Aviation is a growing contributor to climate change, with unique impacts due to the altitude of emissions. If existing traffic growth rates continue, radical engineering solutions will be required to prevent aviation becoming one of the dominant contributors to climate change. This paper reviews the engineering options for mitigating the climate impacts of aviation using aircraft and airspace technologies. These options include not only improvements in fuel efficiency, which would reduce carbon dioxide (CO₂) emissions, but also measures to reduce non-CO₂ impacts including the formation of persistent contrails. Integrated solutions to optimize environmental performance will require changes to airframes, engines, avionics, air traffic control systems and airspace design.

While market-based measures, such as offset schemes and emissions trading, receive growing attention, this paper sets out the crucial role of engineering in the challenge to develop a ‘green air traffic system’.

Keywords: aviation; airspace design and management; aeronautical engineering; climate change

1. Introduction

The impact of aviation on the global climate receives growing attention from the media, the public and politicians. At the heart of the issue is forecast demand. In Europe, the average annual growth (in passenger km) for scheduled traffic approached 6% for the 10 years to 2005. It is expected to continue at or above this level, at least in the short term. Faster growth is forecast for Asia/Pacific (6–7%) and the Middle East (above 10%; International Civil Aviation Organization 2006).

The atmospheric concentration of carbon dioxide is rising. From a pre-industrial value of 280 parts per million (ppm), it has now reached 377 ppm (Keeling & Whorf 2005). Of this increase, approximately 1 ppm can be attributed to aviation (Penner et al. 1999). Aircraft engines account for 2–3% of current global emissions. If demand continues to grow, so will this share. Many industry sectors are reducing emissions under the Kyoto Protocol, but the agreement does not include international aviation, calling instead for developed countries to work through the International Civil Aviation Organization (ICAO). This has yet to result in action. With only domestic traffic, and with key nations not participating and others exempt from restrictions, the reach of
the Kyoto Protocol is limited. For the 10 states with the most passenger air transport (as measured in passenger km, rather than aircraft km or aircraft movements), only 6% of their total air traffic is included in the current national targets (International Civil Aviation Organization 2006).

There are other pressures to bring aviation into efforts to reduce our influence on climate. Aviation is a minority activity: only 1% of the global population has ever flown (Humphreys 2003). The benefits are largely confined to the affluent, both in the global distribution of traffic and in the demographic patterns of passengers within society. At the same time, developing nations are most vulnerable to climate change. This adds a strong ethical dimension. For individuals concerned with their personal carbon footprint, a long haul flight can nullify the carbon savings achieved by changing behaviour in other areas of daily life. Another factor is the unique climate impacts associated with emissions at high altitude.

Circumstances are changing. Aviation will meet new policies to improve environmental performance. Market-based approaches, as currently proposed, may suppress demand, slowing the growth in air travel, but the main benefits are likely to come from other emission reductions. Indeed, including aviation in the European emissions trading scheme is not expected to have a substantial impact on traffic. With the scheme set for introduction in 2011, growth in the 15 years to 2020 is expected to be at least 135%, compared with 142% for the business-as-usual scenario (European Commission 2006). The scheme encourages emission reductions to be made where they are cheapest. Most assessments suggest that aviation will be a net purchaser of emission permits or credits. The industry has a relatively high economic yield per unit of carbon dioxide emitted. It also has slow time scales of industry change—the aircraft development process is slow and the service life is long.

Modest fare rises due to emissions trading are unlikely to slow growth dramatically, but should encourage airlines to reduce their own emissions. Emissions will cost more. If an airline exceeds its allocation, it will need to purchase additional permits; if it does not reach its allocation, surplus permits can be sold.

By bringing some environmental costs into airline budgets, emissions trading will affect decision making. In the short term, many of the decisions will be operational, making better use of existing systems and practices. In the longer term, new engineering approaches will be required. Effective solutions require collaboration across a wide range of disciplines but broadly relate to two types of engineering. The first is the design of the aircraft itself, including aircraft configurations, propulsion systems, avionics, materials, airframe design and other disciplines. The second challenge lies in the way aircraft flows are optimized to make efficient use of the capacity available.

