the wings) that would cause a laminar boundary layer to transition prematurely. Morphing structures, discussed in Section 4.3.5, is a promising means of eliminating such geometric features. Finally, natural laminar flow control may be combined with other flow control techniques (as discussed below).

4.2.3 Discrete Roughness Elements for Laminar Flow Control

For long-range aircraft flying at higher Reynolds and Mach numbers, there are additional challenges to realizing laminar flow. For example, on highly swept wings the prospect of maintaining natural laminar flow is hindered by laminar-turbulent transition due to crossflow instabilities. Thus, a careful balance must be achieved between reducing wing-sweep for natural laminar flow and ensuring other sources of drag do not increase, particularly wave drag due to shock-wave formation. In an attempt to address the crossflow dilemma, a promising flow control technique in early development is that of *discrete roughness elements* distributed near the leading-edge of the wings. The roughness elements attempt to stabilize the crossflow instabilities on swept-wing boundary layers. Preliminary investigations have been performed both numerically [52] and through flight testing [93]. Significant action must be taken to develop both natural laminar flow and discrete roughness element strategies such that they may be reliably and safely deployed in the fleet.

4.2.4 Active Flow Control Techniques

Active flow control is a mitigation strategy that represents one of the greatest technological opportunities to reduce drag, and may pave the way to ultra-low drag aircraft in the decades to come. As such, it is an excellent long-term R&D investment opportunity. The general goal of active flow control is to dynamically alter the flow to reduce aerodynamic drag (by delaying transition and/or reducing turbulent skin-friction drag). For example, engineers are studying pneumatic systems along the surface of the wing that provide boundary layer suction, which has the effect of stabilizing the boundary layer, in turn delaying transition. When combined with natural laminar flow control, this technique is often referred to as hybrid laminar flow control. The ability to employ hybrid laminar flow control has been tested experimentally on the Airbus 320 and Boeing 757 aircraft. Another approach under investigation is to use more advanced actuators making use of closed-loop feedback based on sensors placed on the wing [67]. These actuators are being investigated for the purpose of controlling turbulent boundary layers and to delay the transient growth of instabilities that lead to transition [67]. These active flow control techniques involve additional power requirements, weight, and complexity, which will require significant research in order to assess and optimize their net fuel efficiency gains. It is critical that the development of active flow control technologies be properly supported in order to more rapidly develop these technologies.

4.3 Structures and Materials

Reducing the weight of the aircraft is critical to reducing fuel burn and hence all aircraft emissions. Recall from Section 3.5 that operational strategies also exist to reduce take-off weight. In this section, we review the advanced structures, materials, and related technologies that have significant potential to reduce airframe and engine weight. An engineer's ability to significantly reduce weight is primarily dependent on the continued development of new materials with desirable properties, such as: high strength-to-weight ratio, thermal conductivity, fatigue life, manufacturability, and maintainability [109]. Composites, titanium, steels, and aluminums are used extensively in the design of transport aircraft. Note that, in Section 4.5, we will review various unconventional aircraft configurations (beyond the conventional tube-and-wing) from a multidisciplinary perspective, which includes the structural benefits of such configurations.

4.3.1 Advanced, Hybrid and Super-Alloys

The overall role of aluminum alloys has recently decreased due to the increased use of composite materials (discussed below); however, they remain critical to aircraft and engine design, and continue to be actively developed as a cost-effective option where metals are required. A recent review by Dursun and Soutis [32] calls for more action to research and develop advanced aluminum alloys for airframe structures, including the 2000 and 7000 series aluminums, as well as low-density high-strength aluminum-lithium alloys. By advancing the design and control of chemical compositions, as well as developing more effective heat treatment techniques, engineers can improve the static strength, fracture toughness, fatigue and corrosion of these advanced alloys [32]. It is also believed that advanced hybrid materials, such as fibre metal laminates, may provide promising high-strength and lightweight material options to the aerospace industry, as discussed in [32]. Furthermore, there is a continuing effort to develop superalloy materials for the engine's turbine blades, which must withstand the extremely high temperatures of the flow exiting the combustor. This has the potential to improve the engine's thermal efficiency, in turn reducing fuel burn (as discussed in Section 4.4.1). The advanced materials that are employed (and continuously under development) for this purpose are low-density, creep-resistant, single-crystal, superalloys; further discussion on recent and potential advances may be found in Mackay *et al.* [70]. Ultimately, investment into new aluminum and super-alloys for aircraft and engine structures is necessary in order to provide designers with the lightest, strongest, and most affordable metals.

4.3.2 Advanced Composites and the PRSEUS Concept

Advanced composite materials have become critical to the aviation industry due to their ability to provide a lightweight alternative to the aluminum alloys traditionally employed. In fact, approximately 50% of the total materials used in the design of the new Boeing 787 aircraft are made from composites (the same is true for the new Airbus 350). While composites have become a mainstay in aircraft production, they can be difficult to manufacture and maintain, particularly on large aircraft components, such as wings. Investment in advanced composites and their manufacturing methods is needed to address these challenges. For example, improving the capacity to manufacture composite materials can allow for fully three-dimensional components to be designed, in turn reducing our dependence on laminate plates [109] and further reducing aircraft weight.

In response to NASA's ERA program (introduced in Section 1.6) and the blended wing-body design developed by NASA and Boeing (and discussed in Section 4.5), engineers are developing the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept to address the unique structural and manufacturing challenges of such unconventional aircraft configurations. A comprehensive review of the technology can be found in Velicki and Jegley [107]. The PRSEUS approach "represents a bold vision in composite design theory and oven-cure manufacturing methods. It is a departure from conventional multi-detail laminated and bonded/bolted composite assembly practices, and is an evolution toward larger, one-piece, cocured panel designs with seamless transitions and stitched interfaces" [107]. Investments in technologies such as PRSEUS will pave they way to lightweight, robust, and unconventional composite airframes that will reduce the impact of aviation on climate change.

4.3.3 Additive Manufacturing

New additive manufacturing technologies have the potential to revolutionize the manufacturing process of airframe and engine technologies, particularly for the complex alloy-based components. The bottom-up manufacturing method can be significantly faster than conventional manufacturing methods and "gives the engineer design freedom by removing geometric and processing constraints that are required by conventional manufacturing methods. Additive manufacturing, therefore, has the potential to enable the design and production of low-weight high-performance structures" [62]. In February 2015, engineers at Australia's Monash Centre for Additive Manufacturing (MCAM) successfully printed and assembled the components of the world's first 3D-printed jet engine (as a demonstration of the abilities and speed of additive manufacturing). With sufficient investment and support, engineers believe that within a few years, improvements to manufacturing tolerances and surface finish may facilitate the first ground test of a gas turbine engine made almost entirely of 3D-printed components. It remains to be seen what new weight-saving structural designs may arise given the new-found flexibility that additive manufacturing provides.

4.3.4 Active Load Alleviation

The basic premise of active load alleviation is to employ control surface deflections on an aircraft in flight in order to concentrate the wing's lift forces closer to the fuselage of the aircraft. This strategy includes employing maneuver load alleviation along with dynamic gust load alleviation. By concentrating the lift inboard on the wings, the wings experience significantly less bending stress for the same overall lift requirement [108]. Thus, a wing with active load alleviation can potentially be made lighter, or longer and thinner at the same weight. Various studies have shown that aircraft with active load alleviation can have anywhere from 10-15% longer wing span at fixed weight [108]. The increase in span can result in significant aerodynamic benefits, potentially leading to an 8-13% savings in drag [108]. Furthermore, thinner wings can lead to lower-seep angles on transonic wings, in turn facilitating laminar flow wings (as discussed in Section 4.2).

