Aviation and the Environment

A study on ways to limit the environmental harm caused by engine emissions and an assessment of future environmentally friendly aircraft technologies.

Submitted by
Eric Cordina

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Supervisor: Prof. L.R. Wootton

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This thesis is dedicated to my parents for their constant love and support and to my fiancée Claire for her love and inspiration.

Executive Summary

The aviation industry is a major player in the social and economical scenarios of an increasingly globalised World. However despite the benefits it brings aviation also has a negative impact on the environment. Amidst increasing concern about the state of the environment the airline industry will have to act to limit the harm it causes.

This study has concentrated on the environmental harm caused by aircraft engine emissions and on ways of limiting them. The aviation industry is the transport sector that has continuously improved its environmental performance the most but current technological improvements are not offsetting the increase in emissions due to traffic growth. Technological improvements are nearly always economically driven and this at times means that the environment will not benefit as a result of improvements. Current technological improvements are likely to see a 3% increase in emissions for every 5% increase in traffic growth effectively meaning that aviation's emissions will double in 23 years time.

Better operational procedures such as improved air traffic management, operational measures and also infrastructural improvements can together help reduce worldwide fuel burn by up to 18%. Measures such as market based options will eventually be taken in order to limit the environmental damage caused by aviation, making the industry pay for the external costs it incurs. Emissions trading, taxes and charges are all options which have been analysed in this report. It has been concluded that an open emissions trading system coupled with emission charges will best help limit emissions without discriminating against or punishing airlines too much financially. It is however to be noted that any market based options implemented will see an increase in costs for airlines, a decrease in travel demand and finally a decrease in profits and possibly job losses within the industry.

The report concludes that it is only through future technologies and the substitution of fossil fuels with an environmentally friendly fuel such as

hydrogen that a win-win situation can be achieved. Aircraft with radical designs will offer massive fuel savings and when propelled by hydrogen they will only have a fraction of the impact on the environment that current aircraft have. However before such aircraft materialise there is the need of a lot of research and the need of political backing and funding. In the meantime the airline industry can implement other measures which will help reduce the environmental impact of the industry.

Acknowledgements

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1 AVIATION AND THE ENVIRONMENT

1.1 Aviation

Aviation plays a major role in today's social and economic scenarios. It offers a quick, reliable and safe way of taking people to their destinations whether it is for business reasons, holidays or family visits. Aviation provides easy access to remote areas of the globe and is helping turn the world into a "Global Village". Compared to other traditional forms of travel aviation shortens travel times considerably. In the year 2000 over 1.6 billion passengers were carried by airlines worldwide [1]. Since aviation helps enable goods to reach their destinations very quickly it has helped to increase and diversify the amount of import and export of goods in the world. Today 40%, by value, of the world's manufactured exports are carried by air [1]. Over 29 million tonnes of freight were carried by air in 1998 [2].

The aviation industry is a major force in the global economy. Tourism and travel is the world's largest industry making up 10% of the world Gross Domestic Product (GDP) and aviation is a key component of this sector [2]. In the year 2000 the aviation industry employed over 28 million people [1] and many other jobs are also created as a ripple effect in other sectors such as hotels, car hire, travel agencies etc. In 1998 the world's airlines generated an annual turnover of US$307 billion [2].

However one must note that despite its obvious benefits aviation does have a negative impact on the environment both at a local and also at a global level.

1.2 The Environment

Today we often hear about the environment and its countless plights. There existed a time when man went about his ways without stopping to think about the impact human activities had on the environment. Nowadays there is an increased awareness and understanding that man's activities do affect and alter the environment that surrounds him. This can have effect in the form of deforestation, top-soil erosion, a reduction in the quantity and the diversity of wildlife, poor air quality and even in climate change.

Over the years there were individuals concerned about the state of the environment but there was no true environmental awareness or any major pro-environmental movement until the 1960s. These came about mostly as a result of concerns about air quality due to pollution caused by automobile exhaust fumes, smog in industrial cities and also partly due to concern about the alarming rate of destruction of forests and the depletion of wildlife and their habitats. There is now an increased lobby for more responsible development, development that takes into consideration the impact on the environment. The phrase used is sustainable development. This phrase was coined up and defined by the World Commission on Environment and Development then presided by then Norwegian Prime Minister Gro Harlem Brundtland. In 1987 they released a report called *Our Common Future*, [3] in which sustainable development was defined as follows:

"Sustainable development meets the needs of the present without compromising the ability of future generations to meet their needs"

The report advocated responsible use of the earth's resources in order not to compromise the needs of future generations, stressing that current industrial practices challenged the ability of the biosphere to absorb the effects of our economic activities.

In 1992 the United Nations held a conference in Rio called the United Nations Conference on Environment and Development (UNCED). This conference left its mark as for the first time in history governments admitted that human activities did have a negative impact on the environment. It was concluded that there was the need for a new global effort to relate the elements of the international economic system and mankind's need for a safe and stable natural environment. The conference showed that the environment was not being taken for granted anymore. Since then further progress has been made. The UNCED later devised a global environment action plan known as Agenda 21.

The 1997 Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) was a further step taken internationally to address the global environmental impact of human activities and to limit and prevent further significant environmental damage as a result of certain emissions into the atmosphere. The protocol, when it enters into force, will require countries listed in Annex I to the Convention (industrialised countries) to reduce their collective emissions of six greenhouse gases.

1.3 Aviation's impact on the Environment

Aviation's impact on the environment is significant and negative. The impact on the environment is in various forms, most of which are listed here below:

- Aircraft engine emissions which at altitude, contribute towards climate change in various manners. Aircraft emissions also cause poor local air quality in airport environs and various human health problems such as respiratory problems.

- Aircraft noise which besides being a nuisance is also linked to various auditory problems and recently to learning disorders in children living in affected areas.
- The use of land, many a time fertile land, forest areas and wildlife habitat areas, for the land take of airports.
- Waste problems due to the large amount of waste produced by the industry e.g. de-icing fluids, plastic food utensils and paper waste amongst others. Certain airports incinerate their waste on site causing further environmental problems.

Aviation's impact on the environment is now well documented and the industry is also taking note of it. The International Civil Aviation Authority (ICAO) has its Committee on Aviation Environmental Protection (CAEP) which is responsible for keeping the Annex 16 Standards (Environmental Protection) under review and for recommending new or amended certification standards on noise and emissions. The CAEP consists of various working groups and it has members from various countries scattered across the globe. Other countries and organisations e.g. the International Air Transport Association (IATA) and the European Union (EU) Commission have observer status.

Whereas airlines used to be traditionally very defensive of their industry when it came to the environment, they nowadays have a more proactive approach. Today some airlines publish their annual environmental reports in which they detail their effort to reduce the impact their activities have on the environment. Aircraft and engine manufacturers always emphasise improvements in their products which will benefit the environment. Countless advertisements can be seen nowadays in which reduced noise and fuel burn are highlighted. Whilst such reports and advertisements are often used as vehicles for a better image and hence better business, they also show that efforts are being made by the aviation industry to improve the environmental performance of aircraft and aviation related activities.

The environmental problems caused by aviation are very extensive and can all be studied and discussed in detail. However, this study will only deal with the effect on the environment of engine emissions from civil aviation. Military aviation, despite contributing significantly to the amount of emissions in the atmosphere, will not be considered.

2 The effect of engine emissions on the environment

2.1 World energy use and dependence on fossil fuels

It is estimated that in 1999 alone the whole world used approximately 380 quads of energy [4]. 1 quad = 1 quadrillion (× 10^{15}) British Thermal Units (**Btu**) =1.055 × 10^{18} Joules (**J**).1 quad is roughly equivalent to 30 billion litres of gasoline. The energy sources were as in Figure 1 below:

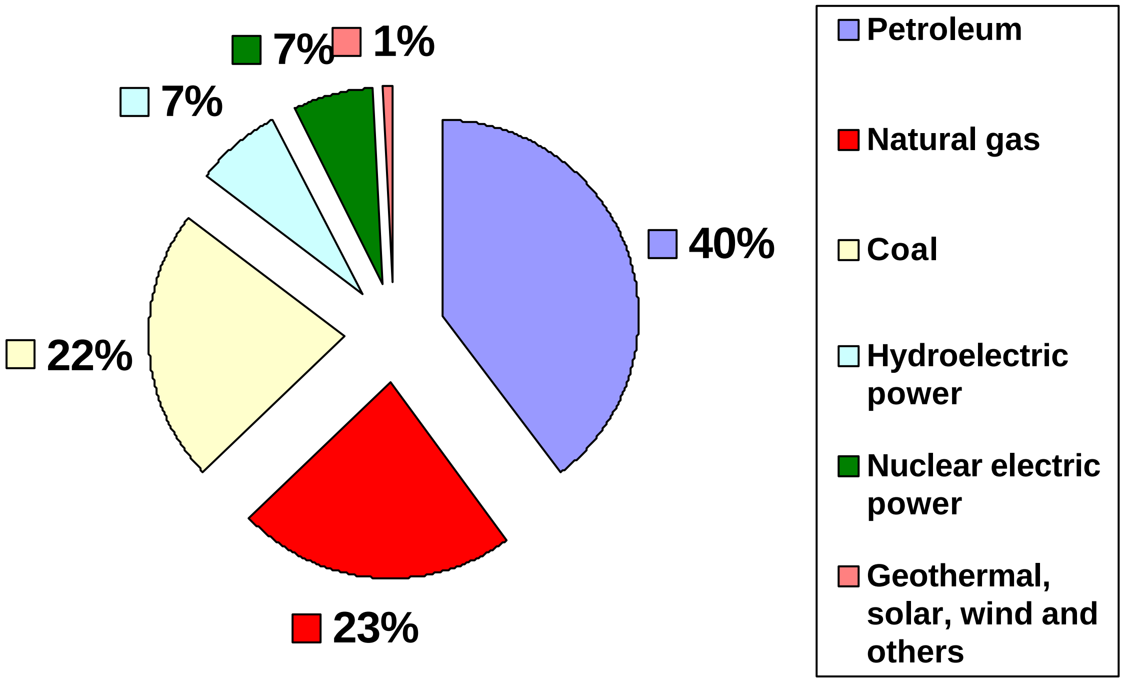


Figure 1: World Energy Use

One can see that most energy (85%) is produced from fossil fuels, all of which emit greenhouse gases into the atmosphere. The World population is increasing and in search of a better lifestyle people are using more and more energy per capita. The United States alone consists of only 5% of the world population, but consumes approximately one third of the energy consumed worldwide. One can immediately see the problems the world will face as large populations such as that of China justly aspire to a better lifestyle, which would obviously entail much greater consumption of energy per capita compared to today's levels for those countries. The problems will be many, including the availability of such energy. If such populations had to base their energy demands on fossil fuels the amount of greenhouse gases released into the atmosphere would increase tremendously.

2.2 Fuel used, the various engine emissions and their effect

Aviation accounts for 5% of the total world transport passenger market (measured in passenger-km). Road vehicles account for 75% whilst rail accounts for another 5% [5]. Transportation accounts for approximately 20-25% of all fossil fuels used worldwide. Aviation uses approximately 12% of the fossil fuels used for transportation purposes [6]. The US Energy Information Administration (EIA) estimated that in 1999 alone over 200 million tonnes of aviation fuel were used worldwide [7] (Figure 2) which is roughly equivalent to 250 billion litres (over 8 quads of energy).