This paper considers the role of engineering in mitigating the climate impacts of aviation. Both aircraft and air traffic management changes are considered.

2. Aviation’s contributions to climate change

The atmosphere has different chemical and physical properties at high altitudes than at the surface. At cruise, nitrogen oxide emissions from aircraft have a much greater impact than at low altitudes, increasing ozone and reducing methane. Cold, high-altitude conditions can also allow the formation of contrails and cirrus
clouds; both have a net warming impact. These effects occur in addition to emissions of carbon dioxide from aircraft engines.

Aviation’s climate impacts have different lifetimes (table 1). Carbon dioxide emissions persist in the atmosphere for decades or longer, while a contrail will typically disperse in a few hours. These differences in lifetime make comparison between the impacts difficult. One approach is to use radiative forcing—a globally and annually averaged measure of the additional energy trapped in the lower atmosphere. This measure is, as a first-order approximation, proportional to the expected change in global average surface temperature associated with an atmospheric change. Radiative forcing has been widely misapplied to compare the different impacts of an individual flight, e.g. in recommendations for a multiplier or uplift factor to reflect the additional effects of aircraft relative to other carbon dioxide emission sources. This fails to reflect the different future impacts and can distort policy priorities (Forster et al. 2006). For example, considering the impacts of a single pulse event, the time-integrated effect over 1 year is more than 25 times larger for contrail than for carbon dioxide. Over 500 years, the CO2 impact is 4.5 times larger than the contrail impact (Forster et al. 2006). Targeting short-lived impacts could cut the total radiative forcing rapidly, but even a small trade-off increase in carbon dioxide emissions could increase the total radiative impact in the longer term.

These trade-offs are important. Improving fuel efficiency may not reduce all impacts. Only carbon dioxide and sulphate emissions are explicitly proportional to fuel. For these, any efficiency improvement (whether operational or from engineering changes to the aircraft or engine) will reduce the impacts. For the remaining mechanisms, impacts are also related to factors including altitude and background atmospheric conditions. Indeed, some improvements in efficiency can increase some non-carbon impacts. These are discussed in §3 in the context of engineering changes to aircraft and airspace.

### Table 1. Comparing the mechanisms for aviation’s impact on climate. (Radiative forcing (RF) values from the trade-off study (Sausen 2005). Smaller contributions from soot and water vapour are not shown.)

<table>
<thead>
<tr>
<th>mechanism</th>
<th>RF (mW m⁻²)</th>
<th>lifetime</th>
<th>confidence</th>
<th>≈ fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>increased carbon dioxide</td>
<td>25.3</td>
<td>decades</td>
<td>good</td>
<td>yes</td>
</tr>
<tr>
<td>increased ozone</td>
<td>21.9</td>
<td>weeks</td>
<td>fair</td>
<td>no</td>
</tr>
<tr>
<td>reduced methane</td>
<td>−10</td>
<td>years</td>
<td>poor</td>
<td>no</td>
</tr>
<tr>
<td>contrail formation</td>
<td>10</td>
<td>hours</td>
<td>fair</td>
<td>no</td>
</tr>
<tr>
<td>increased cirrus</td>
<td>0–80</td>
<td>hours</td>
<td>very poor</td>
<td>no</td>
</tr>
<tr>
<td>increased sulphate</td>
<td>−3.5</td>
<td>weeks</td>
<td>fair</td>
<td>yes</td>
</tr>
</tbody>
</table>

3. Engineering new aircraft systems

Designing a new aircraft brings together many engineering disciplines. Most aspects of the process are relevant to the environmental performance, particularly to fuel efficiency and carbon dioxide emissions. This section considers several key (and interrelated) elements of the aircraft system and identifies the role of engineering in delivering further improvements.
Productivity is affected by the efficiency of the engine, the aerodynamic efficiency and the configuration and operation of the aircraft, including factors such as seating configuration and payload (Peeters et al. 2005).