4.3.5 Morphing Structures

Conventional aircraft make use of hinged flaps and leading-edge slats that effectively change the shape of the wing to deliver the required aerodynamic performance (high lift at low speeds) required for take-off and landing. They also make use of deflecting control surfaces such as ailerons, rudders, and elevators for the stability and control of the aircraft. However, the mechanisms required to actuate and deploy these

Figure 10: The FlexSys morphing wing geometry on a Gulfstream III flight test aircraft with no external flap-track or distinct control surfaces under the wing, source: [40]

devices have a negative impact on the structural weight and aerodynamic performance of the aircraft. Furthermore, the flaps and slats are not employed during the majority of a flight.

Barbarino *et al.* state that "the current trend for highly efficient and green aircraft makes such compromises less acceptable, calling for innovative morphing designs able to provide more benefits and fewer drawbacks" [11]. A morphing structure aims to provide the necessary changes in wing shape, by using flexible skins and distributed actuators. The morphing structure approach has the potential to altogether eliminate the protruding geometries and deflected control surfaces (such as flaps and ailerons), resulting in seamless and continuous wing surfaces. The much smoother wing design has the potential to significantly improve aerodynamic performance, and would help to overcome some of the difficulties in actualizing natural laminar flow in flight, as discussed in Section 4.2.2. Noise generation from the airframe can also be significantly reduced by eliminating slats and flaps. However, the development of flexible materials and their actuation for the purposes of morphing structures is challenging, as the material must be soft enough to be flexible, but strong enough to maintain their shape and carry the aerodynamic loads [11].

In November of 2014, the US Air Force Research Laboratory, in conjunction with FlexSys Inc. and NASA, conducted preliminary experimental flight tests of the so-called FlexFoil morphing wing technology on a retrofitted Gulfstream III aircraft, as pictured in Figure 10. It can be seen that the underside of the wing has no external flap-tracks or distinct control surfaces. Morphing wing shapes for optimal cruise performance at different cruise conditions are also being investigated. However, the complexity, robustness, safety, and maintenance of such systems must be addressed. As such, morphing structures are considered to be a medium to long-term mitigation strategy. Indeed, innovative and reliable structures that are deformable and continuously adaptable in real time and during flight (according to the operational conditions and requirements) will require significant investment moving forward [11].

4.4 Engine Technologies

Improvements in engine technologies have the potential to significantly reduce aviation's climate change impact by improving the overall propulsion efficiency and by developing cleaner combustion technologies. In this section we will briefly review some of the most promising propulsion technologies currently under development.

In order to discuss the various opportunities to advance the state-of-the-art in efficient gas turbine technology, let us consider some additional efficiency metrics. The overall efficiency of a gas turbine engine may be calculated by multiplying three factors: 1) the transfer efficiency, 2) the thermal efficiency, and 3) the propulsive efficiency. Green states that a typical transfer efficiency of a modern gas turbine engine lies between 85% to 88%, with thermal efficiency around 55%, and propulsive efficiency around 84%, giving an overall efficiency of around 40% [44]. The advanced technology concepts that follow are primarily aimed at improving one or more of the three engine efficiency factors. An improved overall efficiency results in reduced fuel burn, but it must be noted that trade-offs in emissions often exist, as will be highlighted throughout. The following review is largely based on an assessment by Green, titled "The potential for reducing the impact of aviation on climate" [44].

4.4.1 High Pressure Ratio and Turbine Entry Temperature Engines

The thermal efficiency of a gas turbine engine increases with the Overall Pressure Ratio (OPR) as well as the Turbine Entry Temperature (TET) [44]. The former is the ratio of the air pressure before and after passing through the compressor stages, the latter is the temperature of the extremely hot flow exiting the combustion chamber. In fact, the limiting factor on TET is the ability of the turbine blade materials to withstand the high temperatures. This continues to drive research into advanced materials (as previously discussed in 4.3.1) and turbine cooling. While OPR and TET have improved significantly with each generation of gas turbines, an important trade-off between fuel consumption and NO_X exists. Green suggests that an upper limit should be placed on the thermal efficiency [44], since increases in OPR result in increases in NO_X emissions. Thus, a reduction in fuel burn at the expense of NO_X emissions may be more harmful to the atmosphere. Certification requirements on NO_X may help guide the appropriate design considerations for engineers; the design objective might be to maximize thermal efficiency (or maximize OPR and TET) while satisfying a certification constraint on NO_X emissions. Further R&D is required to optimize this trade-off. Advanced combustor technologies are also being developed to reduce NO_X emissions, as discussed below.

4.4.2 Ultra High-Bypass Ratio Turbofans

The air passing through a turbofan is split into two annular regions, with a portion of the air passing around the core and another portion passing through the core. The ratio of the amount of air passing through these two regions is referred to as the bypass ratio of a turbofan engine. Propulsive efficiency typically increases with increasing bypass ratio. As such, turbofan technology has evolved over several decades to higher and higher bypass ratios. The main challenges in moving to ultra high-bypass ratios, which typically involves increasing the fan diameter, includes: optimizing the engine such that fan blade tip speeds do not exceed sonic speeds, as well as addressing the increased weight, drag, and size of the larger engine and nacelle. Advanced concepts must be further developed and deployed to address these challenges, such as the geared turbofan and open rotor engine discussed below.

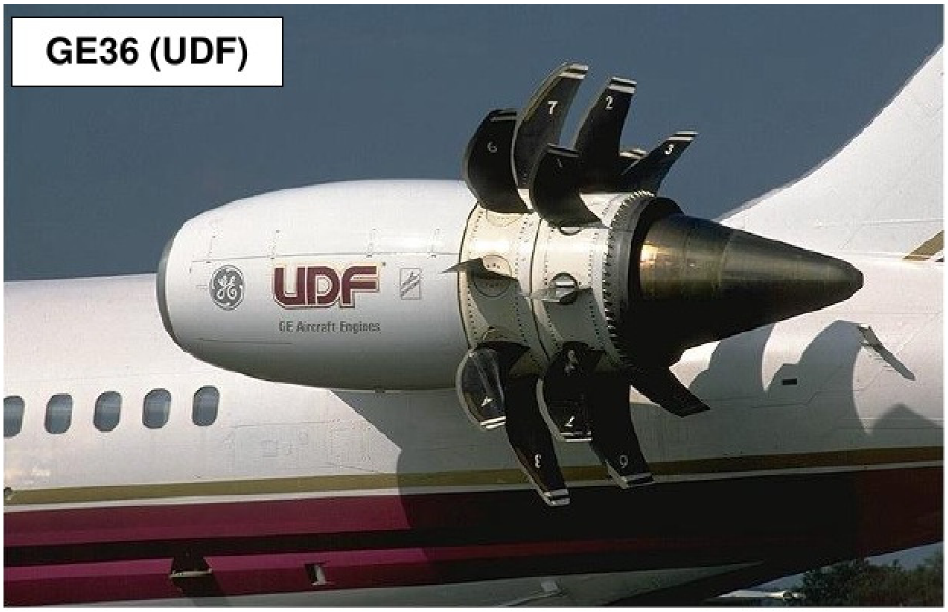


Figure 11: The open rotor concept (experimental GE36 engine), source: [3]

4.4.3 Geared Turbofans

The geared turbofan engine is an excellent example of a best practice that reduces emissions through improvements in efficiency. Examples of the geared turbofan are the Honeywell TFE731, the Honeywell ALF 502/507, and the brand new, much larger scale, PW1000G, which will be used on Bombardier's upcoming C-Series aircraft. In typical turbofans, the low pressure turbine shaft is connected directly to the fan, and they rotate at the same speed. This results in a compromise between propulsive efficiency and thermal efficiency, which results in slower shaft speeds as fans become larger. The geared turbofan engine introduces a gear-drive system that allows the low pressure turbine and the fan to spin at different speeds which can each be optimized independently. Agarwal [3] states that improvements to fuel efficiency may be upwards of 20% as compared to present alternatives.

