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Sustainable (Green) Aviation: Challenges and Opportunities

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Washington University in St. Louis

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AE/AIAA William Littlewood Memorial Lecture

Established in 1971, this lecture promotes civil air transportation and broadly addresses the current interests and major developments in this field. The objective is to advance air transport engineering and to recognize those who make personal contributions to the field.

This lecture honors the memory of William Littlewood, the only person ever to serve as President to both SAE International (SAE) in 1954 and the American Institute of Aeronautics and Astronautics (AIAA) in 1959. He was renowned for his contribution to the design of, and operational requirements for, civil transport aircraft. He was an active participant in educational, governmental, association, and engineering society affairs. In 1958, Littlewood was recognized as a recipient of the Daniel Guggenheim Medal which is awarded for great achievements in aeronautics. To perpetuate his memory, many of his friends requested SAE and AIAA to sponsor a series of lectures to be known as the "William Littlewood Memorial Lecture."

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2009 Recipient



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Professor Ramesh K. Agarwal is the William Palm Professor of Engineering and the director of Aerospace Research and Education Center at Washington University in St. Louis. From 1994 to 2001, he was the Sam Bloomfield Distinguished Professor, Chair of Aerospace Engineering Department (1994-96), and Executive Director of the National Institute for Aviation Research (1996-2001) at Wichita State University in Kansas. From 1978 to 1994, he worked at McDonnell Douglas Research Laboratories in St. Louis in a variety of research and administrative positions eventually becoming the Program Director and McDonnell Douglas Science and Engineering Fellow (1990-

94). Dr. Agarwal obtained his Ph.D. from Stanford University in 1975. Since then, he has worked in Computational Fluid Dynamics, Computational Magneto-hydrodynamics and Electromagnetics, Semiconductor Device Simulation, Rarefied Gas Dynamics, Bio-fluid Dynamics, Flow and Flight Control, and Multidisciplinary Design and Optimization. During his sixteen years with McDonnell Douglas Research Laboratories, Dr. Agarwal and his colleagues developed codes that have been used for the analyses of flow fields of all categories of air and space vehicles (transport- and fighter aircrafts, helicopter rotors, missiles and launch vehicles, and hypersonic space configurations). He is author/co-author of over 300 publications, and he has supervised 23 Ph.D. and 23 M.S. theses. He serves on the editorial board of several journals, and has served on several state and federal government advisory committees and university and industry advisory boards.

Dr. Agarwal is the recipient of many awards and honors which include AIAA Distinguished Lecturer; ASME Distinguished Lecturer; IEEE Distinguished Lecturer; Kansas Academy of Science Distinguished Lecturer; American Physical Society Forum on Industrial and Applied Physics Distinguished Speaker; Missouri Academy of Science "Most Distinguished Scientist Award;" AIAA Civic Service Award; AIAA Sustained Technical Achievement Award; ASME Fluids Engineering Award; ASME Charles Russ Richards Memorial Award; Royal Aeronautical Society Gold Award; AIAA Aerodynamics Award, WSU President's Award for Distinguished Service; AIAA Engineer of the Year Award; University of Kansas Irving Youngberg Research Award in Applied Sciences; WSU Excellence in Research Award; WSU College of Engineering Award for Continuing Education; AIAA Technical Achievement Award - St. Louis Section; IEEE Award of Honor - St. Louis Section; and I.I.T. Kharagpur Distinguished Alumni Award.

Dr. Agarwal is a Fellow of nine professional societies: American Association for Advancement of Science, American Institute of Aeronautics and Astronautics, American Physical Society, American Society of Mechanical Engineers, Institute of Electrical and Electronics Engineers, Society of Automotive Engineers, Society of Manufacturing Engineers, Royal Aeronautical Society, and World Innovation Foundation.

Dr. Agarwal received Ph.D in Aeronautical Engineering from Stanford University in 1975, a M.S. in Aeronautical Engineering from the University of Minnesota in 1969 and a B.S. in Mechanical Engineering from Indian Institute of Technology, Kharagpur.