Carbon dioxide emissions (per passenger km) have fallen steadily since the first jet aircraft were introduced. Emissions were not then a driver for improvements, but the pressure to reduce fuel cost has always been strong. Efficient operations can also allow less fuel to be carried, allowing the aircraft to carry a larger payload or to fly further, potentially offering new direct routes.

The achievements have been substantial. Carbon dioxide emissions per seat km for newly certified aircraft are now 70% lower than for the early jets. Engine improvements have delivered almost two-thirds of the efficiency benefits, with the rest linked to airframe improvements and a trend towards larger aircraft (Lee 2003).

Climate impacts are balanced against other concerns. The compromise between noise and emissions continues to prove challenging. To facilitate night operations at London Heathrow, the new A380 aircraft and engine designs were refined to reduce noise. The adjustments increased the mass and reduced fuel efficiency by an estimated 1–2% (Green 2003). Emissions trading and other market-based measures may alter the priorities by bringing external costs into decisions. One estimate of external costs at Heathrow values the climate impact at £30 per passenger, compared with £0.40 for aircraft noise and £0.75 for air quality degradation (Brooker 2006).

(a) Propulsion

(i) Engines

A number of elements contribute to propulsion efficiency. One is thermal efficiency, which gauges the conversion of the chemical energy of the fuel into physical energy available to perform work. This is currently approximately 55% (Green 2006). Thermal efficiency can be improved by increasing the temperature of the air passing from the combustor to the turbine (figure 1), while increasing the ratio of the maximum pressure in the engine to the ambient atmospheric pressure (the overall pressure ratio). Thermal efficiency is expected to improve by 3% over the next 20 years, if the supporting technologies in materials and cooling technologies can be developed (Lee 2003).

Improvements in propulsive efficiency—the proportion of the energy from the fuel used to propel the aircraft—are also required. Current values are typically 84%. It can be improved by reducing the velocity of the jet. In a modern turbofan engine, as used for civil aviation, some of the air passing through the engine diverts around the engine core, missing the compressor, combustor and turbine stages. The two flows of air then mix at the exhaust. Increasing the proportion that bypasses the core (raising the bypass ratio) reduces the jet velocity, improving the propulsive efficiency. This approach is limited by weight and size constraints on the engine (Penner et al. 1999; Lee 2003). Further improvements in propulsive efficiency could be achieved by improving the mixing of gases before exhaust (Penner et al. 1999). The third element of the propulsion efficiency is the efficiency of transfer between the turbine and
the fan, which is already above 85% and offers little scope for improvement (Green 2006). Currently, the overall propulsion efficiency stands at approximately 40%. The engineering challenges will increase as the physical (thermodynamic) limits on efficiency are approached and improvements beyond 25% are unlikely (Green 2006).

In general, improving the overall efficiency of the engine (the fuel burn per kg thrust) also reduces nitrogen oxide emissions, but there are exceptions. Increasing the temperature and pressure within the combustor can increase the output of nitrogen oxides, as can increasing the bypass ratio (Penner et al. 1999; Haglind et al. 2006; table 2). There are other trade-off effects. Improving the propulsive efficiency of the engine can cool the exhaust gas, extending the range of ambient temperatures over which contrails will form. This has been observed: of two aircraft, flying closely in parallel through air close to the predicted threshold conditions for contrail formation, only the more efficient (higher bypass) A340 produced a contrail (Schumann 2000).

The physical properties of contrail change depending on the particulate emissions from the engine, as these particles act as condensation nuclei. However, there are sufficient condensation nuclei in the background atmosphere for...
contrail formation to occur. A novel engine concept could reduce emissions of carbon dioxide and nitrogen oxides and avoid contrail formation by removing liquid water from the exhaust gas, but such an engine may be bigger and heavier than existing engines, which would present extra challenges for installation (Noppel et al. 2006). Engine weight is significant; lighter engines reduce fuel and allow smaller, lighter components to be used for aircraft structures like landing gear. The net empty aircraft weight saving can be up to four times the reduction in the engine weight (Penner et al. 1999; Lee 2003).