A further advantage of the geared turbofan is a truly common (scalable) core among aircraft applications [7]. Given a thrust requirement by the airframe manufacturer, an engine manufacturer can quickly develop an engine optimized to the application by simply scaling the core and mating it to an appropriate fan size [7]. This has the potential to reduce development costs of future engine programs, and allows the engine manufacturers to invest more in the R&D of the common core design.

4.4.4 The Open Rotor Concept

The open rotor concept does away with the nacelle and makes use of two rows of counter-rotating propellers, as shown in Figure 11. The advantage over a conventional turboprop is the open rotor's ability to operate more efficiently at higher speeds with smaller blade lengths. This is made possible by having two rows of propeller blades; the second row entrains the flow, delaying its outward expansion, straightening out its direction, and effectively creating a virtual fan case [29]. The open rotor engines are still limited to lower speeds than a conventional turbofan, but allow for higher speeds than a turboprop. The potential efficiency gains of the open rotor concept are significant. Green states that these engines "offer significantly higher propulsive efficiencies, in excess of 90%" [44]. One of the main challenges facing the open rotor design is the high noise levels it produces. Finding a solution to the open rotor noise dilemma is an important area of research which will require innovative solutions.

4.4.5 Advanced Combustor Design for NO_X Reduction

To directly reduce the NO_X emissions from engines and meet the certification requirements on NO_X, as discussed in Section 2.3, engine manufacturers must invest heavily in advanced combustor design. Designing combustors for reduced NO_X formation is a major challenge for combustion engineers [43]. As mentioned in Section 1.4, the formation of NO_X depends on several factors, including: the stoichiometric (air-to-fuel) ratio, the flame temperature in the combustor, and the resident times at the flame temperature. Current NO_X mitigation in aviation gas turbines is achieved primarily by staged combustion configurations such as rich burn / quick quench / lean burn [109]. One of the most promising techniques to achieve ultra-low levels of NO_X is known as lean premixed combustion [65]. The objectives of this approach are to (i) mix the fuel and air thoroughly before combustion and (ii) evaporate all the fuel. This eliminates the burning of liquid droplets of fuel, which reduces flame temperature and eliminates hot spots from the combustion zone [65], in turn reducing NO_X emissions. There are, however, several challenges in applying this approach, including autoignition and flashback, as described in [65]. Significant research efforts are underway in both academic and industrial laboratories to find innovative solutions to address these challenges [109]. With suitable investment in R&D it is believed that NO_X emissions can be greatly reduced, thus enabling the focus to be placed on CO_2.

4.5 Unconventional Aircraft Configurations

The need to improve fuel efficiency, while reducing noise and emissions, has led to the consideration of novel unconventional aircraft configurations. While the standard tube-and-wing has dominated commercial aviation since its beginning, new unconventional configurations promise significant improvements in the overall energy efficiency of flight. As such, they represent an important investment opportunity for the development of technologies capable of significantly reducing the long-term climate change impact of aviation.

In this section we briefly review and compare four of the most promising unconventional aircraft configurations. These designs are being developed by a combination of teams from NASA, industry, and academia. Many of the proposed ideas have sprung from the NASA ERA program, which has contracted teams from Boeing, Lockheed Martin, and Northrop Grumman to study advanced technologies and configurations that could help the aviation industry meet its aggressive environmental goals. In Figure 12, the four configurations are illustrated. These configurations have different variations, currently being studied by many different teams around the world. The following list provides a summary of the configurations and their primary development teams:

(a) Blended wing-body design, source: [80]

(b) Double bubble (D8) design, source: [81]

(c) Box-wing design, source: [27]

(d) Strut-braced wing design, source: [21]

Figure 12: Unconventional aircraft configurations

- the blended wing-body design (Boeing, NASA, and Northrop Grumman);
- the D8 or double bubble design (Massachusetts Institute of Technology);
- the box-wing configuration (Lockheed Martin); and
- the strut-braced wing design (Boeing, Georgia Tech, and Virginia Tech).

The multidisciplinary design approach brings together the disciplines that we have previously discussed in this section, including aerodynamics, structures, and propulsion, as well as other disciplines, such as aeroacoustics, aeroelasticity, and stability and control. The result is a set of configurations with greater performance and energy efficiency than the conventional tube-and-wing design.

Table 2: Performance and drag reduction of the optimized practical designs, data source: [42]

	Conventional tube-wing	C-tip blended wing-body	Box-wing	Strut-braced wing
e	0.9982	1.1730	1.2322	0.9909
Lift/Drag	55.5	84.3	64.9	110.0
Weight [N]	370,068	407,321	395,099	397,336
Drag [N]	6,668	4,832	6,088	3,612
ΔDrag [%]	0	28	9	46

The first configuration (depicted in Figure 12(a)) is the blended (or hybrid) wing-body aircraft. This configuration promises a greatly improved lift-to-drag ratio by seamlessly merging the fuselage and wing sections. This design also facilitates lower structural weight (due to reduced bending moments in the wings), boundary-layer ingestion and distributed propulsion (leading to improved propulsive efficiency), and natural noise shielding [109]. The blended wing-body design is best suited to replace large long-range tube-and-wing transport aircraft.

Another promising configuration, depicted in Figure 12(b), is the D8 (or double bubble) twin-aisle aircraft developed by Drela [31]. The fuselage in this configuration, while distinct from the wings, is a lifting body that contributes to the generation of lift. The aircraft flies at a slower speed than conventional transport aircraft of similar size; this allows for nearly-unswept wings and facilitates natural laminar flow [109]. Boundary-layer ingestion is also facilitated in this design by the rear engine installation that sits between a twin "pi-tail" configuration [31]. In Drela's work [31], the merits of each of these features is evaluated in relation to mission fuel burn through a multidisciplinary design optimization strategy.

Other non-planar configurations that have been proposed include the box-wing and the strut-braced wing configurations, depicted in Figures 12(c) and 12(d), respectively. These configurations promise significant savings in induced drag reduction, while attempting to simultaneously reduce aircraft weight. The box-wing configuration, for example, creates a closed wing system with the engines rear mounted on the aft wing, facilitating the use of high-bypass ratio engines (as discussed in 4.4.2). The strut-braced wing extends a bracing strut from the fuselage to support each wing. The struts, which themselves contribute to lift generation, reduce the aircraft weight and allow for higher span wings, which in turn reduce the induced drag.

In a recent study by Gagnon and Zingg [42], various unconventional aircraft configurations were compared to a conventional tube-and-wing design. This study included a blended wing-body with a C-tip extension aimed at reducing induced drag, a strut-braced wing, and a box-wing design. Aerodynamic shape optimization was employed to minimize the induced drag of each configuration subject to lift and moment constraints; viscous effects were not included in the study. Table 2 from [42] shows the relative performance of each configuration that was studied. The results point to the strut-braced wing as the most promising configuration (of those included in the study), with induced drag reduction on the order of 46% relative to a conventional tube-and-wing design. More research is required (and underway) to refine these studies and to bring such configurations to market.