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ABSTRACT

Air travel continues to experience the fastest growth among all modes of transportation. Therefore the environmental issues such as noise, emissions and fuel burn (consumption), for both airplane and airport operations, have become important for energy and environmental sustainability. This paper provides an overview of issues related to air transportation and its impact on environment followed by topics dealing with noise and emissions mitigation by technological solutions including new aircraft and engine designs/technologies, alternative fuels, and materials as well as examination of aircraft operations logistics including Air-Traffic Management (ATM), Air-to-Air Refueling (AAR), Close Formation Flying (CFF), and tailored arrivals to minimize fuel burn. The ground infrastructure for sustainable aviation, including the concept of 'Sustainable Green Airport Design' is also covered.

INTRODUCTION

In the next few decades, air travel is forecast to experience the fastest relative growth among all modes of transportation, especially due to many fold increase in demand in major developing nations of Asia and Africa. Figure 1 shows the expected growth in passenger traffic volume in Passenger Kilometers Traveled (PKT) by major modes of transport [1]. Air travel and other high speed transport accounted for less than 1% of world passenger traffic volume in 1950 and for 10% in 2005; they are forecasted to account for between 36 to 40% by 2050. These projections are based on 3% growth in

world Gross Domestic Product (GDP), 5.2% growth in passenger traffic and 6.2% increase in cargo movement. As shown in Figure 2, as the GDP/capita of nations increases, the demand for travel follows [1].

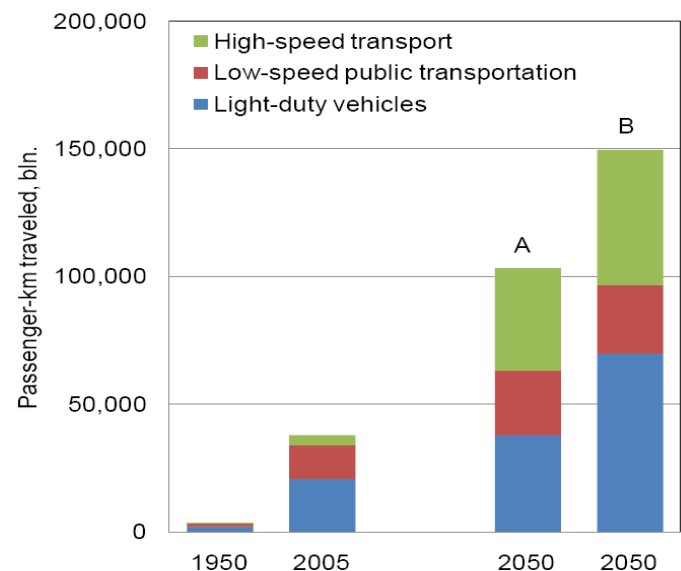


Figure 1 Projected Growth in World Passenger-Kilometers Traveled (PKT) [1]

Based on these demands for air travel, Boeing has determined the outlook for airplane demand by 2025 as shown in Figure 3 [2]. Figure 4 shows various categories of 27,200 airplanes that would be needed by 2025 [2]. The total value of new airplanes is estimated at \$2.6 trillion. As a result of three fold increase in air travel by 2025, it is estimated that the total CO₂ emissions due to commercial aviation may reach between 1.2 billion

tonnes to 1.5 billion tonnes annually by 2025 from its current level of 670 million tonnes. The amount of nitrogen oxides around airports, generated by aircraft engines, may rise from 2.5 million tonnes in 2000 to 6.1 million tonnes by 2025. The number of people who may be seriously affected by aircraft noise may rise from 24 million in 2000 to 30.5 million by 2025. Therefore there is urgency to address the problems of emissions and noise abatement through technological innovations in design and operations of the commercial aircraft.