Other radical approaches to aircraft propulsion are being considered, including building cooling systems into the engine’s thermodynamic cycle to reduce both fuel consumption and nitrogen oxide emissions and using electricity generated by the engine to power a range of aircraft systems (Lee 2003). Another possibility is to use a much larger number of small engines distributed along the wing (Sehra & Whitlow 2004).

(b) Fuel

Amid concerns about both greenhouse gas emissions and the long-term security of oil supplies, alternative fuels are being considered for aviation. In the near term, synthetic kerosene is the most promising fuel, as it requires few changes to aircraft and supply infrastructure. This can be a renewable fuel, if biomass (rather than natural gas or coal) is used (Lee 2003). With no sulphur in the manufactured fuel, sulphur dioxide emissions would be eliminated. Lower combustion temperatures would also mean reduced NOx emissions. However, there is a significant energy cost in production and the land required for biomass could be a deterrent (Lee 2003; Haglind et al. 2006).

Conventional kerosene can be blended with ethanol to reduce emissions (Haglind et al. 2006). Again, there are some environmental concerns. These include potentially hazardous emissions at low power and issues about the land and energy required for cultivation and transport, particularly where states may produce lucrative biofuels instead of securing domestic food supplies. For aviation, the energy content of ethanol per unit mass or volume is also a factor, being half that of kerosene.

Liquid hydrogen aircraft (cryoplanes) are considered for the longer term. To deliver the same energy, the mass required is 36% of that required of kerosene. However, the density is much lower, so radical aircraft redesign would be needed to accommodate fuel tanks four times larger. Also, using liquid hydrogen requires additional components, including a heat exchanger to produce the vapour required for combustion, reducing the benefit gained from the lower mass of fuel required (Haglind et al. 2006). A further concern is the absence of sustainable hydrogen production methods on the scale needed to meet the energy demands of the air industry.

A hydrogen engine would emit no carbon dioxide. It could also be designed to significantly reduce nitrogen oxide emissions (Svensson & Singh 2004). Water vapour emissions are significant for very high-altitude flights, as emissions into the stratosphere are long-lived and can have a significant warming impact, but the overall effect is expected to be limited (Ponater et al. 2006). Increased water vapour would also increase the probability of contrail formation, but the optical properties would be different and the net climate impact may be smaller than for
kerosene aircraft (Ponater et al. 2006). The impacts of additional water vapour emissions could be reduced by restricting cruise altitudes below their current levels (Svensson et al. 2004).

Liquid methane would require similar supply infrastructure changes to liquid hydrogen, but offers an energy density more similar to that of kerosene (Haglind et al. 2006). However, there would be little purpose to a major change in aviation fuel if it does not represent a switch away from reliance on fossil fuels. Non-fossil options for methane production present their own challenges for large-scale production and are unlikely to play a significant role in aviation (Haglind et al. 2006).

Fuel additives to reduce contrail and cirrus cloud formation are not thought to offer an effective solution (Gierens 2007). There is also little potential to reduce sulphate emissions by reducing fuel sulphur content. Kerosene already has a low sulphur content and further reductions would require energy-intensive hydroprocessing, which would increase carbon dioxide emissions (Penner et al. 1999).

(c) Airframe

Improving the aerodynamic efficiency of the aircraft can contribute to emission reductions. These improvements aim to maximize lift and minimize drag, and can include changes in the aircraft geometry, weight reduction measures or changes in the materials used for the aircraft structure and surfaces. Increasing wingspan can improve the lift-to-drag ratio, but efficiency benefits must be set against performance requirements and weight. A larger (more efficient) wingspan can be accommodated if the cruise speed is reduced (Green 2006). Newly developed composite materials could allow a larger wingspan without increasing weight. New aircraft including the Airbus A350 and the Boeing 787 make use of these materials for some structures to reduce aircraft weight (Green 2006). More applications are expected. Existing maintenance and inspection regulations are designed for conventional materials and can be inappropriate when applied to materials that behave differently. The regulatory system should adapt as understanding of the materials improves. These composite materials may offer fuel savings (and hence carbon dioxide emission reductions) of 10–15% for new aircraft entering service in 2020, compared with those in 2000 (Royal Aeronautical Society 2005).