Also under consideration, as a strategy to further improve the efficiency of unconventional configura-

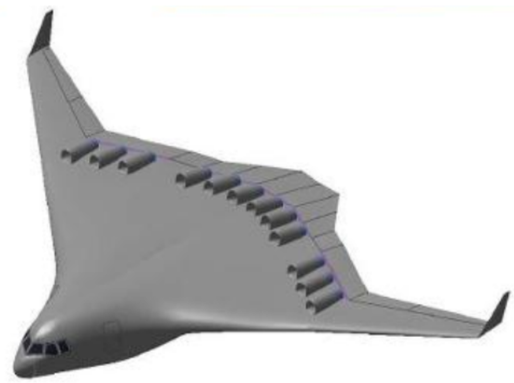


Figure 13: Distributed propulsion system on the CESTOL blended wing-body, source: [48]

tions, is the notion of distributed propulsion systems. For example, NASA and Boeing are considering the application of a blended wing-body in conjunction with upwards of 12 smaller engines that are distributed and partially embedded along the upper-backside of the wing-body [66]. The resulting Cruise Efficient Short Take-Off and Landing (CESTOL) aircraft is depicted in Figure 13. The aim of distributed propulsion systems is to improve fuel efficiency, significantly reduce noise, and reduce the required runway field length for landing and take-off. The CESTOL-BWB would require the development of many new technologies, including revolutionary engine concepts, active flow control inlets, and variable geometry noise reflection nozzles [66]. The distributed propulsion concept also lends itself to the hybrid-electric aircraft concept, thus, the CESTOL concept has paved the way to a very recent concept by NASA called N3-X, discussed further in Section 4.6.

Finally, all of these concepts present their own set of challenges. Addressing these challenges will require further innovation and a well supported and collaborative research effort. The proper incentivization and assistance is required to facilitate these ongoing collaborations in order to accelerate the development and technology readiness of these concepts.

4.6 Electric Aircraft Technologies

Efficient electric power sources may be used to provide a significant portion of the energy required by transport aircraft. This mitigation strategy has significant potential to reduce aviation's impact on climate change, particularly in the medium to long-term. In this section we briefly review some of the electric technologies currently under development.

4.6.1 Towards More Electric Aircraft

The goal of moving towards more electric aircraft is to transfer most or all of the secondary power requirements of an aircraft to electrical power, as opposed to the mechanical, hydraulic, and pneumatic (bleed-air) power sources currently employed. The secondary power of an aircraft in flight is generated by the gas turbine engines and is used to power many systems, with the most safety-critical systems being the fuel pumps, control surface actuators, and the environmental cabin control [15]. With a move toward more electric secondary power systems, the secondary power requirements on the gas turbine engines may be optimized for the efficient production of electricity, in turn improving engine efficiency. In addition, alternative energy sources (such as fuel cells) are being investigated to generate the electrical power required for the secondary power systems, further reducing the power requirements on the gas turbine engines. Ultimately, by revisiting and optimizing the secondary power architecture of an aircraft, there is potential for significant efficiency gains, which will ultimately reduce the fuel burn and emissions of the aircraft.

For example, the prospect of introducing electromechanical and electrohydraulic actuators for the actuation of the flight control surfaces on an aircraft would be a move from the conventional "fly-by-wire" system to a new "power-by-wire" system, representing a step change in the electrical load requirements on an aircraft [15]. The design of such systems presents significant challenges, as the reliability and robustness of the flight control system is of utmost importance to flight safety and must meet a strict set of certification standards [15]. The move to a fully electrical power-by-wire system may lead to the removal of the engine hydraulic pump, in turn transferring hydraulic power requirements to electric power requirements [15]. Furthermore, the removal of bleed air off-takes from the engine will directly result in higher engine efficiency. This strategy will require innovative solutions and new high-voltage electrical networks, such as air-conditioning, wing ice protection, and electric engine start-up [15]. Indeed, significant investment will be required in order to develop the reliable technologies necessary for the wider adoption of electrical solutions on aircraft. In the next two sections we consider the electric APU options for electric power generation and the possibility of distributed hybrid-electric propulsion systems for future transport aircraft.

4.6.2 Electric Auxiliary Power Units

While taxiing or at the gate, an aircraft's power is often supplied by an APU. While some new operational strategies are being proposed to make use of ground-based electrical power feeds (as discussed in Section 3.3), new on-board fully electric and hybrid electric fuel cell APU technology is being investigated to potentially replace the gas turbine APUs that reside in the tail of modern transport aircraft. Furthermore, in moving toward more electric aircraft with very high electric power requirements, these electric APUs are being considered for continuous operation in order to provide electric power while in flight (not only on the ground). For example, a report by Rajashekara [91] proposes the use of a hybrid solid-oxide fuel cell, gas turbine APU (the SOFC–GT APU) for ground and in-flight electrical power generation. The review demonstrates that in conjunction with a more electric aircraft approach the hybrid-electric APU can deliver "large savings in fuel consumption, operating costs, and emissions" [91]. The review also identifies several areas requiring significant R&D to advance the technology readiness of electric APUs, including system weight, safety, and reliability [91].

4.6.3 Hybrid-Electric Propulsion

Several hybrid-electric propulsion technologies are under preliminary study by research teams around the world. In the US, for example, the Subsonic Ultra Green Aircraft Research (SUGAR) program [17] brings together engineers from Boeing, General Electric, Georgia Tech, and NASA to investigate several novel concepts for fully electric and hybrid electric air travel. The potential technologies identified include: fuel cells, hybrid-electric-gas-turbine engines, distributed propulsion hybrid-electric, and low energy nuclear reactor technologies [17]. For example, NASA has extended the CESTOL blended wing-body concept (depicted in Figure 13) to include a fuel efficient distributed hybrid-electric propulsion system. The new concept aircraft has been dubbed N3-X [25] and is under preliminary review. All of the emerging hybrid-electric propulsion technologies seek to significantly reduce the fossil fuel dependence of future air transport systems with corresponding reductions in aviation emissions. These concepts are still in their infancy and will require significant R&D to further investigate and identify their potential benefits, feasibility, and safety for commercial air transport. Nonetheless they offer some exciting prospects for the very long-term environmental sustainability of the aviation industry.

4.7 Biofuels

Biofuels present a significant opportunity to reduce not only aviation's climate change impact, but also the industry's exclusive dependence on fossil fuels. Biofuels are a renewable source of energy derived from living (or very recently living) matter, such as crops, plants, animals, trees, and algae. Unlike fossil fuels, biofuels do not require thousands or millions of years of geological changes [90]. Their use as an aviation fuel is largely motivated by the potential environmental benefits; in addition to being a renewable source of energy, biofuels burn more cleanly than fossil fuels, resulting in significantly reduced emissions [90]. In this section, we briefly review the existing initiatives, potential benefits, and challenges facing the development and use of biofuels for commercial aviation.

In the near term, the ability of biofuels to replace conventional kerosenes is limited. As such, biofuels should not be regarded as a silver bullet solution to reducing aviation emissions [82]. However, with significant effort and investment over the coming decades, it is expected that biofuels will play an important role in reducing aviation's climate change impact. Ultimately, the aviation industry must continue to investigate biofuels as an alternative energy source, while simultaneously developing strategies and technologies that reduce the overall energy requirements of air transportation.

4.7.1 Existing Initiatives

In Canada there are several initiatives underway regarding the research and development of aviation biofuels. One such initiative is the Sustainable Alternative Fuels Evaluation (SAFE) program, which is a public partnership sponsored by Transport Canada, Environment Canada, the Department of National Defence, and the National Research Council, with voluntary engagement from industry and academia [19]. The goal of the SAFE program is to "facilitate and promote introduction and commercialization of sustainable alternative fuels without bias with respect to feedstock and conversion methodology", with special emphasis on emissions evaluation and reduction [19].