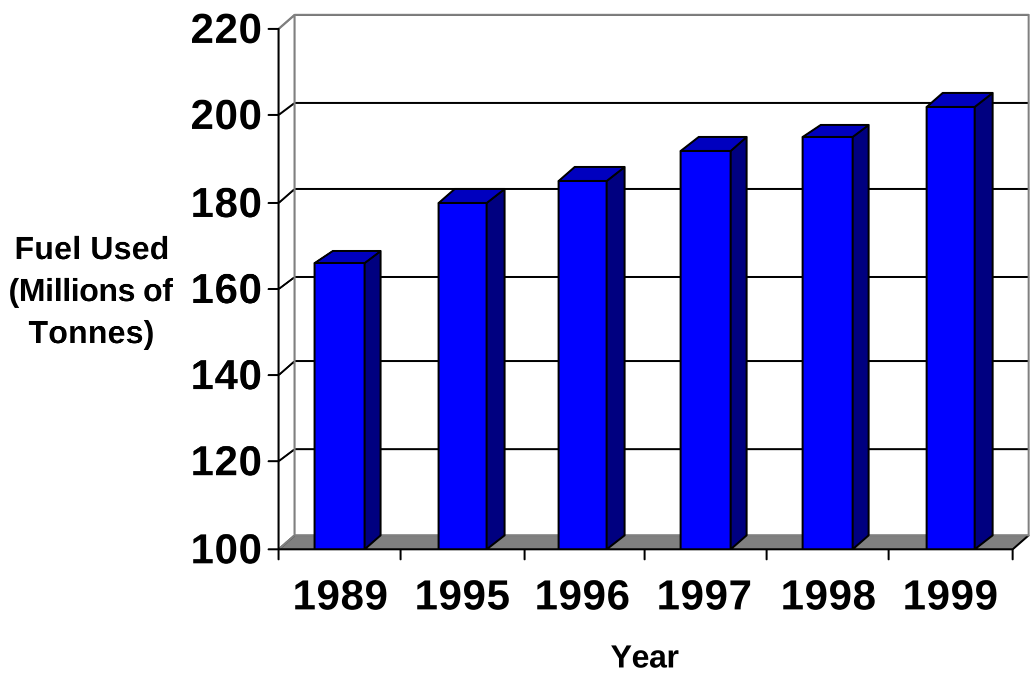


Figure 2: World Aviation Fuel Use

In 1996 ICAO requested the Intergovernmental Panel on Climate Change (IPCC) to prepare a report which would help achieve a better scientific understanding on aviation's impact on the atmosphere. In 1999 the IPCC presented the report, their first report dealing with a specific industrial sub-sector. Titled *'Aviation and the Global Atmosphere'* [6], the report listed all the emissions produced by aviation, their quantities and also their known effects.

Aircraft engines emit many different types of anthropogenic emissions and all these emissions have an effect on the environment. The aviation industry contributes about 3.5% of the total radiative forcing as a result of human activities. The term radiative forcing is used to express the change in the balance of the Earth's atmosphere system in Watts per square metre (**Wm^{-2}**) [6]. Positive values of radiative forcing imply a net warming, while negative values imply cooling. About half of all aircraft engine emissions are emitted at an altitude of 8-12km above the Earth's surface in the upper troposphere and lower stratosphere. At this altitude emissions have a more serious and longer lasting effect than at ground level. At ground level emissions can also lead to human health problems. The emissions and their effects on the atmosphere are here listed:

i. Carbon Dioxide (CO_2)

CO_2 is probably the most notorious of all greenhouse gases. Aircraft presently release approximately 2.5% of the total global emissions of CO_2 as a result of the burning of fossil fuels. This is equivalent to approximately 12% of the total emissions released by the transport industry (Figure 3) [6]. In 1992 alone approximately 514 million tons of CO_2 were emitted by aircraft [6]. CO_2 contributes to the warming of the Earth's atmosphere by retaining part of the solar radiation reflected off the Earth's surface. Every unit of fuel burned produces approximately 3.15 units of CO_2. When compared to 1750 (pre-industrial times) the level of CO_2 in the atmosphere in 1992 was 30% greater and this was mostly due to fossil fuel usage and partly due to land-use change and agriculture [6].

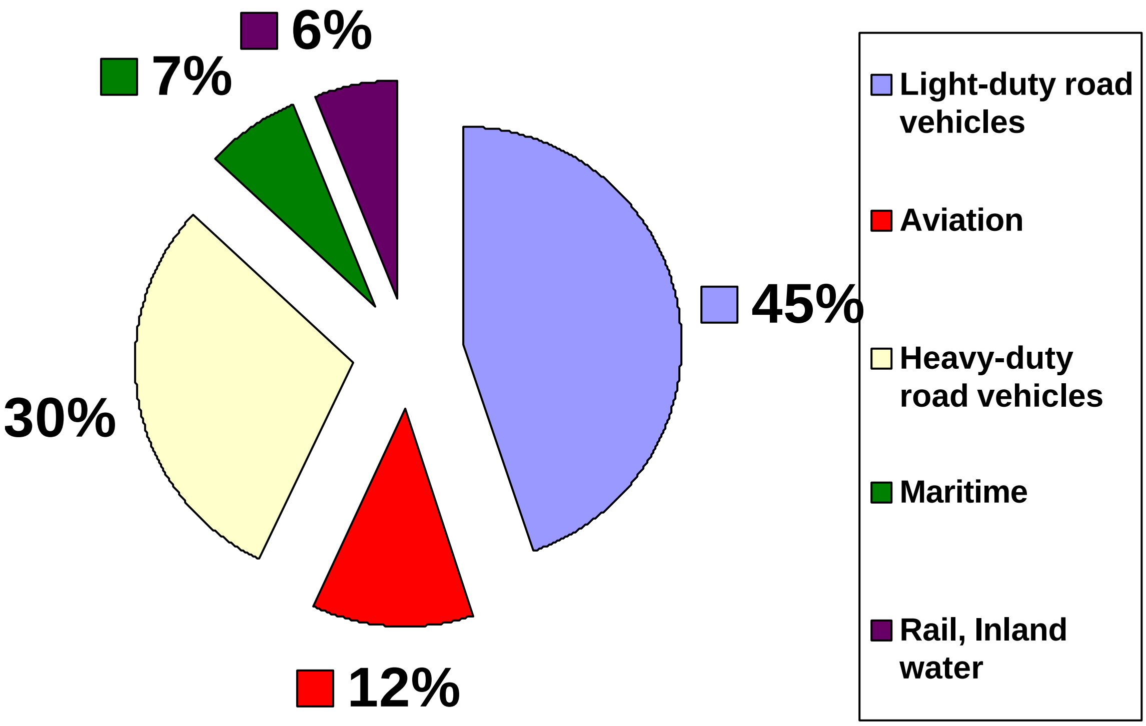


Figure 3: World Transport CO_2 Emissions

ii. Carbon Monoxide (CO)

CO is a poisonous gas and is a product of incomplete combustion. Its emissions are of particular concern in urban areas because of its effect on human health. It is not a greenhouse gas contributing to climate change. Two thirds of global CO emissions come from transportation sources. Increasing levels of CO reduce the atmosphere's ability to clean out pollution as it reduces the atmosphere's hydroxyl content. Atmospheric hydroxyl acts as what scientists define nature's detergent.

iii. Nitrogen Oxides (NO_X)

Nitrogen Oxides (NO and NO_2) are a by-product of combustion, created by the oxidation of nitrous oxide (N_2O) in the air. Usually the higher the temperature and pressure of the engine, the higher the amount of NO_X produced. Aviation accounts for 2-3% of all global man-made NO_x

emissions [6]. At low levels NO_X emissions increase the formation of ozone. This potentially affects local air quality. At cruise altitudes the effect of an increase in ozone is that of greater radiative forcing than at the surface and this contributes towards the warming of the earth's surface. In 1992 ozone concentrations at cruise altitudes in the northern mid-latitudes increased by approximately 6% as a result from emissions by subsonic aircraft.

NO_x emissions also react with tropospheric methane (CH_4) and as a result CH_4 concentration decreases. This tends to cool the surface of the earth as CH_4 is a greenhouse gas. In 1992 the CH_4 concentration in the atmosphere was estimated to be approximately 2% less due to the effects of aviation [6].

iv. Water Vapour (H_2O), contrails and cirrus clouds

Like CO_2, water vapour is also part of all natural combustion processes. Aircraft emit H_2O mostly in the form of contrails and the vapour also forms cirrus clouds. In 1992 approximately 0.1% of the earth's surface was covered by contrails. 30% of the earth's surface is covered by cirrus cloud and aircraft induced cirrus formation was estimated at 0-0.2% in the late 1990s [6].Contrails and cirrus clouds warm the earth's surface like greenhouse gases do, by retaining part of the solar radiation reflected by the Earth's surface. The full impact on the atmosphere of water vapour, contrails and cirrus clouds is still uncertain and is subject to further research.

v. Unburned Hydrocarbons (UHC)

During combustion, some of the carbon atoms of the hydrocarbon fuel (all fossil fuels are hydrocarbon fuels) may remain bonded to each other and to some hydrogen atoms forming unburned hydrocarbon molecules (mostly smaller than the ones in the original fuel) that may also be emitted.

These molecules react with nitrogen oxides in the presence of sunlight to form ozone, which is a lung irritant (the "ozone layer" in the stratosphere is a shield against the sun's ultraviolet light, but at ground level ozone is the main component of "photochemical smog").

vi. Other emissions

Aircraft also emit other pollutants into the atmosphere such as Sulphur Dioxide (SO_2), lubricating oils, metals, sulphates and soot. Some of these are in the form of aerosols. Sulphate and soot aerosols have opposite effects. Soot aerosols tend to warm the Earth's surface, whilst sulphate aerosols tend to cool it. Aircraft aerosol emissions are very small when compared to those emitted by surface sources and their residence time is very short, but they may cause additional cloud formation and also alter the radiative properties of existent clouds. SO_2 effects local air quality and causes many respiratory diseases. It also contributes towards acid rain after mixing with water vapour to produce sulphuric acid.

vii. Contribution towards climate change and residence times

CO_2 and water account for 35% of the contribution of aviation towards climate change whilst the other 65% is attributed to NOx emissions and contrails [2]. The radiative forcing effects of CO_2 and water are positive whilst those of NO_x and contrails are a mixture of positive and negative although they result in a net positive radiative forcing. The residence times of emissions varies. It is thought that CO_2 emissions have a residence time of approximately 100 years in the atmosphere, which means that they accumulate and that to stabilise the atmospheric CO_2 concentration at current levels there must be a 60% decrease CO_2 in emissions [6]! Other emissions are thought to have a much shorter residence time with water vapour having the least of all (1-2 weeks). CO_2 and CH_4 are also thought to mix with other gases and diffuse themselves throughout the atmosphere whilst the other emissions are thought to be more localised, remaining close to the flight path and altitude of the aircraft emitting them. However, the full effect of all emissions is yet to be properly determined. This is especially so with regards to water vapour, cirrus clouds and certain effects of NO_x. Their effect probably differs with altitude, latitude, climate and season. This could also mean that whilst CO_2 emissions contribute more to global climate change, water vapour, contrails and NO_x emissions have more of a localised effect. The IPCC [6] has determined the knowledge of all the emissions and their effects as shown in Table 1.

Table 1: Knowledge of effect of emissions on atmosphere

Type of emission	**Knowledge on effect on atmosphere**
CO_2	Good
Ozone (from NO_x)	Fair
Methane (from NO_x)	Poor
Water vapour	Poor
Contrails	Fair
Cirrus clouds	Very Poor
Direct Sulphate	Fair
Direct soot	Fair

2.3 Future Scenarios

Due to the uncertainty of the effects of certain emissions it is hard to predict the long-term effect of aviation emissions. What is known for sure is that the current trend of air traffic growth will mean that the amount of emissions in the atmosphere will increase drastically. The IPCC report [6] featured different models on air traffic growth, including high growth, normal growth and low growth scenarios.

The possible effects the projected increase in traffic will have on the environment were listed. With 2050 set as a target date (sometimes 2100) some of the possibilities we are facing are as follows:

- The radiative forcing caused by aviation may increase from 3.5% at present to as high as 15%, with the greatest probability of it being in the 5-6% region.
- The earth's average temperature could rise by approximately 1.6 Fahrenheit by 2050, 0.09 degrees of which would be attributable to aviation. Regional temperature rises could differ greatly from the global mean. Due to global warming average sea levels are expected to rise by 15-95 cm by the year 2100 compared to the levels in 1990.
- It is estimated that $C0_2$ emissions in 2050 could be range from 843 - 5317 million tonnes per year compared to 514 million tonnes in 1992. Air transport CO_2 emissions may represent as much as 3-11% of man-made CO_2 emissions compared to 2.5% today.
- Increased ozone concentrations at cruise altitudes in the northern latitudes may increase from 6% to as much as 13%.
- Atmospheric concentrations of methane may be about 5% less in 2050 than those calculated for an atmosphere without aircraft.
- The area of the earth's surface covered by contrails could increase from 0.1% to at least 0.5%. This rate of growth is greater than the rate of growth for aviation traffic and is due to the fact that more traffic seems likely to be concentrated in the upper troposphere where contrails form more easily.

It is accepted that with the current uncertainties over the effects of many emissions, that estimates for 2050 are far from accurate. However, the estimates also included projected technological and operational improvements including a 40-50% fuel efficiency gain by 2050. This shows the gravity of the situation we are facing.

The future fleet of aircraft will possibly also include a considerable amount of supersonic aircraft. Boeing has set the trend by announcing its intentions to produce the Sonic Cruiser. Supersonic aircraft as a rule fly higher than subsonic aircraft and also consume more fuel. Their effect on the environment will be much worse due to the increase in fuel burn and also due to the fact that the harm of emissions increases with altitude. Also the effects of emissions at such a high altitude (19km rather than 8-12km) will make it easier for emissions in the Northern Hemisphere, where there are much more emissions, to be transported to the Southern Hemisphere thus making the effects of the emissions more widespread.