Composite materials can control small-scale turbulence on the aircraft’s surface, reducing drag. This displaces the onset of turbulence away from the aircraft surface, allowing smooth laminar flow of air. Hybrid laminar flow control, in which the engineering of the wing surface includes suction systems, could improve fuel efficiency by 16% and increase the efficient operating range. The engineering challenges include the development of lightweight suction systems (Green 2006).

(d) Whole aircraft systems

In the long term, radical redesign of aircraft configurations could occur. Current aircraft have developed iteratively from early designs, becoming quieter, faster, larger and more efficient, but ultimately adopting the same fuselage and swept-wing configuration.
The blended wing body is a design concept receiving renewed attention as environmental concerns grow. The aircraft is a single wing shape, with engines embedded in the aircraft. The streamlined shape improves efficiency, but also shields the ground from engine noise (Dowling & Hynes 2006). Combined with laminar flow technologies, it could deliver an efficiency improvement of up to 80% for some routes (Green 2006).

Changing the priorities of design by optimizing aircraft systems for shorter journeys, replacing very long haul trips with multistage flights or using in-flight refuelling may offer considerable benefits for fuel efficiency (Nangia 2006).

4. Engineering airspace

The opportunities to manage the climate impacts of aviation are not confined to changes to the aircraft. The services provided to air traffic can significantly affect efficiency. Indeed, as the development of new aircraft is necessarily a slow process and the lifetime of aircraft in the operating fleet is long, changes to the way air traffic flows are guided and controlled may offer the best opportunities for the mitigation of climate impacts of aviation in the short and medium term.

Air navigation services (ANS) include a whole range of activities undertaken by diverse actors in the air traffic system. Air traffic management tasks operate alongside communication, navigation and surveillance (CNS) and meteorological and other services. These tasks have been categorized by the International Civil Aviation Organization (ICAO 2004) and are summarized in figure 2, with those activities linked to engineering opportunities to mitigate climate impacts of aviation shown in black. For completeness, the remaining categories of air navigation activities are also shown.

Changes to ANS are typically developed to address capacity constraints, to improve safety or to reduce workload or cost. Some measures will have direct fuel efficiency benefits. The development of new systems and concepts for air navigation will also offer new opportunities for alternative approaches to be considered, potentially targeting the non-carbon impacts. In particular, the impacts of both nitrogen oxides and contrails could be reduced with more flexibility in the selection of flight trajectories and better awareness of background atmospheric conditions (Grewe et al. 2002; Williams & Noland 2005). In the case of contrail, the layer of air to be avoided is on average only 500 m thick (Spichtinger et al. 2003), so only small changes in altitude would be required (Mannstein et al. 2005).

(a) Communication, navigation and surveillance

Improvements in CNS through the use of satellite technologies will contribute to reducing the reliance on ground-based navigation systems. This will allow routes to be flown more directly and enable flight plans to be renegotiated to take account of changing conditions. Increasingly automated exchange of common flight data, including information on the aircraft’s intent, will support decision making (EUROCONTROL 2003). The increased precision of navigation and surveillance systems could lead to reduced separation minima between aircraft (if wake vortex conditions allow), increasing capacity and allowing aircraft to follow preferred routes more closely. These tools will
contribute to more flexibility in the selection of routes, transfer of some responsibilities for separation to pilots and ultimately lead to autonomous aircraft operations (EUROCONTROL 2003). In conjunction with changes to air traffic management, these improvements in CNS technologies are expected to reduce carbon dioxide emissions per passenger km by 5% by 2015, with similar reductions expected for nitrogen oxide emissions (International Civil Aviation Organization 2000).