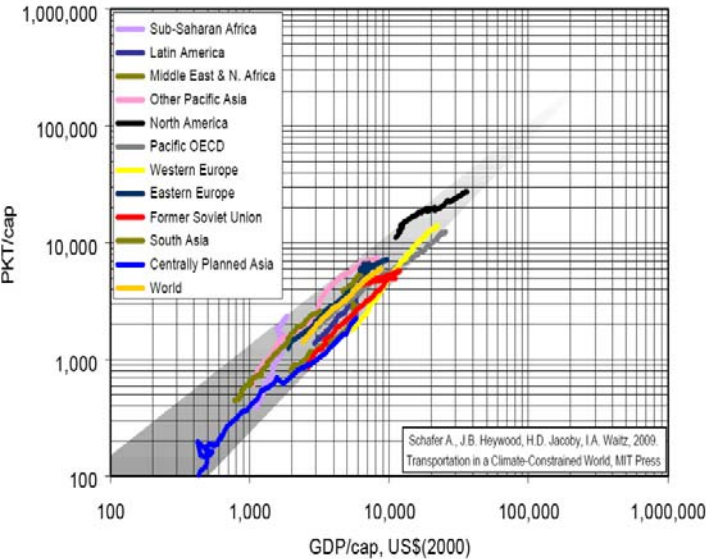


Figure 2: Increase in Travel Demand/Capita with Increase in GDP/Capita [1]

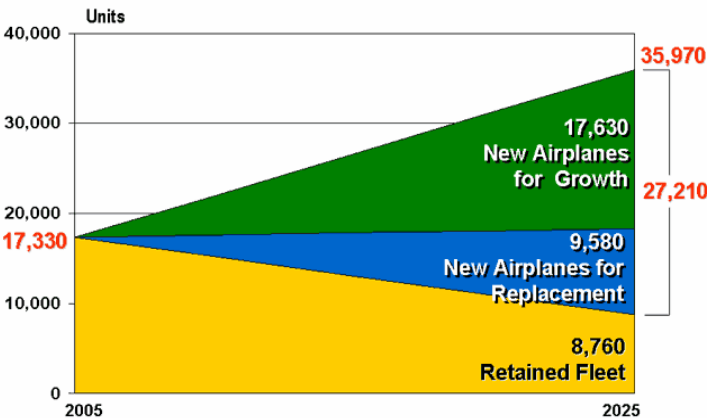


Figure 3: Boeing Market Forecast for New Airplanes [2]

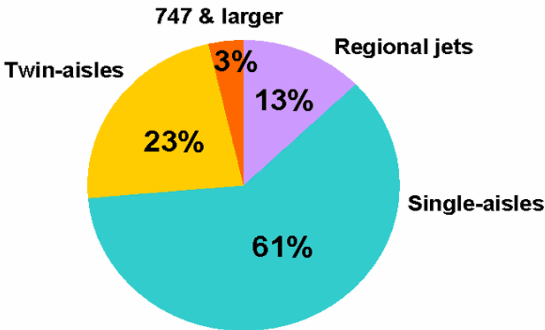


Figure 4: Boeing Demand Forecast for Various Types of Airplanes by 2025 [2]

ENVIROMENTAL CHALLENGES

To meet the environmental challenges of the 21st century, as a result of growth in aviation, the Advisory Committee for Aeronautical Research in Europe (ACARE) has set the following three goals for reducing noise and emissions by 2020; (a) reduce the perceived noise to one half of current average levels, (b) reduce the CO₂ emissions per passenger kilometer (PKM) by 50%, and (c) reduce the NO_x emissions by 80% relative to 2000 reference [3]. NASA has similar objectives for 2020 as shown in Figure 5 for N+2 generation [4]. It is expected that the technology readiness level (TRL) of N+1, N+2 and N+3 generation will be between 4 and 6 in 2015, 2020 and 2030 timeframes respectively. The NASA definitions of TRL are given in Reference [5]. TRL 4-6 implies that the key technologies readiness will be somewhere between component/subsystem validation in laboratory environment to system/subsystem model or prototyping demonstration in a relevant environment.