Further studies into the effects of emissions are therefore essential. The findings will also help shape future technological advances and also measures taken to reduce the harm caused by emissions. Two issues requiring further research and which could significantly alter future developments are:

i. The effect of altitude on emissions is such that the higher the release of the emissions the more harm is done to the environment. What must be confirmed is the rate at which the effect worsens with altitude. The increase in harm caused by emissions may be such that the drive to save fuel by flying higher could well turn out to be counter-productive if would be confirmed that the increased harm offsets the savings in emissions released into the atmosphere as a result of reduced fuel burn.

ii. The effect of NO_x when fully determined must be compared with that of CO_2. Current technology, in its drive to reduce fuel burn and hence CO_2 emissions, at times improves fuel burn at the expense of increased NO_x emissions. Whilst benefiting airlines economically, such a scenario may be counter-productive in environmental terms, despite claims to the contrary.

3 Limiting emissions by means of technological improvements

The air transport industry is one of the most efficient sectors in the transport industry and it is the sector that has continuously improved its environmental performance the most over the years. If one looks at the achievements over the years, they are impressive. A few of them are listed here below:

- New aircraft today are 20dB quieter than those 30 years ago. This corresponds to a reduction in noise annoyance of about 75%. At London Heathrow traffic has increased by 60% since 1974, but only one fifth of the people are now affected by aircraft noise [5].
- Modern fleets are 70% more fuel efficient per passenger-kilometre than 40 years ago. This has been brought about by improvements in engine and airframe technology [5].
- Compared to an average mid-sized car a modern aircraft like the A330 burns less fuel per passenger kilometre (assumed 70% plus load factor for A330, 2 passengers for car). The A330 burns 3.4 litres per 100km compared to the car's 4.7 per 100km making it 28% more fuel efficient [8].
- New aircraft entering the market emit fewer emissions per passenger than older aircraft. Airbus estimates that the new A380 will emit 15% less emissions per passenger-km than the Boeing 747 does [8].
- With cleaner fuels and better engines certain emissions have been reduced drastically and some even practically eliminated e.g. UHC and CO [5].

3.1 How improvements have been achieved

Aircraft and engine manufacturers are always looking at ways of improving aircraft. The various fields of study include aerodynamics (leading to less drag), weight savings and also better engine efficiencies (less fuel combustion and cleaner combustion). The advances in fuel burn per passenger kilometre over the years have been achieved as follows:

- Two-thirds from improved engine technology leading to less fuel consumption
- One third from advances in the structure (material and weight) and aerodynamics of the airframe

3.2 What further improvements can be achieved and the limitations and problems of current technological improvements

Whilst we have seen enormous improvements over the years we are fast approaching the limit of what can be achieved with current technology. Assuming that the shape of aircraft remains the same (the conventional swept winged, cigar shape with podded under wing engines) the aerodynamic limits have been practically reached and no major improvements can be made. This design is now over 50 years old. The same can be said about improvements in engine technology. This can be seen by the fact that 53% out of the 70% gain in fuel efficiency achieved in the last 40 years was reached in the first 10 years with the remaining 17% in the last 30 years [2].

With regards to structures and materials used for the production of aircraft there is potential for further improvements. Airbus has been carrying out tests on a new glass fibre laminar composite called GLARE. It is said to give 15-28% weight savings when compared to aluminium alloys with the added benefit of higher strength, damage tolerance, better flame resistance and easier maintenance [8]. The take up of GLARE and also of carbon-fibre reinforced plastics (CFRP) and other materials is largely dependant on the price of such materials. The cost of the aircraft would likely increase due to the more advanced structural materials and airlines would only take up such an option if the extra money forked out would be regained relatively quickly through fuel savings. If fuel prices were to go up, such materials would become more and more attractive to the airlines. Research into reducing engine weight is also being carried out. This is more complicated as engines are full of complicated components. Also the benefits of a reduction in engine weight, whilst still offering fuel savings, are not much. A 10% reduction in engine weight reduces fuel burn by only 1.4% for a plane flying 15,000km [2]. Whilst any improvements resulting in a gain help it is obvious that improvements in engine weight are not going to be that effective.

Improvements are mainly economically driven rather than environmentally driven. The only environmentally driven improvements are those in engine noise and emissions affecting local air quality and only because laws have been passed to enforce noise and emission limits. All improvements in fuel burn at cruise altitudes have been made because they lead to economic gain for airlines. It is obviously a good marketing ploy to claim environmental awareness as the reason behind the improvements. We have now reached a stage where there is a clash between environmental and economical gains due to technological improvements. Aircraft are becoming more and more fuel efficient, however whilst CO_2 emissions are reduced with reduced fuel burn, the current engine technology means that more NO_x is emitted and more contrails are formed. Newer engines have higher pressure ratios and inlet temperatures resulting in a greater output of NO_x. This means that the effect on climate change of emissions could be worsening rather than improving as not all emissions and their greenhouse effect are directly linked to fuel burn. Aircraft are also being designed to fly higher and thus further reduce fuel burn but this also means that the greenhouse effect of emissions is increasing.

In a few years time there will be technology available to counter this e.g. inter-cooled recuperative engines (ICR) which offer higher thermal efficiencies and lower NO_x emissions. However at present such technologies would mean that engines would be heavier, need more maintenance and burn more fuel. Whilst making environmental sense this option does not make economic sense for airlines and would not be adopted unless it is enforced by means of stricter NO_x limits and regulations. This was the case with noise reduction. The trade off for reduced engine noise is higher fuel consumption, and airlines would have never complied unless regulation stated it! Nonetheless it is expected that these obstacles should be overcome in the next few years and some engine manufacturers predict a decrease in engine NO_x emissions by close to 30-50% below ICAO CAEP/2 limits by 2010 [1].

Greener by Design [2] expect the following to be achieved with improvements in current airframe and engine technology:

- Aircraft noise will be reduced by a further 10dB over the next decade. However sometime between 2010 and 2020 the downward trend will probably reverse as air travel growth will outstrip technological improvements.
- By 2050 aircraft will be 30-35% more fuel efficient than today. This is less than the IPCC's forecast of 40-50% [6]. However yet again and in both the Greener by Design and IPCC scenarios the growth in air travel will outstrip technological advance and more fuel will be burnt in total. In its report the IPCC projected a decrease in NO_x emissions per aircraft by 30-50% below ICAO CAEP/2 limits by 2020 [6].

It is clear that current advances in technology, with all their benefits, will ultimately not benefit the environment. Whilst airlines will benefit greatly from reduced fuel burn and reduced noise, the growth in traffic will always result in greater amounts of emissions in total. There is also a problem in the fact that the life cycle of modern aircraft is getting longer with aircraft nowadays expected to remain in service for at least 25-30 years. Whilst this is definitely of benefit to airlines as their investments are paying off better as a result of their assets having a greater life span, it also means that newer technology is now taking longer to enter into service than before.

It is estimated that with current technological improvements we will see a 3% increase in emissions for every 5% increase in traffic [5]. Some publications term it as “only 3%”. Whilst it is a positive sign that specific emissions per aircraft are being reduced, this is being more than offset by the increase in traffic and an increase of 3% per annum in emissions (assuming the forecast that traffic will increase at 5% per annum) will effectively mean that in just over 23 years there will be double the amount of emissions being released into the atmosphere by aircraft than today. Current levels are thought to be harmful, let alone double that, so the term “only 3%” is inappropriate.

4 Limiting emissions by means of operational procedures, infrastructural improvements, regulation and market based options

The other ways of limiting emissions besides technological improvements are by means of better operational procedures, infrastructural improvements, regulation and market based options. The possibilities and implications of such factors are discussed in this chapter.

4.1 Operational Procedures and Infrastructural Improvements

Operational procedures and infrastructural improvements can have an effect on the amount of fuel burnt per flight with 94% of fuel savings made at cruise levels, whilst the remaining 6% would be saved in the Landing and Takeoff (LTO) phases [1]. These improvements alone are said to be capable of helping reduce NO_x emissions by 10-16%.Some of the various operational procedures and infrastructural improvements are discussed here below:

i. Improved Air Traffic Management (ATM)

Studies have shown that an improved Air Traffic Control (ATC) infrastructure and improved ATM procedures can lead to a reduction in fuel burn of up to 6-12% worldwide [1]. These improvements can come in various forms such as:

- Better traffic flow management in terminal areas resulting in less holding patterns and radar vectors.
- Having aircraft fly at optimum altitudes to reduce fuel burn
- More direct routings for aircraft at cruise altitude thus shortening sector length and reducing fuel burn.

An ATM procedure which has already greatly reduced fuel burn is the introduction of Reduced Vertical Separation Minima (RVSM). At higher levels aircraft used to fly with a 2000ft vertical separation between them but now fly within 1000ft of each other. This means that more aircraft are filling the higher levels and RVSM has therefore contributed to less fuel burn per flight. It is estimated that the introduction of RVSM in European airspace in early 2002 will result in savings of over 290,000 tonnes of fuel each year. This would translate into approximately 913,500 fewer tonnes of CO_2 and 4,350 tonnes less of NO_x being emitted into the atmosphere [9].

The problem with such procedures aimed at enabling aircraft to fly higher is that they could be doing more harm than good. Whilst the amount of emissions released is being reduced, the damage caused could be worse if it is confirmed that the increased damage emissions cause when emitted at a higher altitude offsets the benefit of emitting less emissions. The emissions total is less but the greenhouse effect could be worse.

Making ATM more efficient and also able to cope with a greater traffic demand is also a good step forward. EUROCONTROL's Performance Review Commission, in a report in November 1999, stated that with no additional airspace capacity a 1% increase in demand would generate a 6% increase in ATM delays [1]. Therefore having the capacity to meet the anticipated traffic growth would reduce delays and their associated environmental impact. The environmental impact of these delays is in the form of:

- Fuel being burnt whilst taxiing in congested airports,
- Fuel burnt by APUs due to slot times keeping aircraft on the ground for longer periods
- More fuel being burnt en-route due to longer routings, flying at lower altitudes and more holding patterns.

In 1999 alone it was estimated that delay costs to airlines in Europe alone totalled approximately US$ 5 billion. IATA estimated that redesigning Europe's air routes could increase capacity by 30% at no additional cost for European States. Better traffic management on ground at London

Heathrow could save as much as 90,000 tonnes of fuel a year [10]! However it is generally accepted that as the airline industry grows more and more infrastructural problems will be encountered and this issue has not been dealt with in this report.

ii. Operational Measures

Certain operational measures are said to able to bring down fuel use by a further 2-6% [1]. These include the following:

- Elimination of non-essential aircraft weight e.g. lighter seats and in-flight entertainment systems
- Optimising aircraft speed
- Limiting Auxiliary Power Unit (APU) use
- Shortening taxiing distances

iii. Sector length, speed and cruise altitude

Modern aircraft are being designed to fly longer sectors as passengers and also airlines prefer flying direct routings rather than lengthening journey times by having fuel stops. Also there is a general trend for people have their holidays in further destinations. From 1982 to 1991 the average length of an air journey increased by 10% [11]. Aircraft manufacturers build aircraft to meet customer demand and this is also reflected in the advertisements made by the aircraft manufacturers to promote these aircraft such as

“A fuel stop has never been our idea of in-flight entertainment”

used by Airbus when advertising the A340. Studies have shown that aircraft designed to fly shorter sectors are more fuel efficient than those that fly longer ones. Greener by Design [2] compared an aircraft designed to fly 15000km in one sector at an altitude of 40,000ft and another designed to fly the 15000km in three sectors also at 40,000ft [2]. The following figures shown in Table 2 do however show how much extra fuel is being burned in order to provide passengers with quicker travelling times.

Table 2: Aircraft design range comparison

Design range (km)	Payload tonne	Fuel tonne	Max TOW tonne	Empty tonne	Fuel for 15000km tonne
15,000	44.8	120.4	300.0	134.8	120.4
5,000	44.8	28.6	169.0	95.6	85.8

(**Source: Greener by Design [2]**)

For a given payload an aircraft designed to fly a single 15000km sector burns 40% more fuel by completing the 15000km distance in one go compared to the one which performs three 5000km trips. The aircraft designed to fly the longer distance carries a lot of extra fuel, some of which is burnt in carrying the extra fuel weight over that distance. It also heavier (empty tonne) as a result of larger fuel tanks which lead to even more fuel being burnt! If the aircraft designed to fly 15000km had to fly the distance in three sectors the fuel savings, assuming the same given payload, would be of approximately 4%, which when converted into fuel figures means a saving of over 4.5 tonnes.