There have also been a number of Canadian biofuelled flight demonstrations. For example, in 2012 Porter Airlines flew the first revenue generating flight on a biofuel mix in Canada, and both Porter and Air Canada flew the ICAO Secretary General on bio-fuelled flights enroute to the Rio+20 United Nations Conference on Sustainable Development. Also in 2012, the National Research Council of Canada flew the world's first unblended (100%) biofuel flight. Information collected and analyzed both in flight and on the ground showed a reduction in aerosol emissions upwards of 50% as compared to conventional kerosenes burned in the same engines [83].

In 2007, the government of Canada, through the Sustainable Development Technology Canada program, established the NextGen Biofuels Fund. The $500 million budget has been made available to invest with the private sector in developing large-scale facilities as demonstrators for the production of next-generation biofuels. The goals of the fund are to [84]:

- facilitate the establishment of first-of-kind, large-scale demonstration facilities for the production of next-generation biofuels and co-products in Canada;
- improve the sustainable development impacts arising from the production and use of biofuels in Canada; and
- encourage retention and growth of technology expertise and innovation capacity for the production of next-generation biofuels in Canada.

Unfortunately, the NextGen Biofuels Fund is now in its wind-down phase and is no longer accepting applications for funding. It is recommended that the Canadian government replenish the existing fund or establish a new fund in order to continue investing in the development of large-scale biofuel production technologies with the goal of reducing the climate change impact of the transportation sector, including aviation. However, it is important to recognize that there are other issues besides large-scale production that need to be addressed in order to enable widespread use of biofuels in aviation, particularly with respect to their properties in an aviation context.

4.7.2 Certification of Biofuels for Jet Fuel

The development of biofuels for use in aviation is typically more challenging than in other sectors, primarily due to the safety and reliability demands of aircraft gas turbine engines and the extreme conditions in which they operate. As such, jet fuels are highly regulated by the American Society of Testing and Materials (ASTM) and are subject to a set of strict requirements regarding their combustion properties and characteristics [8]. Furthermore, an important characteristic of aviation biofuels is that they should be compatible with existing aircraft and engine technology [3]. In turn, these so-called *drop-in* fuels can be blended (up to a maximum certified ratio) with conventional kerosene.

To date, three pathways to the production of biofuels suitable for use in aviation have been certified by the ASTM under three annexes of ASTM D7566 [8]. These drop-in biofuels have chemical and combustion properties that closely mimic that of conventional kerosenes [43]. The three pathways are [88]:

- Annex 1: Gas To Liquid (GTL) Synthetic Paraffinic Kerosene (SPK)
  - Process: Fischer-Tropsch Hydrogen Treatment
  - Feedstock examples: biomass, agricultural waste, coal, natural gas, municipal solid waste, and tires
  - Certification: 2009

- Annex 2: Hydrotreated Renewable Jet (HRJ) or Hydroprocessed Esters and Fatty Acids (HEFA)
  - Process: Hydrogen treatment of renewable oils (similar properties to SPK)
  - Feedstock examples: camelina, animal fats, jatropha, canola, algae
  - Certification: 2011
- Annex 3: Alcohol To Jet with Aromatics (ATJ-A)
  - Process: Fermentation of sugars to alcohol, catalytic conversion: alcohol to fuel
  - Feedstock examples: sugar cane, corn, energy crops, woody biomass
  - Certification: 2014

4.7.3 Climate Change Benefits

The potential for biofuels to reduce aircraft emissions is significant. In Table 1 from Section 3, the Sustainable Aviation Alliance in the UK estimates that the use of biofuels in aviation has the potential to reduce CO_2 emissions by upwards of 24% by the year 2050. This value is obtained assuming "a 25-40% penetration of sustainable fuels in to the global aviation fuel market, coupled with a 60% life-cycle CO_2 saving per litre of fossil kerosene displaced" [95]. Furthermore, Agarwal [3] projects that by the year 2050, the use of aviation biofuels has the potential to reduce NO_X emissions by a factor of 10, and contrail and contrail-cirrus formation by a factor of 5 to 15. Indeed, biofuels have great potential in reducing aviation's impact on climate change. While biofuels represent a potentially important component to the overall effort to reduce GHG emissions from aviation, the actual reduction in GHG emissions taking into account the entire lifecycle of the fuel varies greatly depending on the feedstock and many other issues. In general, global metrics that include the entire lifecycle of biofuels are challenging to establish and evaluate, as discussed in the next section.

4.7.4 Production and Economic Challenges

In moving toward large-scale biofuel production, the net GHG emissions resulting from both the supply and combustion of such fuels must be fully accounted for. Such a move would require significant evidence demonstrating that a net GHG emissions reduction is possible in comparison to the supply and combustion of conventional kerosene [43]. Furthermore, the production of biofuels at large scales must not have an indirect adverse impact on food production, forests, or the supply of freshwater through any potential changes in land use. This concept is referred to as Indirect Land Use Change (ILUC) [12]. A review by Bearman [12] presents recent ILUC findings by the EU's Joint Research Centre, which found that the indirect carbon emissions resulting from the production of biofuels from food crops are significantly higher than previously estimated. Further research, a better scientific understanding, and improved metrics for the net environmental impacts are required.

Indeed, the land use needed to produce sufficient biofuels (particularly through to 2050 and beyond) are significant. Recent studies (reviewed by Upham [43]) have estimated that there is and will be sufficient land to cultivate the necessary biomass required across all industries (not just aviation). Researchers such as Doornbosch and Steenblik [43] see the potential expansion as mainly concentrated in Africa and South and Central America, as more than 80% of the available cultivable land is located in these regions. As such, there are social, political and distribution challenges that must be overcome to achieve this global effort. Indeed, while significant progress has been made toward the certification and demonstration of biofuels for commercial aviation, the number of large-scale production plants has yet to take off [12].

Finally, the economic concerns of producing biofuels must also be addressed. Ultimately, if biofuels result in any significant increase in the direct operating cost of airlines, it is unlikely that they will adopt the practice of blending biofuels with conventional kerosenes, or at least not to an extent that will have a significant impact on climate change. As such, significant R&D is required to reduce the costs of producing and supplying biofuels at large scales.

4.7.5 Second and Third Generation Feedstocks

As mentioned, the net effect lifecycle metrics of biofuels are heavily dependent on the feedstocks employed. This continues to motivate the development of second and third generation feedstocks. While first generation feedstocks typically make use of potentially valuable food crops, the goal of developing second and third generation biofuels is to make use of a sustainable resource for the production of an alternative jet fuel without consuming valuable food, and while minimizing the required land and water resources required. Significant investment is required in order to develop the necessary techniques to source and grow these feedstocks at large scales in locations worldwide, while providing more stable and affordable price points. NASA has recently purchased (March 2015) an isobutanol based ATJ fuel for testing in their alternative fuels research program [47]. On a longer term, likely beyond 2025, the ATJ-process based on bioethanol from algae may be a possibility for third generation aviation biofuels. However, significant challenges exist in terms of the water and fertilization resources needed to grow the algae, as well as the volatility of the unsaturated oils found in algae [13].