CORNERS OF THE TRADE SPACE	N+1 (2015 EIS) Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020 IOC) Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2030-2035 EIS) Advanced Aircraft Concepts (relative to B737/CFM56)
Noise (cum below Stage 4)	- 32 dB	- 42 dB	better than -71 dB (55 LDN at average boundary)
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75% plus mitigate formation of contrails
Performance: Aircraft Fuel Burn	-33%***	-40%***	better than -70% plus non-fossil fuel sources
Performance: Field Length	-33%	-50%	exploit metro-plex concepts

*** An additional reduction of 10% may be possible through improved operational capability; metro-plex concepts will enable optimal use of runways at multiple airports within the metropolitan area

Figure 5: NASA Subsonic Fixed Wing System Level Metric for Improving Noise, Emission and Performance Using Technology & Operational Improvements [4]

The achievement of these goals will not be easy; it will require the cooperation and involvement of airplane manufactures, airline industry, regulatory agencies such as ICAO and FAA, R & D organizations, as well as political will by many governments and support of public. However, these challenges can be met with concerted efforts as stated beautifully by the Chairman, President and CEO of Boeing Company, W. J. McNerney, “Just as employees mastered “impossible” challenges like supersonic flight, stealth, space exploration and super-efficient composite airplanes, now we must focus our spirit of innovation and our resources on reducing greenhouse- gas emissions in our products and operations.”

A LIST OF NEW TECHNOLOGIES AND OPERATIONAL IMPROVEMENTS FOR GREEN AVIATION

Recently, Aerospace International, published by the Royal Aeronautical Society of U.K., has identified 25 new technologies, initiatives and operations

improvements that may make air travel one of the greenest industries by 2050 [6]. These 25 green technologies/concept areas are listed below from Reference [6].

1) *Biofuels* – These are already showing promise; the third generation biofuels may exploit fast growing algae to provide a drop-in fuel substitute.

2) *Advanced composites* – The future composites will be lighter and stronger than the present composites which the airplane manufacturers are just learning to work with and use.

3) *Fuel cells* - Hydrogen fuel cells will eventually take over from jet turbine Auxiliary Power Units (APU) and allow electrics such as in-flight entertainment (IFE) systems, galleys etc. to run on green power.

4) *Wireless cabins* – The use of Wi-Fi for IFE systems will save weight by cutting wiring - leading to lighter aircraft.

5) *Recycling* - Initiatives are now underway to recycle up to 85% of an aircraft's components, including composites - rather than the current 60%. By 2050 this could be at 95%.

6) *Geared Turbofans (GTF)* - Already under testing, GTF could prove to be even more efficient than predicted, with an advanced GTF providing 20% improvement in fuel efficiency over today's engines.

7) *Blended wing body aircraft* - These flying wing designs would produce aircraft with increased internal volume and superb flying efficiency, with a 20-30% improvement over current aircraft.

8) *Microwave dissipation of contrails* – Using heating condensation behind the aircraft could prevent or reduce contrails formation which leads to cirrus clouds.

9) *Hydrogen-powered aircraft* - By 2050 early versions of hydrogen powered aircraft may be in service - and if the hydrogen is produced by clean power, it could be the ultimate green fuel.

10) *Laminar flow wings* – It has been the goal of aerodynamicists for many decades to design laminar flow wings; new advances in materials or suction technology will allow new aircraft to exploit this highly efficient concept.

11) *Advanced air navigation* - Future ATC/ATM systems based on Galileo or advanced GPS, along with international co-operation on airspace, will allow more

aircraft to share the same sky, reducing delays and saving fuel.

12) *Metal composites* - New metal composites could result in lighter and stronger components for key areas.

13) *Close formation flying* - Using GPS systems to fly close together allows airliners to exploit the same technique as migrating bird flocks, using the slip-stream to save energy.

14) *Quiet aircraft* - Research by Cambridge University and MIT has shown that an airliner with imperceptible noise profile is possible - opening up airport development and growth.

15) *Open-rotor engines* - The development of the open-rotor engines could promise 30%+ breakthrough in fuel efficiency compared to current designs. By 2050, coupled with new airplane configurations, this could result in a total saving of 50%.