This study did however exclude the delays that would be caused by the increase in aircraft movements as a result of shorter sectors flown. More fuel would be burned due to congestion in terminal areas and airlines would face increased operating costs including handling costs, landing fees and also with the prospect of having to set up more hubs. Such a solution is highly unlikely to be implemented. The current trend seems to be more towards larger, long range aircraft such as the A380 as infrastructural limits are being reached, delays are increasing and airlines look to have more passengers travel per aircraft movement.

Flying at lower speeds means that less fuel is burnt. A reduction of 150 km/h decreases the energy requirement of an aircraft by 10-15% [11]. This is roughly equivalent to the fuel saved by flying 1000m higher. On the other hand maintaining the same speed at lower altitudes would result in a much greater fuel burn. Greener by Design calculated that an aircraft flying a distance of 15,000km would decrease its greenhouse impact by 30% if it flew at 35,000ft rather than 40,000ft [2]. This would however translate into a 24% increase in fuel burn if the same speed is maintained. In this case the costs for airlines would increase significantly. Therefore the amount of emissions would be the same if a plane flew slower and lower with the difference being that the reduced altitude would make the emissions less harmful. On the other hand flying lower and slower would result in more congestion at cruise level and terminal areas with lesser utilisation of aircraft for airlines, something airlines such as Ryanair rely on heavily in order to keep their costs down [12]. Also the current trend towards faster flying aircraft initiated by Boeing's Sonic Cruiser project shows that the industry is heading in a different direction.

iv. Load factors

There have been suggestions that in order to reduce the amount of emissions per passenger, there must be an effort to increase the load factors per flight. In the US the average load factor per flight is of 63%, in the UK it is 69% whereas in China it is 85% with the world average being 66%. With other things being equal in the US there is 10% more pollution per passenger-km compared to the UK and 35% more when compared to China [11]. A lot of this discrepancy in load factors can be attributed to the greater wealth and the deregulated aviation industry found in the US. An increase in world load factors to China levels could see a reduction in emissions of as much as 30%. There would also be greater savings due to less congestion and delays, whilst less aircraft would be needed which would also mean that the most modern and efficient aircraft would be kept.

Flights would have to be encouraged to depart with greater load factors by means of either movement taxation (discussed in 4.3) or attempting to reduce the problem of "no shows" which is common especially in business travel where people are booked onto more than one flight. Enabling tickets to be used on various airlines is another suggestion. Such suggestions would drastically alter aviation as a whole and alter the way in which airlines compete for passengers especially business travellers. There are also legal problems when it comes to transferring tickets and one must conclude that these suggestions are very unlikely to ever be taken up by the airline industry.

Another idea was to increase the number of seats on aircraft. Flights which operate with a business class section usually have a much greater seat pitch in the business class section, carry less passengers and therefore pollution per passenger is greater. This again is very problematic as it would primarily mean a great reduction in the service airlines can offer and business class traffic generates a lot of money for airlines. Also current concerns over Deep Vain Thrombosis (DVT) being caused by cramped seating conditions has led to lobbies pushing for greater spacing in-between seats in economy class.

4.2 Regulation

There are presently no international laws on emissions at altitude. This can be partly attributable to the fact that until recently there has been no strong lobby to reduce emissions at altitude such as those against aircraft noise and pollution in the areas around airports. The effects of noise and emissions in the vicinity of an airport are felt immediately, whilst in the case of emissions at altitude the effects are seen as of no immediate concern by a large percentage of the public.

Countries are currently looking into ways of reducing emissions, especially following the Kyoto Protocol in 1997. However the main obstacle to any international laws is the difficulty of ownership of emissions and allocation to countries. Should emissions be allocated to the country or countries which own the airline? Depending on the nationality of the passengers?

What if there are interlining agreements between airlines? It is very hard to find a way of allocating emissions, although the nationality of the passengers seems to be the fairest method. A quick and easy solution is not likely to be found. As a matter of fact, international aviation has been excluded from the Kyoto Protocol due to the ownership difficulties! This is not implying that nothing will be done; in fact there are recommendations within the Kyoto Protocol stating that steps must be taken in this regard. Domestic aviation emissions must be tackled as they have been included in the protocol.

The European Parliament (EP) adopted a report in 2000 which called for a reduction in greenhouse gas emissions from aircraft in line with Kyoto Protocol targets but it will not be easy to find an acceptable solution to all parties involved within the EU. This problem will be even more pertinent in the international arena. We have already witnessed many obstacles and a lack of political will to accept the Kyoto Protocol, the most obvious example being it’s rejection by the US. We have also seen the failure of the EU and the US to reach an agreement with regards to new and more stringent aircraft noise regulations. The US objected to the EU’s proposal to ban the operation of hush-kitted aircraft within the EU and the proposal was later shelved after the US threatened economic sanctions. The problem that Kyoto only addresses CO_2 emissions could have a detrimental rather than beneficial effect on aviation. NO_x emissions will probably increase and the greenhouse effect of emissions will also worsen as a result of aircraft flying higher in order to burn less fuel and hence reduce their CO_2 emissions.

ICAO regulations require aircraft to meet the engine certification standards contained in ICAO Annex 16- Environmental Protection, Volume II – Aircraft Engine Emissions. ICAO has historically only set limits for emissions at ground level mainly due to concerns over air quality in the vicinity of airports. Current limits are for NO_x, CO and UHC for a reference LTO cycle below 915 metres of altitude (3000ft). Whilst these limits are set for low-level emissions they do help control emissions at higher altitudes as technological improvements also affect the amount of emissions released at altitude. ICAO is currently considering parameters with a view of eventually introducing high-altitude emission controls. The main focus will be on NO_x as ICAO believes that enough effort is being made to reduce CO_2 emissions due to the fact that they are directly linked to fuel burn (economic gain the driver) and also partly due to anticipated difficulties in designing a certification condition for CO_2 emissions.

Until now there has been great opposition to very stringent NO_x limits for the LTO cycle. The effects of NO_x emissions are not yet fully known and it is argued that the costs incurred to abide to stricter limits, such as those proposed by CAEP/3, could far outweigh the benefits gained environmentally. At the present time the current limits in force which were recommended by CAEP/4 and later adopted by the ICAO council are seen to strike a balance between the environmental concerns and the technical feasibility to adopt them. The limits will obviously be reviewed if further studies do confirm that NO_x emissions cause significant harm to the environment.

4.3 Market Based Options

Market based options for reducing emissions are being studied. These include emissions trading, levies and charges, carbon offsets and taxation. The argument in favour of market based options is that aviation, like many other industries, does not account for the external costs it incurs. These include infrastructure use, noise and health costs as a result of transportation use, accidents and also environmental pollution. It is also argued that failure to account for external costs often leads to excessive use of a good or service, in this case air travel. Therefore the environmental and other external costs should be incorporated into the product price. Many different options and combinations have been suggested.

i. Emissions Trading

The concept of emissions trading comes from Article 17 of the Kyoto Protocol. An emissions trading system is a system whereby the total amount of emissions would be capped and allowances in the form of permits to emit greenhouse gases could be bought and sold to meet emission reduction objectives. Therefore the market would establish the price of the emissions certificates as those companies or industries able to reduce their emissions would sell their emission permits to other companies and industries that would prefer to buy permits rather than to reduce their emissions. This is considered as a cost-effective measure to limit or reduce greenhouse gases emitted by civil aviation and all other industrial sectors in the long term.

ICAO has endorsed the development of an open emissions trading system for international aviation. The ICAO Council is currently developing the guidelines for open emissions trading, focussing on establishing the structural and legal basis for aviation's participation in an open trading system, and including key elements such as reporting, monitoring, and compliance, while providing flexibility to the maximum extent possible consistent with the UNFCCC process.

There are two main obstacles related to emissions trading. The first one is that is should be an international system, with all industries involved. If aviation alone were to be targeted, it would be considered discriminatory and would place a great expense burden on the industry. It will already be very hard to get all countries to agree on a global aviation emissions trading system, let alone one in which all industries are involved. The setting of emission limits, means of trading, reporting etc. will all have to be agreed and implemented and that will take time. The second problem is the fact that only CO_2 emission trading is being considered by ICAO and other organisations (check 4.2 above for details). An option put forward is to give a warming index to each emission and this could be measured in CO_2 equivalent. Such a method could simplify emissions trading and most importantly include all emissions in an effort to curtail all their effects.

There is however the difficulty in comparing various emissions as the effects such as residence time and diffusion vary considerably.

Despite these problems, interest in trading is on the increase and countries like Norway and Denmark are already developing national trading schemes. The Kyoto Protocol has suggested that international trading schemes could begin in 2008. With time it is expected that the initial teething problems for emissions trading will be sorted and emissions trading will almost surely play a major part in a worldwide effort to reduce emissions.

ii. Levies and Charges

Other options being considered are levies and charges, all of which have been the subject of discussion. Two types of charges considered by the CAEP's market based options working group were en-route emissions charges and revenue-neutral aircraft efficiency charges.

The en-route emissions charge would work in a simple way. It could be charged by the countries which an aircraft over flies during a flight. The charge could be per distance flown or say for CO_2 emissions per distance unit or per aircraft type. The revenues retrieved from such a charge would then be used within the aviation sector in other mitigation measures. The problem with such a charge would arise if it were not to be introduced globally. Airlines could re-route their flight to avoid airspaces which enforce the charge and in the process distance flown and emissions released by the aircraft could increase.

The revenue-neutral aircraft efficiency charge system works in a different manner. The aim here would not be to raise money through the charges, which could be added to the existing air navigation charges, but to reward those airlines using more fuel-efficient and environmentally friendly aircraft. The less fuel-efficient aircraft would be charged more whilst the more fuel-efficient aircraft would be charges less. The total revenue gathered would be practically the same. The aim here is to create an incentive for airlines to use more environmentally friendly equipment. Here again if such charges are not implemented globally, competitive distortions could arise.

Currently one can find emission charging schemes at all Swedish airports and also at some Swiss airports. The charges here are added to the landing fees and are on NO_x emissions. The landing fees have been reduced accordingly to make the system a revenue-neutral one but the money from these environmental surcharges is nonetheless used for various environmental programmes at the airports such as air pollution monitoring stations and ground power stations. There is no charge for aircraft using engines in the “best” category and a 30-40% surcharge for those aircraft using engines in the “worst” category [1].

There are currently plans with the EU to introduce an environmental movement charge on flights. The charge will be per ticket meaning that passengers will foot the bill. Charges are expected to be approximately $ 7-15 on short haul sectors within the EU and as high as $ 70 per ticket on long-haul flights departing the EU [13]. Environmental protection is the main argument in favour of such charges and it is claimed that current fares set by airlines, especially low-cost carriers, create an artificial demand. If travelling costs were to increase people would not travel as much and less greenhouse gases would be emitted. Another argument is that most of the people travelling on planes are doing so for their holidays and that it is no injustice in taxing something that is basically non-essential.

There is great objection to such a tax within the aviation industry. Airlines see this increase in costs for the traveller conducive to reduced business and have spoken strongly against such plans. They argue that departure taxes paid by passengers which total close to $ 1.5 billion pay for the environmental damage caused by aircraft [13]. There is also the justified critique that the introduction of such a charge would place all passengers in the same basket irrelevant of the technology they use when travelling and amount of pollution they create. Would it be fair on the passenger who travels on an airline utilising a modern fuel efficient Boeing 737-800 to be charged the same as a passenger travelling on an airline using older, more polluting technology such as a Boeing 737-200? If such a charge had to be adopted without discriminating between emissions per passenger-km it and the engine technology used, it could actually slow down the drive for the introduction of more environmentally friendly aircraft. Whilst fuel burn will always be the subject of further research as it pays off in economical terms, there would be no drive to reduce other emissions such as NO_x. The net result would be higher ticket prices for the passenger and no real long-term environmental benefit.

Another argument is that such a charge would not be effective on certain routings. If one had to take the example of a UK resident travelling to the Far East one can immediately see that the Far East is much cheaper than the UK. This means that the price of the ticket is more than made up for by cheaper accommodation, food and other costs when compared to the UK. The ticket price increases will not affect travellers to certain destinations such as China as the holiday would still work out cheaper than living in the UK, especially a long holiday.

iii. Carbon offsets

Carbon offsets or carbon sequestration is being touted as another method of reducing the amount of CO_2 in the atmosphere. This method is used to offset the impact of the fossil fuels burned by aviation by investing in "carbon sinks" [14]. A carbon sink is defined as a natural or a man-made system that absorbs CO_2 from the atmosphere and stores it. Trees, plants and also oceans absorb CO_2 and store it or "sequester" it, hence the term carbon sequestration.