5 Concluding Remarks

The primary objective of this report has been to inform the Secretariat of the Canadian Transportation Act Review of potential recommendations and actions to mitigate the escalating impact of aviation on climate change. A sustainable aviation sector will require significant and strategic investment to mitigate its escalating impact on climate change. Research for this report has included a thorough review of international best practices, initiatives, and research programs, which have been presented as an organized set of actionable strategies to reduce aviation's impact on climate change. Actions have been divided into governmental, operational, and technological mitigation strategies.

The impact of aviation on climate change was presented in the larger context of sustainable aviation. The various aviation emissions and their climate change effects have been reviewed, highlighting their trade-offs and the current levels of scientific understanding, along with the need for a better understanding in specific areas. The business-as-usual projections presented demonstrate a continuous increase in the climate change impact of aviation as a result of the projected growth of the industry exceeding efficiency gains. Potential government actions have been reviewed, including new regulations, incentives, and assistance. The necessary certification standards and market based measures will require significant global collaboration, with oversight from ICAO, in order to forge an international path forward. When combined with financial support, these actions will drive research and development toward the new technologies required to address climate change in an economically-driven industry.

Next, a number of operational strategies were reviewed with the goal of improving the gate to gate efficiency of flight operations. Strategies were reviewed in the areas of air traffic management, ramp and taxi operations, continuous decent, enroute cruise, and flight mission design. Several of these strategies require no new technologies, representing excellent near-term mitigation options. Finally, the advanced technologies representing the most promising investment opportunities were categorized and reviewed. These technologies have the greatest potential for climate change mitigation and aim to ensure the long-term sustainability of the industry. The advanced technologies were divided into six categories, including: (i) aerodynamics, (ii) advanced structures and materials, (iii) efficient and clean engine technologies, (iv) unconventional aircraft configurations, (v) electric aircraft technologies, and (vi) biofuels. By investing in these advanced technologies, the Canadian aviation sector can take a leadership role in guiding, assisting, and participating in the competitive (but often collaborative) global research effort.

Ultimately, the Canadian aviation sector (including government, industry, and academia) must take urgent and significant action to address its impact on climate change, while responsibly meeting the growing demands for air transport and, in turn, improving the quality of life of all Canadians for the foreseeable future.

References

[1] R. Abeyratne. Aviation and climate change: In search of a global market based measure. *SpringerBriefs in Law*, 2014.

[2] R. Agarwal. Environmentally responsible air and ground transportation. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, number AIAA–2011-965, Orlando, Florida, Jan 2011.

[3] R. K. Agarwal. *Recent Advances in Aircraft Technology*. InTech, Feb 2012.

[4] Air Transport Action Group. Towards sustainable aviation. 2012. Signed on Thursday 22 March 2012, at Geneva, Switzerland.

[5] Air Transport Action Group. *Aviation Benefits Beyond Borders: Global Summary*. 2014.

[6] Airbus. Future concepts. Available at `http://www.airbus.com/innovation/eco-efficiency/design/future-concepts/`. Accessed March 2015.

[7] AirInsight. *Airinsight Technical Analysis: The Core of the PW1000G Geared Turbo-Fan*. October 2012. Available at `http://airinsight.com/2012/10/02/airinsight-technical-analysis-the-core-of-the-pw1000g-geared-turbo-fan`. Accessed March 2015.

[8] American Society of Testing and Materials. Standard specification for aviation turbine fuel containing synthesized hydrocarbons. 2012. ASTM D7566.

[9] N. E. Antoine and I. M. Kroo. Framework for aircraft conceptual design and environmental performance studies. *AIAA Journal*, 43(10):2100–2109, Oct 2005.

[10] H. Balakrishnan and R. J. Hansman. Reducing airport surface operation environmental impacts. In *AeroAstro, the annual publication of the MIT Department of Aeronautics*, 2010.

[11] S. Barbarino, O. Bilgen, R. M. Ajaj, M. I. Friswell, and D. J. Inman. A review of morphing aircraft. *Journal of Intelligent Material Systems and Structures*, 22(9):823–877, Jun 2011.

[12] P. Bearman, J. Green, R. Howell, and J. Jupp. *Air Travel – Greener By Design Annual Report*. 2014.

[13] Biofuel UK. Third generation biofuels. Available at `http://biofuel.org.uk/third-generation-biofuels.html`. Accessed March 2015.

[14] Boeing. *Current Market Outlook 2013–2032*. 2013. Available at `http://www.boeing.com/assets/pdf/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2013.pdf`. Accessed March 2015.

[15] A. Boglietti, A. Cavagnino, A. Tenconi, S. Vaschetto, and P. di Torino. The safety critical electric machines and drives in the more electric aircraft: A survey. In *35th Annual Conference of IEEE Industrial Electronics*, pages 2587–2594. Institute of Electrical & Electronics Engineers, Nov 2009.

[16] G. Bower, T. Flanzer, and I. Kroo. Formation geometries and route optimization for commercial formation flight. In *27th AIAA Applied Aerodynamics Conference*, number 2009-3615. American Institute of Aeronautics and Astronautics, Jun 2009.

[17] M. K. Bradley and C. K. Droney. Subsonic ultra green aircraft research phase II: N+4 advanced concept development. Technical Report NASA/CR-2012-217556, NASA, 2012.

[18] M. Carr. Carbon market value to gain 15% in 2014 on EU surplus fix. Bloomberg Business Article (Jan 8, 2014). Available at `www.bloomberg.com/news/articles/2014-01-08/global-carbon-market-value-to-gain-15-in-2014-on-eu-surplus-fix`. Accessed March 2015.

[19] W. A. Chishty. Performance and emissions characterization of alternative aviation fuels at altitude conditions. In *4th UTIAS International Workshop on Aviation and Climate Change*, 2014. Available at `http://www.utias.utoronto.ca/sustainable-aviation/international-workshop`. Accessed March 2015.

[20] Clean Sky Joint Undertaking. Clean Sky Joint Technology Initiative. Available at `http://www.cleansky.eu/content/homepage/about-us`. Accessed March 2015.

[21] M. Cooney. Network world online article (May 17, 2010). Available at `http://www.networkworld.com/article/2230748/security/nasa--what-cool-future-passenger-aircraft-will-look-like.html`. Accessed March 2015.

[22] R. A. Coppenbarger, R. W. Mead, and D. N. Sweet. Field evaluation of the tailored arrivals concept for datalink-enabled continuous descent approach. *Journal of Aircraft*, 46(4):1200–1209, Jul 2009.

[23] David Suzuki Foundation. Air travel and climate change. Available at http://www.davidsuzuki.org/issues/climate-change/science/climate-change-basics/air-travel-and-climate-change/. Accessed March 2015.

[24] J. Dawson. The NAV CANADA air navigation system plan. Presented at NAM/CAR ANI/WG/1, 2013.

[25] R. Del Rosario. Propulsion technologies for future aircraft generations: Clean, lean, quiet, and green. In *3rd UTIAS International Workshop on Aviation and Climate Change*, 2012. Available at `http://www.utias.utoronto.ca/sustainable-aviation/international-workshop`. Accessed March 2015.

[26] P. Dempsey. Environmental law and sustainability in international aviation. Availailable at `www.mcgill.ca/iasl/files/iasl/aspl-633-m119_3-paul-dempsey.pdf`. Accessed March 2015.

[27] Designs You Trust. Online gallery. Available at http://main-designyoutrust.netdna-ssl.com/wp-content/uploads/2012/02/1302.jpg. Accessed March 2015.

[28] G. L. Dillingham. *Impact of Aviation Noise on Communities Presents Challenges for Airport Operations and Future Growth of the National Airspace System*. United States Government Accountability Office, 2007.