(b) Air traffic management

Air traffic management includes the design and allocation of airspace, the planning of traffic flows and the services that are provided to air traffic, including air traffic control. The aim is to manage the flows of air traffic through controlled airspace safely and efficiently. Aircraft currently navigate using a series of ground-based navigation aids or waypoints. Flight plans are filed in advance and define the sequence of points to be reached along the route and at what altitude. These flight plans use route structures planned to manage the flow of traffic and the workload of controllers, e.g. by limiting the number of entry and exit points for an air traffic control sector. The shape and size of sectors can also be governed by other factors. In Europe, for example, there has been division of airspace along national boundaries, with each state retaining sovereignty, leading to significant inefficiency in the routing networks and contributing to high air traffic control costs (Helios Economics and Policy Services 2006). As demand for air travel continues to rise, there is scope to improve the existing airspace designs to improve efficiency. Economically, there are several potential savings to be made, including increased capacity, reduced need for air traffic control infrastructure and reduced costs per flight.
Environmentally, redesign of airspace can offer more direct routings. This can reduce emissions associated with flight at cruise altitude. Redesigning airspace to optimize the efficient flow of air traffic can also reduce en-route congestion and minimize the additional time and emission costs associated with avoiding conflicts.

In addition to making better use of existing air traffic management technologies through airspace redesign, future changes to the tools and concepts of air traffic management are expected to contribute significantly to improving efficiency and reducing emissions. In the long term, this is expected to be achieved by a transition towards ‘free flight’.

(c) Meteorological services

Improved communication systems could automate the exchange of weather information. This could improve the pre-flight planning of fuel-optimal flight profiles, taking account of wind conditions, and could contribute to in-flight profile adjustments. Enhanced meteorological services would also be an essential part of any policy to reduce or avoid contrail and cirrus formation, as accurate information on the size and location of contrail formation regions would need to be exchanged between pilots and controllers to determine the diversions required.

5. Aviation targets

The Advisory Council for Aeronautics Research in Europe (ACARE) establishes ambitious goals for the coming years, including the vision of an ultra green air transport system, based on changes to airlines, airports, aircraft and air traffic management. The changes envisioned relate to both operational and engineering challenges. The target for 2020 seeks a 50% reduction in carbon dioxide per passenger km, with 15–20% from engines, 20–25% from airframe improvements and a further 5–10% from air traffic management (ACARE 2002). These targets are challenging. An aircraft efficiency gain of 1% per year for airframe and engines combined has been described as ‘rather optimistic’ as the rate of improvement is already falling (Peeters et al. 2005). The targets relate to new aircraft entering service, so their full impact on the fleet would be delayed. By defining the improvements sought for each aircraft, rather than for total emissions, these goals avoid the issue of traffic growth. This threatens to eclipse the benefits from both improved aircraft performance and reductions in other industry sectors (Bows & Anderson 2007).

If growth in Europe continues at 5%, traffic will double by 2020 (relative to 2005). The expected impact on the demand of emissions trading after 2011 would delay the doubling by just 2 years. Taking the ambitious 1% per annum improvement in the fleet efficiency, carbon dioxide emissions from aviation will rise by over 60% by 2020 (79% if emissions trading does not affect growth). Even if a 10% reduction in carbon dioxide per passenger km is achieved through air traffic management changes in that time, carbon dioxide emissions would still rise by 45%. To constrain emissions and impacts from aviation, demand management policies will be needed alongside the engineering measures outlined here. Such policies include financial, planning and communication strategies to discourage the current growth in demand (Cairns et al. 2006).
6. Conclusion

This paper highlights the role of engineering in determining the future environmental impacts of the aviation system. The engineering community has much to contribute to tackling the climate impacts of aviation in a way that balances the costs and benefits of aviation not just for passengers but also for wider society. Engineering will continue to operate alongside market measures and operational improvements, but is likely to shoulder the largest share of the challenge, unless effective demand management policies are imposed. Market measures, as currently proposed, aim to encourage increased investment in technologies and purchase of emission permits from other industries, rather than expecting substantial reductions in demand. Many of the operational opportunities, like increasing the proportion of seats occupied, are close to their limits, particularly for the low-cost airlines, which have placed the elimination of operational inefficiencies at the core of their business model. If aviation is to achieve significant emission reductions, it will require innovative and ambitious engineering.

Powered flight has transformed the way the world interacts. The industry, built on the work of the visionary engineers and pioneers of the twentieth century, is now facing a new and arguably more difficult challenge. While other industries seek to reduce emissions relative to 1990 levels, stabilization for aviation is still a long way off.

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