The Kyoto Protocol allows developed countries to include changes in net emissions (total emissions minus sequestered CO_2) by means of using forestry activities to offset industrial emissions. Evidence in Appendix I shows that at best carbon sequestration can only be used as one of many measures taken to offset the impact of aviation on the atmosphere.

iv. Taxation

Aviation fuel is currently exempt from taxation. There have been proposals to introduce a tax on aviation fuel, especially within the EU, as a way to reduce demand. It is said that if as a result load factors increase from 66% to 85% they would more than offset the effects of a fuel tax as airline costs would drop due to less flights, increased revenues per flight and the need for less aircraft [11].

In practice such a tax could prove to create more problems than it would seemingly solve. It is generally accepted that fuel costs are pretty low and if the cost of the fuel tax had to be passed on to the passenger by airlines, it would not reduce demand or increase load factors significantly. Also if a fuel tax would be within the EU alone it will create other problems. Airlines from other continents, at times competing on the same routings would have a distinct competitive advantage by having lesser fuel costs. Another problem would be the fact that fuel tankering would increase. Flights departing from airports within the EU flying to airports outside the EU would tanker as much fuel as possible from outside the EU seeing that it would be tax free. Some of the extra fuel taken on board would then be burnt as a result of carrying a greater fuel load than normal, so the emissions released per flight would increase when compared to a situation when fuel was tax free at both ends.

Plans for a fuel tax are also being met with objections from airlines. The airlines' arguments on this issue, although mainly economically driven do however make sense in environmental terms. Airlines have pointed out that such a tax will increase the drive towards reduced fuel burn, which would probably increase NO_x emissions due to even higher engine pressure ratios and also increase the greenhouse effect of gases due to aircraft flying higher in order to reduce fuel burn. A solution to this problem could be to couple such a tax with limits on NO_x emissions at altitude, but the process would be very complicated especially as one cannot calculate NO_x emissions easily as they are not directly related to fuel burn.

Another form of taxation could be in the form of a movement tax on airlines. Each aircraft movement would be taxed. This would lead to airlines trying to increase the load factors on flights in order to decrease movements. Flights as a total would decrease which would also mean that travellers will have less of a choice when it comes to travelling dates and times.

Whilst money collected from charges and levies would usually be used to address the environmental problems caused by aviation, there is no certainty that the money earned by governments from these taxes would be used similarly. Tax money goes into the government coffers and the government then decides how to spend it!

v. Alternative means of transport

Another option which is already being promoted is to try and get passengers to travel by means of more environmentally forms of transport. The focus here is on shorter routes such as short-haul flights within the EU. Many of these routes already have adjoining bus or rail links operating between the cities. Rail travel is being promoted with high-speed rail links between cities looking to be improved. Trains pollute much less than aircraft with typical carbon emissions being 5-50g per passenger-km depending on the source of primary energy, type of locomotive and load factor which is much less than that of air transport (30-110g per passenger-km) [5] and there could be an extra incentive to travel by train in the future if aircraft emissions and/or fuel become subject to charges or taxes.

The same goes for freight. Freight carried together with passengers only entails a small penalty in terms of fuel used. However freighter aircraft are solely dedicated to transporting cargo and the not urgent cargo could be made to travel by other means of transport whilst only freight such as perishable or urgent items e.g. fresh fruit and mail would be allowed to travel by air, especially over long distances. There are alternatives such as fast cargo-ships which can transport goods by sea over long distances in little time (3.5 days across the Atlantic) which could be attractive. High-speed rail could be another option.

IATA launched a study which analysed the impact on the aviation industry of various market based options. The scenario is for the year 2010 and the results are shown in Table 3.

Table 3: Cost/Benefit Analysis-Global Application *

Effects in 2010	Fuel taxation & en-route charge	En-route charge with rechannelling	Aircraft efficiency charge	Closed emissions trading	Open emissions trading
Equivalent fuel price increase (US$/kg)	0.23-1.80	0.50	n.a.	0.61-2.16	0.02-0.32
Demand reduction (% RTK)	6.9-32.4	13.0-14.5	0.0-1.4	17.5-40.5	0.5-9.1
Cost increase per RTK (%)	10.1-77.1	21.1-24.6	2.0-2.1	21.4-74.6	0.7-13.8
Reduction of industry operating results (billions US$)	0.49-19.7	2.6-5.1	0.8-11.7	4.7-8.5	0.0-0.9
"Out of pocket" cost for industry (billions US$)	47.4-245.3	84.5-91.4	0.20-0.30	100.0-246.0	3.6-62.9
Reduction of absolute aviation emissions CO_2 (%)	9.3-40.1	19.7-25.7	6.3-7.5	21.5-46.0	0.7-12.4
Reduction of aviation growth CO_2 (%)	25.6-110.0	54.0-70.6	17.2-20.6	50.8-110.0	2.0-33.9
Approximate cost per tonne of CO_2 removed (US$)	75-570	160	0	195-685	5-100

(Source: IATA [1])

* An increase in fuel price of US$ 0.23/kg equals approximately twice the average fuel price.
* The aircraft efficiency charge is based on a 46% rebate and a 200% surcharge
* The open emissions trading option assumes a permit price range of US$ 5 to 100.
* Results reflect the effects of achieving the assumed targets (aircraft efficiency charge expected). The lower end of the range corresponds to the 25% target, the upper end to the 5% below the 1990 target.
* Closed emissions trading was not analysed in detail.

When analysing the table one immediately notices that a closed emissions trading system will result in a great cost for airlines despite giving the best possible reduction in emissions. On the other hand an open emissions trading regime will cause much less stress for the aviation industry but the decrease in emissions can vary from insignificant to little more than 10%. Fuel taxation and en-route charges can have various effects and it really depends on the level of taxation on fuel and amount of money that is being charged. En-route charges seem to be able to cause quite a significant reduction in emissions and the costs here are much less than in a closed emissions trading system. An efficiency charge for aircraft alone is not too effective.

The best solution could be to have a combination of one or two of the above options. An open emissions trading system could be coupled with some form of charges in such a way that the most economic way of reducing emissions is found. It is clear that each option in isolation is either too costly for the aviation industry or not very effective in environmental terms. A balance has to be found and seems only possible if different measures are coupled together. However one must be straightforward and admit that it is very hard to see an environmentally effective solution in place which does not result in a great decrease in industry operating profits, a significant increase in industry costs, a reduction in demand and ultimately the loss of jobs within the industry. Low-cost carriers and cargo airlines are likely to be the airlines affected most by these measures.

5 Do future aircraft technologies and alternative fuels offer the answer?

From Chapters 3 and 4 one can conclude that no satisfactory solution can be found. Whilst these avenues must still be followed as they still offer a better situation than the status quo, it is obvious that:

- Current technological improvements are reducing emissions, but the increase in air traffic is cancelling out the improvements and actually increasing the total amount of emissions.
- Many of the operational procedures suggested are not feasible as they will create inconveniences and also delays.
- Market based options will cause great distress for the airline industry. Travelling costs will increase for passengers as airlines will face a dip in profits and increase in costs. Jobs will also be lost.

The question is, whether a solution that will benefit all parties involved (the environment and the airline industry) is possible? It is hard to actually come to an answer but a possible solution discussed in detail in this chapter involves:

- Advanced aircraft technologies and designs.
- An environmentally friendly fuel to substitute fossil fuels.

5.1 Advanced aircraft technologies

As shown in Chapter 3, the limits on improvements to current airframe and engine technologies have been nearly reached. Only minor improvements can be achieved and therefore only a radical change in aircraft design and operation can now significantly decrease the impact an aircraft has on the environment. Many studies have been carried out on new technology which would improve the aerodynamic capabilities and hence the fuel efficiencies of aircraft. Some of the most promising technologies being considered by aircraft manufacturers that could be incorporated on current aircraft designs and others that involve new shapes of aircraft, very different from those we see today are analysed below without going into too much technical detail:

i. Riblets

Airbus is currently looking at using thin, grooved layers of plastic called riblets which when fixed to the forward part of the upper wing surface are said to reduce drag by means of reducing skin friction. When applied there and to other parts of the fuselage aircraft drag is said to be reduced by approximately 1% [8]. Flight trials have been carried out but the main concern is the long term maintainability of the riblets.

ii. Hybrid Laminar Flow Control (HLFC) aircraft

Such an aircraft would be designed by having a different shaping to the aerofoil surface and also suction on surfaces to remove the boundary layer from smooth to turbulent airflow and thus reducing friction. Tests have been carried out with A320s and B757s [2]. There would be the benefit of less drag and therefore fuel savings. The downside is that the suction system would take up weight and also need to burn fuel to operate whilst maintenance costs could be expensive. Also, extra fuel might have to be carried to cater for an increase in fuel burn if the suction system fails as more friction would be present. This extra fuel load would also increase weight and fuel burn thus offsetting some of the gains in fuel efficiency.
Further research is required into this technology with the safest step probably being to introduce HLFC on small parts of the aircraft and thus minimising the risks, and unfortunately also the gains, until the technology is mastered.

iii. Blended Wing Body (BWB) aircraft

Nowadays interest in new aircraft designs has increased tremendously as the search for ever more aerodynamically and fuel efficient aircraft goes on. The Blended Wing Body (BWB) aircraft is seen as an extremely attractive option. There are currently two major research projects into this aircraft configuration. The first one is in the US and is being carried out by Boeing, the National Aeronautics and Space Administration (NASA) and Stanford University, whilst the second one is being carried out by the College of Aeronautics at Cranfield in the UK (Figure 4).

The BWB design sees the fuselage and wing becoming less distinct with the aircraft looking like a big flying V-shaped object. The engines would also not remain stuck at the bottom of the wing but would either be incorporated into the wing or placed towards the rear of the aircraft. Such a design would greatly reduce friction and increase aerodynamic efficiency. It is calculated that the Lift-to-Drag (L/D) ratio of such an aircraft would be 15% higher than that of conventional aircraft. The design would also offer a reduction of 14% in take-off weight for a given payload, therefore offering great fuel savings [2].

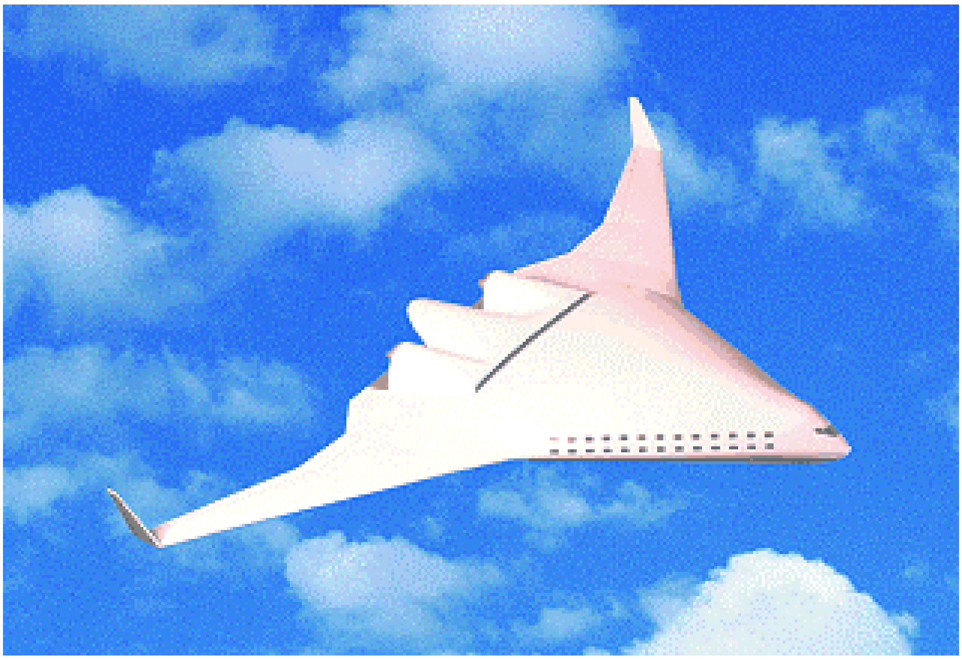


Figure 4: BWB design by College of Aeronautics, Cranfield

(Source: College of Aeronautics, Cranfield)

An even more advanced configuration of the BWB aircraft would see it have Full Laminar Flow Control (FLFC) working on the same principle as the HLFC aircraft but with much greater benefit due to the shape of the aircraft. Here again the same problems as for HLFC aircraft are predicted namely maintenance, added weight and also the carrying of extra fuel. As mentioned before such problems would be solved with time.

Another major step for the BWB aircraft would be it were to be propelled by unducted fan engines (UDF). Such engines are presently being researched and if successful the technology would provide us with the most efficient and least environmentally damaging engines ever seen. Greener by Design made a comparison of these technologies to conventional aircraft and the results are shown in Table 4 on the next page.