16) *Electric-powered aircraft* - Electric battery-powered aircraft such as UAVs are already in service. As battery power improves one can expect to see batteries powered light aircraft and small helicopters as well.

17) *Outboard horizontal stabilizers (OHS) configurations* – OHS designs, by placing the horizontal stabilizers on rear-facing booms from the wingtips, increase lift and reduce drag.

18) *Solar-powered aircraft* - After UAV applications and the Solar Impulse round the world attempt, solar-powered aircraft could be practical for light sport, motor gliders, or day-VFR aircraft. Additionally, solar panels built into the upper surfaces of a Blended-Wing-Body (BWB) could provide additional power for systems.

19) *Air-to-air refueling of airliners* - Using short range airliners on long-haul routes, with automated air-to-air refueling could save up to 45% in fuel efficiency.

20) *Morphing aircraft* - Already being researched for UAVs, morphing aircraft that adapt to every phase of flight could promise greater efficiency.

21) *Electric/hybrid ground vehicles* – Use of electric, hybrid or hydrogen powered ground support vehicles at airports will reduce the carbon footprint and improve local air quality.

22) *Multi-modal airports* - Future airports will connect passengers seamlessly and quickly with other destinations, by rail, Maglev or water, encouraging them to leave cars at home.

23) *Sustainable power for airports* - Green airports of 2050 could draw their energy needs from wave, tidal, thermal, wind or solar power sources.

24) *Greener helicopters* - Research into diesel powered helicopters could cut fuel consumption by 40%, while advances in blade design will cut the noise.

25) *The return of the airship* - Taking the slow route in a solar-powered airship could be an ultra 'green' way of travel and carve out a new travel niche in 'aerial cruises', without harming the planet."

Some of the ideas listed above require technological innovation in aircraft design and engines, use of alternative fuels and materials while others require operational improvement. Some concepts such as electric, solar and hydrogen powered aircraft are currently feasible but are unlikely to become viable for mass air transportation by 2050. In what follows, we describe the current levels of noise, CO₂ and NO_x emissions due to air transportation and possible strategies for their mitigation to achieve the ACARE and NASA goals.

NOISE & ITS ABATEMENT

Historically, the reduction in airplane noise has been a major focus of airplane manufacturers because of its health effects and impact on the quality of life of communities, especially in the vicinity of major metropolitan airports. As a result, there has been a significant progress in achieving major reduction in noise levels of airplanes in past five decades as shown in Figure 6 [7]. These gains have been achieved by technological innovations by the manufacturers in reducing the noise from airframe, engines and undercarriage as well as by making changes in the operations.

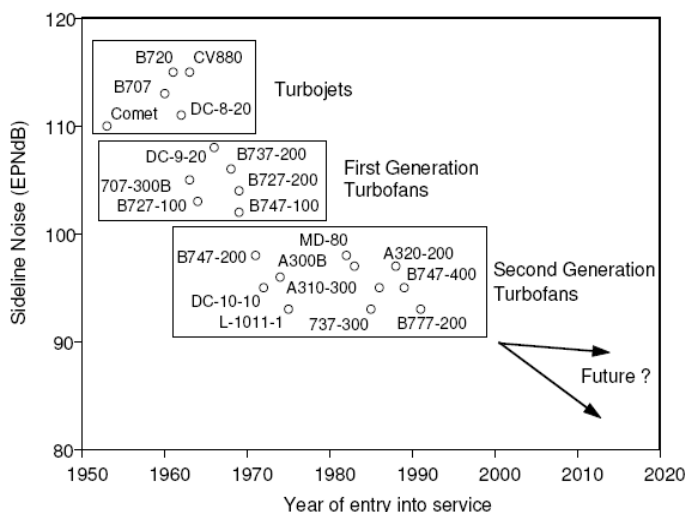


Figure 6: Reductions in Noise Levels of Aircrafts in past Fifty Years [7]

Worldwide, there has been ten fold increases in number of airports since the 1970s that now impose the noise related restrictions as shown in Figure 7 [8]. The airports have imposed operating restrictions and also there has been special attention paid to the planning, development and management of airports for sustainability. Since 1980, FAA has invested over \$5billion in airport noise reduction.