[29] A. Doyle. Open rotor: how does it work? October 2009. Available at http://www.flightglobal.com/news/articles/open-rotor-how-does-it-work-332991. Accessed March 2015.

[30] L. Dray, A. Evans, T. Reynolds, A. W. Schafer, M. Vera-Morales, and W. Bosbach. Airline fleet replacement funded by a carbon tax: An integrated assessment. *Transport Policy*, 34:75–84, Jul 2014.

[31] M. Drela. Development of the D8 transport configuration. In *29th AIAA Applied Aerodynamics Conference*, number 2011–3970. American Institute of Aeronautics and Astronautics (AIAA), Jun 2011.

[32] T. Dursun and C. Soutis. Recent developments in advanced aircraft aluminium alloys. *Materials & Design*, 56:862–871, Apr 2014.

[33] S. Elgie and J. McClay. *BC's Carbon Tax Shift After Five Years: An Environmental (and Economic) Success Story*. Sustainable Prosperity, Canadian Public Policy, 2013.

[34] D. Emerson. *Aerospace Review Report, Volume 1: Beyond the Horizon: Canada's Interests and Future in Aerospace*. Public Works and Government Services Canada, 2012.

[35] European Commission. EU ETS: Reducing emissions from aviation. Available at http://ec.europa.eu/clima/policies/transport/aviation/. Accessed March 2015.

[36] European Commission. Horizon 2020. Available at http://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020. Accessed March 2015.

[37] European Commission. *Aeronautics and Air Transport Research in the 7th Framework Programme (2007-2013)*, volume 3. Luxembourg, 2013.

[38] European Union. Total greenhouse gas emissions by sector in EU, 2009. Available at http://www.eea.europa.eu/data-and-maps/figures/total-greenhouse-gas-emissions-by-sector-in-eu-1. Accessed March 2015.

[39] Federal Aviation Administration. *Aeronautical Information Manual*. 2014. Available at http://www.faa.gov/air_traffic/publications/atpubs/aim/. Accessed March 2015.

[40] FlexSys. Flexfoil wings tests peaking (press release Jan 5, 2015). Available at http://www.flxsys.com/blog/2015/1/5/flexfoil-wing-tests-peaking. Accessed March 2015.

[41] G. J. Follen, R. Del Rosario, R. Wahls, and N. Madavan. NASA's Fundamental Aeronautics Subsonic Fixed Wing Project: Generation N+3 Technology Portfolio. In *SAE International*, number 2011-01-2521, Oct 2011.

[42] H. Gagnon and D. W. Zingg. High-fidelity aerodynamic shape optimization of unconventional aircraft through axial deformation. In *52nd Aerospace Sciences Meeting*, number 2014–0908. American Institute of Aeronautics and Astronautics, Jan 2014.

[43] S. Gossling and P. Upham. *Climate Change and Aviation: Issues, Challenges, and Solutions*. Earthscan Publications Ltd, Sterling, VA, 2009.

[44] J. E. Green. The potential for reducing the impact of aviation on climate. *Technology Analysis & Strategic Management*, 21(1):39–59, Jan 2009.

[45] J. E. Green. Aviation and climate - where do we go from here? In *4th UTIAS International Workshop on Aviation and Climate Change*, Toronto, Canada, May 2014. Available at `http://www.utias.utoronto.ca/sustainable-aviation/international-workshop`. Accessed March 2015.

[46] Green Aviation Research & Development Network. *2013–2014 Annual Report: Reaching Greener Heights*. 2014.

[47] GreenAirOnline. Nasa purchases Gevo's renewable alcohol-to-jet fuel as part of performance testing programme (March 12, 2015). Available at `http://www.greenaironline.com/news.php?viewStory=2058`. Accessed March 2015.

[48] M. Guynn. System studies of unconventional aircraft. In *Workshop on Revolutionary Aircraft for Quiet Communities*, Hampton, VA, July 24–26 2007.

[49] A. Hahn. Staging airliner service. In *7th AIAA Aviation Technology, Integration and Operations Conference*, number 2007–7759. American Institute of Aeronautics and Astronautics, Sep 2007.

[50] C. A. Hall, E. Schwartz, and J. I. Hileman. Assessment of technologies for the silent aircraft initiative. *Journal of Propulsion and Power*, 25(6):1153–1162, Nov 2009.

[51] W. W. M. Heesbeen, D. Lobl, and J. Groeneweg. Human factors aspects of air-to-air refuelling of civil aircraft – a human-in-the-loop study. In *Royal Aeronautics Society Applied Aerodynamics Conference*, London, UK, July 2014.

[52] S. M. Hosseini, D. Tempelmann, A. Hanifi, and D. S. Henningson. Stabilization of a swept-wing boundary layer by distributed roughness elements. *J. Fluid Mech.*, 718, Feb 2013.

[53] International Air Transport Association. Improving environmental performance. Available at `http://www.iata.org/whatwedo/environment/Pages/index.aspx`. Accessed March 2015.

[54] International Civil Aviation Organization. Committee on Aviation Environmental Protection (CAEP). Available at `http://www.icao.int/environmental-protection/pages/CAEP.aspx`. Accessed March 2015.

[55] International Civil Aviation Organization. Economic development: 2013 air transport yearly monitor. Available at `http://www.icao.int/Sustainability/Documents/Yearly-Monitor.pdf`. Accessed March 2015.

[56] International Civil Aviation Organization. *Convention on International Civil Aviation*. Chicago, December 1944.

[57] International Civil Aviation Organization. *Annex 16 to the Convention on International Civil Aviation: Environmental Protection*. 2011.

[58] International Civil Aviation Organization. *Capacity and Efficiency: 2013–2028 Global Air Navigation Plan*. 2013.

[59] International Civil Aviation Organization. *Destination Green: Driving Progress Through Action on Aviation and the Environment*. ICAO Journal, Montreal, 2013. Vol. 68, No. 2.

[60] International Civil Aviation Organization. *Environmental Report 2013: Aviation and Climate Change*. 2013.

[61] International Civil Aviation Organization. ICAO's CO_2 standard as part of a basket of measures to meet emission reduction goals. Technical Report A38-WP/297, September 2013.

[62] G. Kennedy. Large-scale multi-material topology optimization for additive manufacturing. In *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, number 2015-1799. American Institute of Aeronautics and Astronautics, Jan 2015.

[63] G. Kenway, R. Henderson, J. Hicken, N. Kuntawala, D. W. Zingg, J. Martins, and R. McKeand. Reducing aviation's environmental impact through large aircraft for short ranges. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, number 2010-1015. American Institute of Aeronautics and Astronautics, Jan 2010.

[64] S. Khosravi and D. W. Zingg. A numerical optimization study on winglets. In *15th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, number 2014–2173. American Institute of Aeronautics and Astronautics, Jun 2014.

[65] P. Kiameh. *Power Generation Handbook*. McGraw-Hill Digital Engineering Library, 2004.

[66] H. Kim, J. Berton, and S. Jones. Low noise cruise efficient short take-off and landing transport vehicle study. In *6th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*. American Institute of Aeronautics and Astronautics, Sep 2006.

[67] P. Lavoie, R. Hanson, A. Naguib, K. Bade, C. Rowley, and B. Belson. Towards model-based closed-loop control of transition and turbulence in boundary layers. In *3rd UTIAS International Workshop on Aviation and Climate Change,*, May 2012.

[68] D. S. Lee, D. W. Fahey, P. M. Forster, P. J. Newton, R. C. Wit, L. L. Lim, B. Owen, and R. Sausen. Aviation and global climate change in the 21st century. *Atmospheric Environment*, 43(22-23):3520–3537, Jul 2009.