Table 4: Comparison of present and advanced aircraft designs

Configuration	**Empty tonne**	**Payload tonne**	**Fuel tonne**	**Max Take-off Weight tonne**
Conventional[1]	236	86	178	500
BWB[2]	207	86	137	430
BWB with FLFC[3] (laminar flying wing)	226	86	83	395
Laminar flying wing with UDF[4] engines	219	86	72	377

(Source: Greener by Design [2])

The BWB aircraft is 23% more fuel efficient than the conventional aircraft whilst the BWB with FLFC and the BWB with FLFC and UDF engines are 53% and 60% more fuel efficient respectively. Such an increase in fuel efficiency is exceptional and the impact of these future aircraft on the environment would be much less than that of current aircraft. These

[1] Current large, long range aircraft e.g. B747 or A340
[2] Blended Wing Body
[3] Full Laminar Flow Control
[4] Unducted Fan

aircraft are also said to be able to fly very efficiently at lower altitudes, thus also decreasing the greenhouse effect of emissions enormously. The cost of such aircraft remains to be seen, but such technology may become economically feasible if market based options and other attempts to reduce the impact on the environment caused by aviation and to restrict aviation growth come into play. There are worries as to how the general public would react to BWB aircraft as the design would probably involve a style of seating different to that on current aircraft i.e. longer rows of seats and little if any windows. A major obstacle to the introduction of the BWB is the fact that airports will have to change the design of their terminals to handle such differently shaped aircraft.

5.2 The case for Hydrogen as a fuel

This century will see mankind face the challenge of finding alternative energy sources as fossil fuel reserves dwindle (Appendix II). The research needed and the obstacles facing the introduction of alternative fuels are detailed in Appendix III. The transportation industry is heavily dependant on petroleum products, with 97% of the world's transportation being powered by petroleum products [15]. With an increasing world population, the world energy demand is also increasing.

In various reports about the future of aviation, alternative fuels such as hydrogen are given little mention. The fact that oil production will peak sometime between 2010 and 2020 has led to research into producing fuels from liquefied natural gas, coal, oil sands or biomass in order to satisfy increased energy demands [16]. This would mean that fossil fuel use would be extended, although it will be more expensive to produce, but even coal and natural gas will run out one day .Making fuel from biomass is problematic as it requires enormous land space to grow the crops as they do not have a high energy content. There is also the need of a large amount of energy to produce the biomass fuel. This means that harmful emissions will continue to be emitted into the atmosphere. Although the biomass fuel emissions will be sequestered once an equivalent amount of vegetation is grown to replace that used to make the fuel, the energy used to produce the biomass will not be recovered if it is fossil fuel energy.

Some reports do list hydrogen as a possible future alternative to fossil fuels, but do not consider it currently viable and forecast it's entry into the market towards the end of this century at best. However few reports have gone into the details of what it would entail to manufacture a commercially viable hydrogen fuelled aircraft, the advantages and disadvantages of hydrogen as a fuel and many other implications such as the changes needed in the fuel production, transport and storage infrastructure.

5.3 Facts, myths and realities about hydrogen

Hydrogen, the most abundant element in the universe is an invisible, colourless and tasteless gas. Hydrogen can be stored in various forms such as metal hydrides or nanofibres, as a pressurised gas or in a liquefied form. Studies have shown that to be used as an aircraft fuel, hydrogen should be stored liquefied at -253 C^o [17]. This would entail the least tank volume and hence weight. Using hydrogen fuel cells to power aircraft is practically impossible as the amount of fuel cells needed to store the energy requirements of an aircraft would be too heavy. There might be a case for the use of fuel cells to power APUs and Boeing has stated their intent of having fuel cell powered APUs for their Sonic Cruiser aircraft.

When stored in such a liquefied form, for the same energy content as jet-grade kerosene hydrogen will take up 4 times the volume of kerosene but it would still weigh 2.8 times less than the kerosene equivalent [15]. This would give a good payload advantage although some of it would be offset by the increased weight of the fuel tanks. When hydrogen will be used as a fuel a lot of the emissions currently emitted when fossil fuels are burnt will be eliminated. In fact for a mass of equal energy content hydrogen produces 2.6 times more water vapour than kerosene, but will emit no

CO_2, CO, SO_2, UHC and little quantities of NO_x [17]. The increase in water vapour means that there will be increased radiative forcing due to contrails and cirrus clouds, however the water vapour emissions will be cleaner as a result of having no other particles present as in kerosene and these emissions are the ones with the least residence times. Hydrogen's greenhouse effect is calculated to be 1/4th-1/5th that of kerosene [2].

It would be foolish to say that there will not be problems to solve before introducing hydrogen as an aviation fuel. The main problems are the following:

i. Changes to aircraft structure and aircraft parts

Hydrogen's greater volume and low temperature would require significant changes to the aircraft structure and a much more complicated fuel system. Certain components in the aircraft engine would have to be changed especially the fuel pumps and flow control valves. There will also need to be a new design for the combustion chamber in order to ensure low NO_x emissions. The design of parts that will have a long life is also a major challenge.

There is also the problem of where to place the larger tanks that store the large volume of hydrogen. The fire extinguishing system for the airplane would have to warn against hydrogen leaks rather than be utilised to extinguish a hydrogen fire. The only way of avoiding an explosive mixture of hydrogen and air would be to ventilate the places where such mixtures may form.

ii. The clean and cheap production of large quantities of hydrogen

Nowadays there is no efficient way of producing hydrogen cleanly. This means that there would be problems to produce the large amounts of hydrogen that the aviation industry would need. At present, large quantities of hydrogen can only be produced by methods which involve the burning of fossil fuels. This would just be transferring the emissions problem from one place to another. We would have little emissions at altitude but a significant increase at ground level in the areas where hydrogen will be produced.

The cleanest way to produce hydrogen would be by electrolysis, with the system being powered by solar energy. However current photovoltaic cells are not efficient enough to produce hydrogen in large quantities. A possible way of producing hydrogen is by using geothermal energy. Currently in Iceland there is a lot of research going on with the aim of making Iceland the world's first hydrogen economy with all its transportation systems and other industries powered by hydrogen. There is a lot of interest in this project, even from oil companies, and there is great optimism mainly due to the fact that Iceland is blessed with a lot of geothermal energy. The heat coming up from the ground may be used to produce hydrogen and when this is harnessed Iceland could become a major supplier of cleanly produced hydrogen to the world. Such a method of acquiring hydrogen would be used until other countries can produce their own hydrogen through solar power when that system is improved.

The price of hydrogen would also be a determining factor as to whether it will be commercially viable. Until now the production and storage of hydrogen, especially in liquid state, has been relatively expensive when one compares it to fossil fuels. It is hoped that as technology improves, the price of producing hydrogen will go down. What is certain is that as fossil fuels get scarcer their price will increase too. Another important factor in favour of hydrogen is that it does not carry many external costs with it. The Clean Energy Research Institute of the University of Miami calculated that in 1990 alone the worldwide environmental cost of burning fossil fuels amounted to approximately $2.3 trilion, equivalent to $ 460 for every man, woman and child on the planet [15]. There is also the ecological cost of digging for oil [18]. All of Louisiana's marshes were ruined by oil drilling as they become contaminated by salt water. This caused irreparable damage and resulted in the extermination of many species of fish present [16].

Another cost not calculated in the case of the US is the cost of keeping military forces stationed in the Middle East to ensure that oil shipping lanes remain open and that no rogue states or terrorists disrupt the oil trade. If all the above mentioned costs were to be added it is estimated that the cost per gallon would rise from $1.20 to approximately $4 per gallon (based on 1997 prices) [16]. In the future when hydrogen will be produced cheaply most countries will be able to produce their own energy needs, thus practically eliminating the costs for import and in the case of the US the cost of stationing military forces overseas.

iii. The bad reputation hydrogen has

The aviation industry is renowned for the importance it gives to safety. New aircraft must undergo rigorous testing and require safety certification by the authorities before entering into service. This would also be the case with hydrogen fuelled aircraft and the related fuel infrastructure. Within the aviation industry and also amongst the general public hydrogen has a bad reputation. It is seen as explosive and dangerous and not fit to be a transportation fuel. A lot of the notoriety that hydrogen enjoys comes from the 1937 Hindenburg disaster but a close look at the facts shows a very different picture. That incident which resulted in the death of 37 people actually came about as a result of the presence of static electricity in the air and the presence of highly inflammable materials in the airship's skin. The static electricity set off a spark which ignited the airship's skin. The hydrogen did contribute to the fire but so would have any other fuel as all fuels are inflammable.

In certain instances it is even claimed that hydrogen as an aircraft fuel would actually result in less people dieing in aircraft accidents. G. Daniel Brewer who was the manager of Lockheed's hydrogen programme in the 1970s and 80s made this claim and used the 1977 Tenerife disaster as his proof. That accident, the worst in aviation history, which resulted in the death of 583 people, happened when two B747s collided on ground. It has been calculated that whilst some 30 people died as a direct result of the impact the rest died due to the fire which lasted for over 10 hours. Brewer claimed that had hydrogen been the fuel present and not kerosene a lot of it would have escaped if the tanks had been ruptured. This is due to hydrogen's volatility. The flame would have therefore only lasted for a few minutes and a lot of the liquid hydrogen would have vaporised and dispersed before the flame could have spread. Also the heat radiation from the hydrogen flame would have been much less and hydrogen does not produce any toxic fumes compared to kerosene although this latter advantage may have been partially offset by the toxic fumes from burning material on the planes.

In the 1970s researchers at the Wright-Patterson Air Force Base in the US carried out tests on Styrofoam-lined aluminium containers containing liquid hydrogen and petroleum based jet fuels and achieved the following results [15]:

- Bullets were fired into the tanks but did not detonate the liquid hydrogen.
- The hydrogen fire was less severe and expired more quickly
- The heat content of the hydrogen flame was twice that of the petroleum fuel flame.

Other tests have confirmed that in the event of an accident hydrogen does not spread like hydrocarbon fuels do. The flame is hotter but the heat is radiated over a shorter distance. The only distinct disadvantage when compared to hydrocarbon fuels is the fact that the flame is at times invisible and people could unwittingly walk into it.

People who fear the worst about any possible future hydrogen pipelines which could be used in a hydrogen economy should know that in the industrial Ruhr region of Germany hydrogen has been transported for over 50 years in such a way. In fact many of the large chemical plants over there, which produce fertilizers and food additives amongst other things, are connected by means of a 130-mile system of buried steel pipelines which transports 10.6 billion cubic feet of hydrogen per year [15]. In all these years there have been no incidents arising from escaping hydrogen or potentially explosive hydrogen-air mixtures. NASA over the years has also transported millions of gallons of liquid hydrogen for its space programme without any serious mishap. Therefore transportation within the confines of an airport should not be too problematic.

The conclusion is that whilst like all fuels hydrogen does have its associated risks it poses less of a danger than kerosene. However with hydrogen's bad reputation it would be a must to educate the industry and general public alike before the possibility of a commercial hydrogen-fuelled aircraft becomes reality.

5.4 Hydrogen fuelled aircraft projects

Research into hydrogen fuelled aircraft has been carried out in the past and there have also been some test flights of aircraft which were partially or fully powered by hydrogen. In 1957 an American B-57 twin-jet bomber performed many test flights with one engine operating on pressure-fed liquid hydrogen. In 1988 a modified Tupolev 154 underwent a test flight with one of its engines powered by liquid hydrogen. Also in 1988, this time in Florida, William Conrad made aviation history when he flew his four-seat Grumman Cheetah exclusively on liquid hydrogen [19].

Nowadays the most intense research being carried out on hydrogen fuelled aircraft is by the European Aeronautic Defence and Space Company (EADS). The project, a system analysis of the CRYOPLANE involves thirty-five partners from eleven different European countries representing the aviation industry, research establishments and universities. This working group has been working since mid-2000 and the budget allocated for 2 years of studies is of 4.5 million Euros. The study is aimed at evaluating the feasibility and the environmental advantages of the CRYOPLANE. It is hoped that after the studies are carried out that further tests would then follow with the aim of delivering a first series of aircraft in 10-15 years time [17]. In their design, EADS have chosen to place the large fuel tanks on top of the fuselage (Figure 5).

Figure 5: Cryoplane as designed by EADS

(Source: www.cryoplane.com)

In 1999 NASA launched a 3-year programme with a $7 million budget with the aim to explore the prospects of hydrogen fuelled aircraft. The programme, titled "Zero CO_2 Emissions Technology Project" is also looking at the possibility of powering small (4-6 passengers) aircraft with ultra-lightweight fuel cell systems [15].