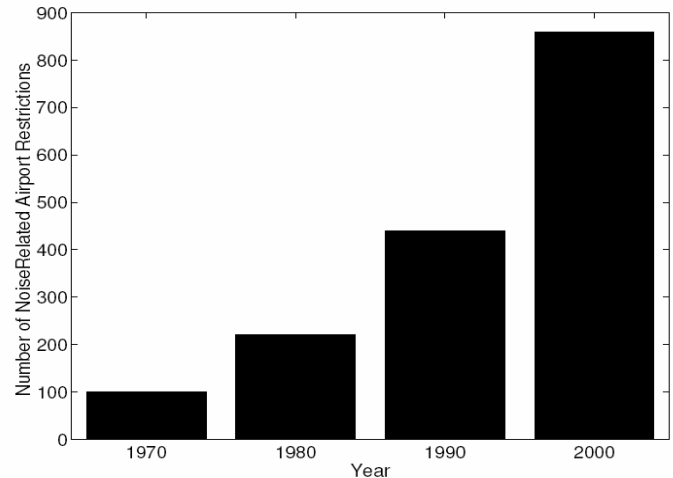


Figure 7: Number of Airports with Noise Related Restrictions in Past Thirty Years [8]

In recent years, the joint MIT/Cambridge University project on "Silent Aircraft" has produced an innovative aircraft/engine design, shown in Figure 8 that has imperceptible noise outside an urban airport [9].



Figure 8: Silent Aircraft SAX - 40 (Joint MIT/Cambridge University Design) [9]

In order to meet the ACARE and NASA goals of reducing the perceived noise by 50% of the current level by 2020, several new technology ideas are being investigated by the airplane and engine manufacturers to both reduce and shield the noise sources as shown in Figure 9 in the chart below by Reynolds [10]. The most promising for the near future are the chevron nozzles, shielded landing gears and the ultra high bypass engines with improved fan (geared fan and contra fan) and fan exhaust duct- liner technology. In addition, new flight path designs in ascent and descent flight can reduce the perceived noise levels in the vicinity of the airports.

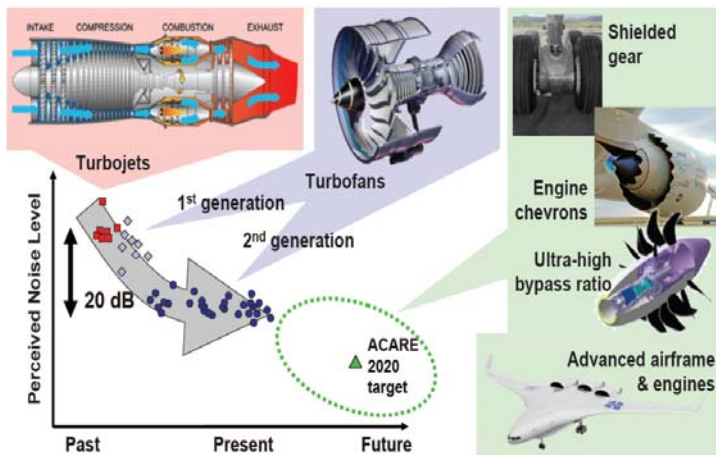


Figure 9: Evolution of Noise Reduction Technologies [10]

EMISSIONS AND FUEL BURN

Aviation worldwide consumes today around 238 million tonnes of jet-kerosene per year. Jet-kerosene is only a very small part of the total world consumption of fossil fuel or crude oil. The world consumes 85 million barrels/day in total, aviation only 5 million. At present, aviation contributes only 2-3% to the total CO₂ emissions worldwide [11] as shown in Figure 10. However, it contributes 9% relative to the entire transportation sector. With 2050 forecast of air travel to become 40% of total PKT (Figure 1), it will become a major contributor to GHG emissions if immediate steps towards reducing the fuel burn by innovations in technology and operations, as well as alternatives to Jet-kerosene are not sought and put into effect.