[69] J. Lee and A. Jameson. Natural-laminar-flow airfoil and wing design by adjoint method and automatic transition prediction. In *47th AIAA Aerospace Sciences Meeting and Exhibit*, number AIAA–2009–897, Orlando, Florida, 5–8 January 2009.

[70] R. A. MacKay, T. P. Gabb, J. L. Smialek, and M. V. Nathal. A new approach of designing superalloys for low density. *JOM*, 62(1):48–54, Jan 2010.

[71] A. Malwitz, S. Balasubramanian, G. Fleming, T. Yoder, and I. Waitz. Impact of the reduced vertical separation minimum on the domestic United States. *Journal of Aircraft*, 46(1):148–156, Jan 2009.

[72] M. Manzoor. Sustainable development - a major challenge to the aviation industry. *Messier-Dowty Inc, Canada*, 2008.

[73] L. Maurice. Aviation environmental impacts and mitigation. Toronto, Canada, June 2012. Presented at the University of Toronto Institute for Aerospace Studies.

[74] L. Maurice and D. Lee. Assessing current scientific knowledge, uncertainties and gaps in quantifying climate change, noise and air quality aviation impacts. Technical report, Final Report of the International Civil Aviation Organization (ICAO) Committee on Aviation and Environmental Protection (CAEP) Workshop, 2009.

[75] Minister of Justice. *Canada Trasportation Act*. S.C. 1996, c. 10, Last amended on May 29, 2014.

[76] G. Monbiot. *Heat: how to stop the planet from burning*. Doubleday Canada, Scarborough, ON, 2006.

[77] G. Murray. *Ontario's Climate Change Discussion Paper*. Ministry of the Environment and Climate Change, 2015.

[78] R. K. Nangia. Air to air refuelling in civil aviation: An opportunity & a vision. In *Royal Aeronautics Society Greener By Design Conference*, London, UK, October 2008.

[79] National Aeronautics and Space Administration. Environmentally Responsible Aviation (ERA) project. Available at `http://www.aeronautics.nasa.gov/iasp/era/index.htm`. Accessed March 2015.

[80] National Aeronautics and Space Administration. Future airplane gallery. Available at http://www.nasa.gov/topics/aeronautics/features/future_airplane_gallery17.html. Accessed March 2015.

[81] National Aeronautics and Space Administration. Future airplane gallery. Available at https://www.nasa.gov/content/the-double-bubble-d8-0. Accessed March 2015.

[82] National Renewable Energy Laboratory. Transportation energy futures: Combining strategies for deep reductions in energy consumption and GHG emissions. Technical Report DOE/GO-102013-3845, U.S. Department of Energy, March 2013.

[83] National Research Council Canada. Analysis of 100 percent biofuel tested in flight by NRC reveals reduction in emissions (press release Jan 7, 2013). Available at http://www.nrc-cnrc.gc.ca/eng/news/releases/2013/biofuels.html. Accessed March 2015.

[84] Natural Resources Canada. Next-generation Biofuels Fund. Available at http://www.nrcan.gc.ca/energy/alternative-fuels/programs/3643. Accessed March 2015.

[85] NAV CANADA. *The Air Navigation System Plan: Charting the Future*. 2012.

[86] S. A. Ning, T. C. Flanzer, and I. M. Kroo. Aerodynamic performance of extended formation flight. *Journal of Aircraft*, 48(3):855–865, May 2011.

[87] F. Noppel and R. Singh. Overview on contrail and cirrus cloud avoidance technology. *Journal of Aircraft*, 44(5):1721–1726, Sep 2007.

[88] ParadigmBioAviation. Alternative aviation fuels. Available at http://www.paradigmbioaviation.com/?page_id=16. Accessed March 2015.

[89] J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken, and M. McFarland. *Aviation and the Global Atmosphere*. Cambridge University Press, Cambridge, 1999. Published for the Intergovernmental Panel on Climate Change.

[90] G. Quaiattini. Biofuels are part of the solution. April 2008. Available at www2.canada.com. Accessed March 2015.

[91] K. Rajashekara, J. Grieve, and D. Daggett. Solid oxide fuel cell/gas turbine hybrid APU system for aerospace applications. In *IEEE Industry Applications Conference Forty-First IAS Annual Meeting*. Institute of Electrical & Electronics Engineers, Oct 2006.

[92] N. Rivers. *The Case for a Carbon Tax in Canada*. Canada 2020, 2014.

[93] W. S. Saric, D. E. West, M. W. Tufts, and H. L. Reed. Flight test experiments on discrete roughness element technology for laminar flow control. In *53rd AIAA Aerospace Sciences Meeting*, number 2015–0539. American Institute of Aeronautics and Astronautics (AIAA), Jan 2015.

[94] H. Slutsken. *Ramp Operations – What's Going on Out There?* July 2014. Available at http://www.airlinereporter.com/2014/07/ramp-operations-whats-going-on-out-there/. Accessed March 2015.

[95] Sustainable Aviation. *Sustainable Aviation CO_2 Road Map*. London, UK, 2012.

[96] G. Taylor. Canada: Alberta's GHG emissions control system: A model for others? Available at `http://www.mondaq.com/canada/x/202178/Clean+Air+Pollution/Albertas+GHG+Emissions+Control+System+A+Model+for+Others`. Accessed March 2015.

[97] The Brigade. Photo of the day. Available at `http://thebrigade.com/2011/07/27/photo-of-the-day-click-here-for-high-res-photo-129/`. Accessed March 2015.

[98] The World Bank. World development indicators: Air transport, passengers carried. Available at `http://data.worldbank.org/indicator/IS.AIR.PSGR`. Accessed March 2015.

[99] D. Theckedath. The Canadian aerospace industry and the role of the federal government. Technical Report 2013-21-E, Library of Parliament, April 2013.

[100] D. Thoma. Space based ADS-B: Global ADS-B coverage. In *Presentation by Aireon*, November 2014.

[101] Transport Canada. *Canada's Action Plan to Reduce Greenhouse Gas Emissions from Aviation*. 2012. TP 15187.

[102] Transport Canada. *Canada's Action Plan to Reduce Greenhouse Gas Emissions from Aviation: 2012 Annual Review*. 2012. TP 15240.

[103] Transport Canada. *Canada's Action Plan to Reduce Greenhouse Gas Emissions from Aviation: 2013 Annual Review*. 2013. TP 15285.

[104] V. M. Tunteng. *Legal Analysis on the Inclusion of Civil Aviation in the European Union Emissions Trading System*. Centre for International Sustainable Development Law, May 2012.

[105] University of Toronto Institute for Aerospace Studies. Centre for Research in Sustainable Aviation. Available at `http://www.utias.utoronto.ca/sustainable-aviation`. Accessed March 2015.

[106] P. Upham, J. Maugham, D. Raper, and C. Thomas. *Towards Sustainable Aviation*. Earthscan Publications Ltd, London, 2003.

[107] A. Velicki and D. Jegley. PRSEUS development for the hybrid wing body aircraft. In *AIAA Centennial of Naval Aviation Forum "100 Years of Achievement and Progress"*, number 2011–7025. American Institute of Aeronautics and Astronautics, Sep 2011.

[108] J. Xu and I. Kroo. Aircraft design with active load alleviation and natural laminar flow. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, number AIAA–2012–1428, Honolulu, Hawaii, Apr 2012.

[109] D. W. Zingg and O. L. Gülder. Technology developments and renewable fuels for sustainable aviation. Chapter to appear in Sustainable Development in International Aviation Law.