5.5 Introducing the new technologies and hydrogen fuel

The introduction of these new technologies will not be easy and the aviation industry would be faced with a transition period especially if it requires a change in the type of fuel used and its associated infrastructure. It is hard to predict when such technologies will become commercial realities. It is obvious that if market based options are utilised to control aviation emissions such technologies would be looked into further and become more and more attractive. If emissions trading certificates become more and more expensive and fuel prices go up the prospects for BWB aircraft will increase. Initial BWB aircraft are sure to cost a lot compared to conventional aircraft but increased commercial advantages and return on investment could quickly make good for the difference in price.

Hydrogen fuelled aircraft will probably face a harder challenge to be introduced than BWB aircraft mainly due to the bad reputation hydrogen has and also due to the requirement of a new fuel infrastructure. If hydrogen were to be successfully used initially to power APUs initial fears will be allayed. It would be very interesting to see which airline would be the first to buy such an aircraft. It is obvious that the option would become attractive if hydrogen was to be exempt from taxation and if the operation of aircraft would need little if any emission trading certificates thus giving potential buyers the prospect of greater or unlimited utilisation. An idea would be to have an airline alliance acquire such an aircraft and to operate it on certain selected routings. Airports used would have to be able and also willing to store hydrogen. If such a project were to take off the alliance and airports concerned would no doubt benefit from extensive media coverage and could also market their environmentally friendly credentials. A similar idea was in fact proposed by Daniel G. Brewer and Lockheed in the late 1970s. Titled the Liquid-Hydrogen Experimental Airline Project (LEAP) the project failed to win any support and was then shelved [15]. However with the greater environmental awareness present nowadays and with the advances made in hydrogen technology such a project would be more likely to take off. Such an aircraft operating on behalf of a large alliance (thereby sharing the costs and risks between various airlines) would operate into selected airports which would have hydrogen delivered from places outside the airport where the hydrogen would be produced. If such a project gains momentum and also acceptance the amount of aircraft and airports involved would definitely increase. Airports would then have hydrogen either pumped in a gas state via pipelines or delivered to the airport in fuel trucks. Airports may eventually produce their own hydrogen too with the use of solar panels as concerns over the safety of hydrogen diminish.

The two paths, the one of new aircraft designs and the one of alternative aircraft fuels, involve a lot of research. Both technologies will hopefully become reality in the future and will offer great fuel savings in the first case and reduced harm to the environment in the second case. The next step would be to make the two technologies meet. Greener by Design [2] have analysed the various designs of hydrogen fuelled aircraft and the results are shown in Table 5. One can see that the empty weights are very similar to the one for the kerosene fuelled aircraft shown in Table 4. The major difference is in the fuel weight which shows the weight savings gained by using hydrogen. From Tables 4 and 5 one can gather that the ultimate environmentally friendly airplane would be the hydrogen fuelled laminar flying wing. It has been calculated that such an aircraft would only have 1/40th of the greenhouse effect that a present day aircraft has. The BWB shape is also ideal for storing the large volume of hydrogen.

Table 5: Comparison of different hydrogen fuelled aircraft

Configuration	Empty tonne	Payload tonne	Fuel tonne	Max Take Off weight tonne
Swept wing (conventional)	238	86	68	392
BWB	204	86	49	339
Laminar flying wing (BWB with FLFC)	220	86	32	338

(Source: Greener by Design [2])

For such an aircraft to become reality there is the need of a lot more research and therefore a lot more funding. Here is where the role of governments is pivotal. Research into future environmentally friendly aircraft is dependant on funding and governments should do their best to increase the amounts of money currently being allocated. Such projects are very long term with target dates well beyond the usual 5-year vision that governments have i.e. by the time a government is up for re-election! Therefore there is a great need for governments to pledge their long term allegiance into helping find environmentally friendly solutions for the air transport industry.

6 Conclusions and Recommendations

One can draw many conclusions from this report. Aviation's impact on the environment is negative and also increasing. Environmental concerns are also increasing and there is an ever increasing lobby for sustainable development. Human activities will have to be controlled and aviation has no special right to be exempt from any effort to stabilise and then decrease harmful emissions. There are many options with which to tackle aviation's impact on the environment. Some of them are presently being carried out, others are planned to be implemented in the near future whilst others are still on the drawing board and depend on many factors to become reality. All these avenues must be followed as they will all bring some form of benefit.

From this reports the following conclusions and recommendations follow:

- Further research on emissions is recommended, especially into the effects of water vapour emissions (contrails and cirrus clouds) and also into the effects of NO_x. A clearer picture is needed before one can justify more restrictive regulation and emission limits. The effects of altitude, latitude, climate and season have on emissions must be known more accurately.
- Advances in current technologies must still be carried out. Whilst not offsetting the amount of emissions emitted due to traffic growth they do help make the situation a little less bad than it could be if no advances were sought. Most advances also offer economical gains with airlines saving on fuel as a result. Care must be taken not to disregard the effects of increased NO_x emissions due to emphasis on fuel savings. Low NO_x technology is available and there must be the necessary incentives to help introduce this technology.
- Better operational procedures must be introduced as soon as practicable. More efficient control of aircraft on ground and in the air can result in massive fuel savings besides reducing delays for airlines. One must however note that infrastructural limitations will come into

play as air travel grows and these limitations have not been analysed in this report.

- Regulation is a major driver to help enable the take up of new more environmentally friendly technologies. The role of ICAO and of governments is crucial. Unfortunately recent failures to achieve an international agreement on certain issues such as Kyoto and the removal of hush- kitted aircraft do not augur well.
- Market based options have been mentioned as a demand management option and it is only a matter of time before they are implemented in one way or another. All industries will be subject to some form of emission controls and the airline industry will be included in any effort to reduce harmful emissions. The aviation industry will not allow for any discrimination to be made against it whilst other industries will surely object if aviation is exempted from any measures taken. Taxation is not that good a route to follow as there is a question mark as to whether revenues collected would be funnelled back into the industry. Also a fuel tax could be counter-productive as fuel burn will be given priority rather than the total greenhouse effect. Environmental charges which revenue would be funnelled back into the industry to offset environmental damage done, help fund research into aviations environmental impact and that would reward the least polluting aircraft are a much better option. An emission trading system coupled with such charges would be the best option to control demand, increase the drive for more eco-friendly aircraft and also harm airlines the least financially. It has been shown that an open emissions trading system would be the fairest as all industries have to be held accountable for the pollution they cause. A closed emissions trading system would be discriminatory and would also drastically increase the costs for airlines. Nonetheless any form of market based options will definitely see a rise in costs for airlines, many of which will be passed on to the passenger and ultimately see a reduction in air traffic growth. It is hoped that market based options would see airlines increase their load factors.

This could partially offset the increased costs of movement charges and would also reduce pollution per passenger-km.

- The report concludes that in the long run it is only future technologies that will be capable of reducing the environmental impact of aviation on the atmosphere. The BWB aircraft which has been forecast to become a reality towards 2030 [10] will greatly reduce fuel burn. Current aircraft being produced will come to the end of their lifecycle towards 2030, so there is an outside chance that BWB aircraft could be their replacement. When FLFC technology will be added to it the fuel burn will once again be greatly reduced. It is hoped that at the same time advances in hydrogen fuelled aircraft technology would have been achieved. Hydrogen fuelled aircraft will face more problems prior to their introduction, mainly in the form of scepticism due to the bad reputation hydrogen has plus also the problems that catering for a new fuel infrastructure would bring. It is hoped that within the next 20 years a few prototype aircraft will be in circulation and that the view on hydrogen fuelled aircraft will change from one of a comic book fantasy into one of an option for environmentally friendly aviation. The introduction of fuel cells to power APUs will be the first step away from the use of fossil fuels. The role of governments is pivotal. Governments should back such initiatives with more funding and also make entry into service of such aircraft more attractive by means of tax incentives and also emission trading benefits. It remains to be seen as to whether governments that have depended on the oil industry in one way or the other will favour alternative fuels.
- It is recommended that the aviation industry should also adopt and encourage other measures which aid the environment. Airlines could promote more environmentally friendly holidays such as eco-tourism even though the environmental damage caused by air travel is much worse than the visible damage caused by other tourism activities. Airlines, airports and aircraft manufacturers could also look into better use of energy in their offices e.g. low energy light-bulbs and solar power, reducing paper waste and purchasing the most fuel efficient

vehicles for company operations. Airports on the other hand could utilise more environmentally friendly ways of transport to and from airports. The use of trains would help reduce the air pollution in airport neighbourhoods as a result of automobile emissions [20]. Car park fees could be raised in order to deter people from travelling to airport by car. Within the confines of airports the use of more environmentally friendly vehicles could be promoted [21]. A hydrogen fuelling station for airport vehicles was built in Munich airport in 1999 [15]. Vehicles working on fuel cell technology are set to become a commercial reality within the next decade and airports could offer to be the test beds for these vehicles. This again would help reduce air pollution in and around airports. Airports could also try to make more efficient use of their land. Certain airports already grow crops within their airport boundaries and such use of land which would otherwise go to waste is to be promoted. It will also give an economic gain to airports when such crops are sold.

- This report boils down to two major issues. The first is how air transport can develop amidst growing environmental concerns. The second is that mankind has a duty towards current and future generations. This duty is to provide sustainable development together with the least impact possible on the environment. This includes the ability to find the right balance between economic progress and environmental care. Whilst the unrestricted growth of aviation and other industries will bring increased economic activities, more jobs and greater wealth it will also bring increased health costs due to air pollution and damage, at times permanently, to frail eco-systems. Climate change as a result of fossil fuel use alone may be causing the most environmental damage of all human activities. The last few decades have seen a change in mentality with regards to the environment but there is still a lot to be done. This year’s UN Earth Summit in Johannesburg will see more than 100 heads of state and 65,000 delegates attend. This shows that the environment is no longer the obsession of the fanatical few people but the concern of all. It is hoped that this summit will see initiatives taken aimed at reducing the impact of human activities on the environment. The time is right to take action before the damage done is irreversible in some cases.

- Aviation like all other industries will have to play its part in a global effort for sustainable development. Aviation's emissions may only constitute 2-3% of the total emitted by human activities but if unrestrained they will grow to make an even larger percentage. Aviation has made the world a smaller place and has brought many benefits but the industry will also have to play its part in safeguarding the environment. The industry must be aware that as time goes on there will be an increasing social demand for change and it must be prepared to face any political measures taken. It must show its commitment towards the environment by helping find environmentally effective solutions in order to avoid the onset of draconian measures. The ideal situation would be for aviation to continue to grow and to also reduce its impact on the environment. The best solution to all this is in future technologies with environmentally friendly fuelled aircraft. The prospects of a hydrogen fuelled laminar flying wing may seem to be too far-fetched for many however with the right funding and the collective effort of governments and the aviation industry such prospects can become a reality midway through this century. Such a prospect may seem far-fetched but who, 100 years ago, would have dreamt that we would today be flying London to Beijing direct?

Glossary of Terms and Units

ATC	Air Traffic Control
ATM	Air Traffic Management
BWB	Blended wing body
C	Carbon
CAEP	Committee on Aviation Environmental Protection
CFRP	Carbon fibre reinforced plastics
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DVT	Deep Vein Thrombosis
EADS	European Aeronautics and Space Company
EIA	Energy Information Administration
EP	European Parliament
EU	European Union
FLFC	Full laminar flow control
GDP	Gross Domestic Product
H_2O	Water
HLFC	Hybrid laminar flow control
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICR	Inter-cooled recuperative engine cycle
IPCC	Intergovernmental Panel on Climate Change
LTO	Landing and take-off cycle
NASA	National Aeronautics and Space Administration
NO	Nitrogen Oxide
N_2O	Nitrous Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
RTK	Revenue Tonne Kilometres
RVSM	Reduced Vertical Separation Minima
SO_2	Sulphur Dioxide

UDF	Unducted fan
UHC	Unburned Hydrocarbons
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNFCC	United Nations Framework on Climate Change
US	United States

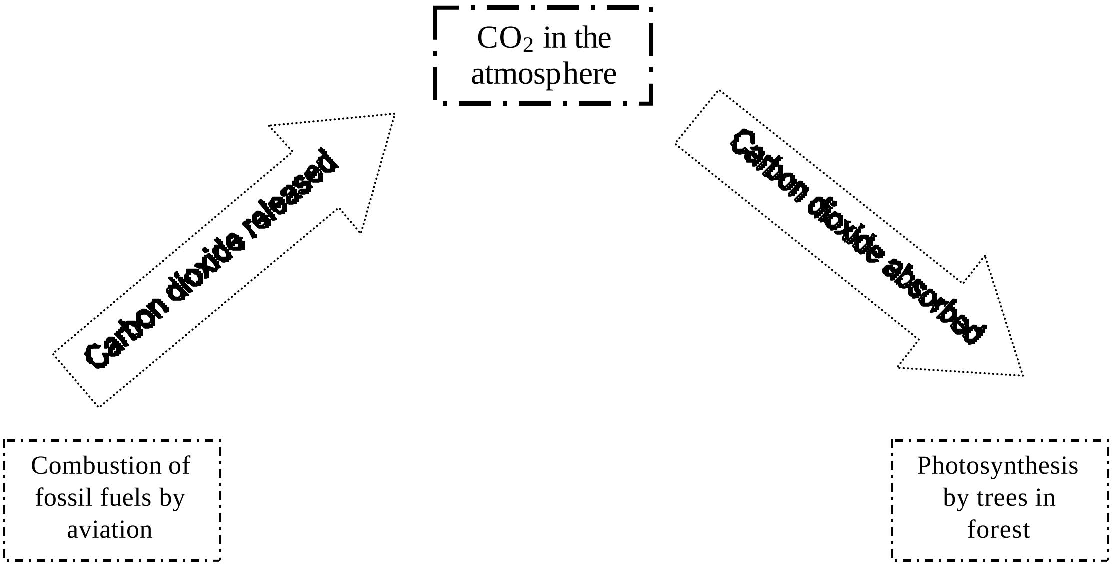
Units and technical terms

Btu	British thermal units
cm	centimetres
C^o	Celsius
dB	Decibel
F	Fahrenheit
ft	feet
J	Joules
kg	kilogrammes
km	kilometres
km^2	kilometres squared
load factor	proportion of aircraft carrying capacity used
passenger-km	distance travelled per passenger in kilometres
tonne	1000 kg
Wm^{-2}	watts per square metre

APPENDIX I

Carbon offset calculation

For this calculation it is assumed that the planting of trees will be used to offset the carbon emitted into the atmosphere as a result of the burning of fossil fuels as aviation fuel.



Forests are a major component of the global carbon cycle and it is estimated that they may absorb up to 25% of the 6 billion tonnes of carbon emitted into the atmosphere each year as a result of fossil fuel combustion [22]. However, deforestation is said to cause the emission of about 1.8 billion tonnes of carbon into the atmosphere each year. If carbon sequestration is to be used as a method of offsetting the carbon released into the atmosphere by human activities, current forests must be conserved and new forests must be created to absorb more and more carbon with their growing trees.

The main problem with this approach is that it is very complicated to calculate the total amount of carbon absorbed by the carbon sinks and also the rate at which it is absorbed. Also this method would never be able to balance the amount of emissions released into the atmosphere. Aviation alone released over 140 million tonnes of Carbon in 1992 and that rate is seen to increase to a much higher value by 2050 (IPPC gives a range of 230 to 1450 million tonnes) [6]. If this amount of carbon had to be translated into trees, it would take an enormous amount of tress planted per year to offset aviation's carbon emissions as shown here below [22]:

- It is assumed that 1200 trees can be placed in one hectare (0.01 km^2) of land. In one hectare, approximately 219 tonnes of carbon are contained 176 tonnes of which in the standing trees and the remaining 43 tonnes as non-decayed wood product.
- Each tree absorbs approximately 183kg of carbon which is equivalent to 669kg of CO_2 per tree {molecular weight of CO_2 is 44 whilst that of Carbon (C) is 12, so to convert C to CO_2 one must simply multiply the weight of C by 44/12}.
- Therefore to absorb 140 million tonnes of carbon each year, one would need to plant 140,000,000,000 ÷ 183 = 765,000,000 trees a year. That would mean that there would be need to convert 765,000,000 ÷ 1200 = over 637,500 hectares of land into forest every year to absorb aviation's emissions alone (only 2.5% of the CO_2 released into the atmosphere by the burning of fossil fuels). 637,500 hectares is equivalent to 6375 km^2.
- The above figures were achieved assuming a model type of tree. However the above figures would rise even more if one had to take account of the biodiversity of trees. Not all trees are of the same size and carbon content. It has been calculated that the average bio-diversity tree contains 268kg of CO_2 on average compared to 669kg for the model tree, nearly tripling the amount of land needed and trees to be planted to 1,590,000 hectares (15,900 km^2) and 1,910,000,000 trees respectively and that is only per year and also assuming no growth in emissions. This effectively means that every year a mass of land equivalent to close to half the size of Switzerland must be utilized to plant forests in order to offset aviation's CO_2 emissions. Therefore an area the size of Switzerland

will have to be afforested every two years, again assuming no growth in aviation CO_2 emissions which is not the case.

Figure 7: Switzerland **(Source: www.idci.gov)**

- The world's airlines have a total fleet of approximately 18,000 aircraft [2] which effectively means that on average each aircraft requires the planting of 1,910,000,000 ÷ 18,000 = over 106,000 trees a year to offset its CO_2 emissions. An A320 flying from Manchester to Malta (3 hrs 15 min flight on average) and carrying a full load of passengers burns approximately 8000kg of fuel. This is equivalent to 8,000 × 3.15 = approximately 25,000 kg of CO_2. Therefore for that flight alone there is need for 25,000 ÷ 268 = over 90 trees to be planted. 180 trees would have to be planted if one takes into consideration that it is a round trip flight (Manchester to Malta and back to Manchester or vice-versa). Therefore if 106,000 trees a year are needed to offset the average CO_2 emissions per aircraft this A320 can fly 106,000 ÷ 180 = approximately 590 round trips between Manchester and Malta a year carrying a full load of passengers. 590 round trips a year with each sector being in excess of 3 hours tallies with the average utilization rates of aircraft.
- Lastly there is the problem of what one must do with these trees once they die. If the trees are to be chopped down and sold to be

use as firewood the whole scope of such an exercise would be futile as the CO_2 would be re-released into the atmosphere. Therefore when dead the wood should be used in a way e.g. furniture so as ensure that there is no CO_2 re-emitted.

APPENDIX II

The Petroleum Interval and the need for alternative fuels

We are currently living in what is defined as the 'Petroleum Interval'. In 1859 Colonel Edwin Drake successfully managed to drill for oil and since then oil started being used as a fuel and gradually replaced coal as the major source of fuel [16]. Oil products are now the source of a great percentage of the energy used worldwide. Fossil fuels total 85% of the energy used worldwide, with petroleum products alone totalling 40% of the energy used worldwide and at economic cost [4]. The transportation industry is also heavily dependant on petroleum products, with 97% of the world's transportation being powered by petroleum products [15]. However, fossil fuels are not a renewable source of energy and one day the world will run out of fossil fuels. It is estimated that towards the end of this century there will be little if any oil left to be used worldwide [23]. This alone is already a worrying fact, but what is even more worrying is the fact that oil production will peak sometime between 2010 and 2020 [16]. This effectively means that if demand increases as a total, there will not be enough oil to meet that demand. With an increasing world population, the world energy demand is also increasing. Following this peak in oil production, oil production will gradually decrease as the century progress. This will also mean that the price of oil will also increase steeply. Despite the occasional hike in price, oil has been relatively cheaply available over the years especially when one considers the great benefits it has brought to the world's population.

The peak in oil production will mean that mankind will have to look at alternative sources of energy to power their homes, vehicles and also their aircraft. Such a scenario is inconceivable for some people, but the next 15 to 20 years will see mankind facing testing times with regards to energy use and availability. We can already see that previously oil rich countries are slowly running out of oil and that more and more countries are now depending on imported oil for their energy needs. Until the early 1970s the

United States was self sufficient in oil, but now it can only provide 41% of its own oil requirements with the rest being imported [24].

As the world oil reserves dwindle, the oil remaining will be mostly situated in the Persian Gulf which is a traditionally politically unstable region. Therefore besides there being a potential future energy crisis, this could also be coupled with a political crisis possibly resulting in economical and even military warfare. The need for an alternative source or sources of fuel has never been more evident.

APPENDIX III

Potential alternative fuels, the research needed and the obstacles facing their introduction

A lot of research will have to be carried out to find a suitable alternative fuel for aviation and other forms of transport. If possible this fuel should be a renewable fuel in order to avoid a repeat of the problems the world will face when its fossil fuel heritage will run out. The use of fossil fuels has been likened to living off the world energy's savings account. The emphasis must now shift more and more towards using the world energy's current account. There must also be a drive to use a fuel that is far more environmentally friendly than the fossil fuels currently being used. Achieving all this will not be as easy as some people may assume and this is due to various reasons. Petroleum products are relatively easy to produce, to use, transport and store, albeit with special care due to their inflammability, so a replacement fuel would preferably have similar characteristics. Petroleum products are also cheaply available (for the time being) so the price at which an alternative fuel is available is also a determining factor. At the moment most alternative fuels do not seem to offer such characteristics, especially as transportation fuels. Whilst solar, wind, geothermal and other energy sources can be used to power (or partially power) homes and industries there seems to be no way of harnessing such energy to be used at a later stage as in the case of fossil fuels. The only possibilities seem to lie in hydrogen (in a liquid state or through fuel cell technology) and maybe nuclear power although the latter's use as an aviation fuel is highly unlikely.

Many people assume that scientists will always have a ready answer to our problems and that this will be the case when there will be a petroleum fuel shortage, but this may not always be the case. Research takes time and a lot of funding is required, something which has been alarmingly lacking over the years with respect to alternative transportation fuels. For example in the US only $24 were allocated for research on hydrogen as a fuel in 1978 compared to $200 million allocated in the same year for research on how to convert coal into natural gas . The funding for hydrogen research was at such a level only due to concerns over energy availability due to the oil embargo on the US by the Persian Gulf states and it actually decreased to only $1 million in the early nineties when oil once again became easily and cheaply available. The funding level is now again at $24 million but it is not what one would call a high level of funding [15].

This shows that there is no real concern at the moment and more is being done to prolong the life of fossil fuels (in one form or another) than to eventually replace them. A lot has to do with the lack of political commitment towards alternative fuel energies. It is no secret that oil is behind the economic wealth of many countries at times helping turn a country from rags into riches especially in the Persian Gulf region. Such countries would like to see oil products used for as long as possible as that would mean that they will have an assured source of income for years to come. All forms of alternative energies are therefore not looked upon favourably. A clear example of this is a quote from Sheikh Ahmad Zaki Yamani, the Saudi Arabian oil minister, who during the oil embargo in 1976 said [15}:

"The big powers are seriously trying to find alternatives to oil by seeking to draw energy from the sun or water. We hope to God they will not succeed quickly because our position in that case will be painful."

Another stumbling block is the fact that the oil lobby and oil companies are very powerful worldwide with many large companies having operations in various countries. The oil industry has created a lot of jobs worldwide and has also supplied millions of people with their energy needs. It has also set up and donated money towards many charities and is therefore not all bad as certain people like to make it out to be. However it is also well known that oil companies fund the political parties in certain countries, who in turn are expected to pay back the companies by not causing them any harm through tougher environmental laws and funding of research into alternative energies when elected into government. Many of the politicians elected are often from the oil rich parts of a country, at times also having made a living from the oil industry. The US rejection of the Kyoto agreement is seen by many as a clear example of the links between politics and the oil industry. The rejection caused international outrage with the US government being accused of not wanting to harm the oil industry which certain political parties so heavily depend upon for funding.

Despite all this, there has recently been a shift towards the promotion of alternative fuels, especially in Europe where the environment is becoming increasingly important on the political agenda. It is obvious that when there is political backing in the form of exemption from taxation or funding, the research into and introduction of alternative fuels will be made easier and more attractive. Solar panels and other clean forms of energy have been subsidised or exempt from tax for quite some time in many countries. A totally perfect and non-polluting source of energy will be hard to find. For example solar cells are difficult to dispose of cleanly whilst wind power generators are very noisy and harm birdlife in the area.

A current major development is the research being carried out to find a substitute for gasoline to fuel cars. The health and environmental problems caused by car exhaust in European cities has reached alarming proportions and there is a drive to find a replacement fuel. The latest budget in the United Kingdom featured major incentives for green vehicles such as exempting hydrogen from any fuel taxes. Target levels for Carbon Dioxide emissions for vehicles are also being set with the aim of reducing them drastically over the next ten years, whilst pushing for the introduction of environmentally-friendly cars on the roads [25].

Such an attitude and actions would have to be adopted if there is to be a viable and environmentally-friendly fuel for aviation in the foreseeable future. Here again, as in the case of automobiles, the only fuel that seems capable of eventually replacing kerosene as an aviation fuel is hydrogen [26].

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