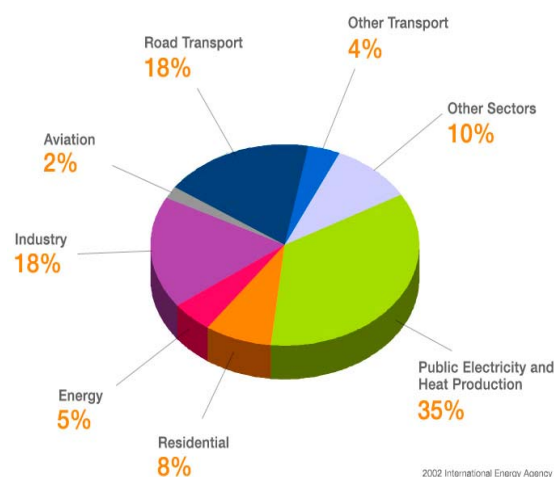


Figure 10: CO₂ Emissions Worldwide Contributed by Various Economic Sectors [11]

Of the exhausts emitted from the engine core, 92% are O₂ and N₂, 7.5% are composed of CO₂ and H₂O with another 0.5% composed of NO_x, HC, CO, SO_x and other trace chemical species, and carbon based soot particulates. In addition to CO₂ and NO_x emissions,

formation of contrails and cirrus clouds (Figure 11) contribute significantly to radiative forcing (RF) which impacts the climate change. This last effect is unique to



Figure 11: Contrails & Cirrus Clouds

aviation (in contrast to ground vehicles) because the majority of aircraft emissions are injected into the upper troposphere and lower stratosphere (typically 9-13 km in altitude). The impact of burning fossil fuels at 9-13 km altitude is approximately double of that due to burning the same fuels at ground level [12]. The present metric used to quantify the climate impact of aviation is radiative forcing (RF). Radiative forcing is a measure of change in earth's radiative balance associated with atmospheric changes. Positive forcing indicates a net warming tendency relative to pre-industrial times. Figures 12 and 13 show the IPCC (Intergovernmental Panel for Climate Change) estimated increase in total anthropogenic RF due to aviation related emissions (excluding that due to contrails and cirrus clouds) from 1992 to 2050 [13]. It should be noted that in Figures 12 and 13, RF scale is given in W/m². It is usually given in mW/m²; then the numbers in Figures 12 and 13 should be multiplied by 1000 as shown. The horizontal line in Figures 12 and 13 is indicative of the current level of scientific understanding of the impact of each exhaust species.

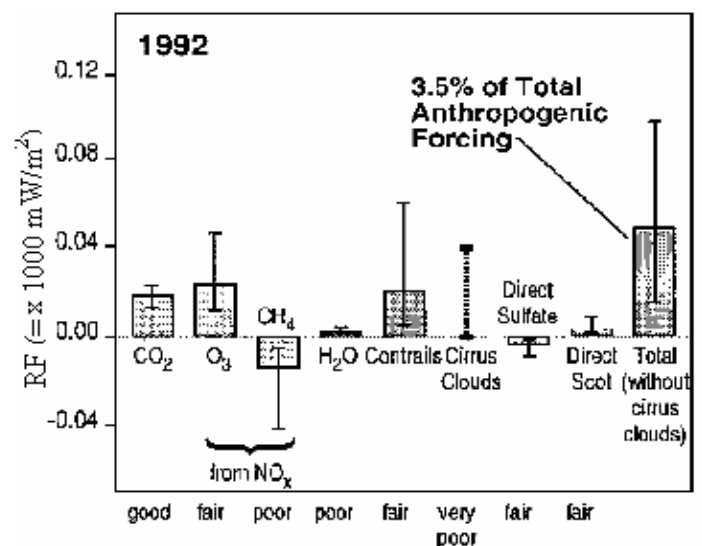


Figure 12: IPCC Estimated Radiative Forcing (RF) due to Emissions – 1992 [13]

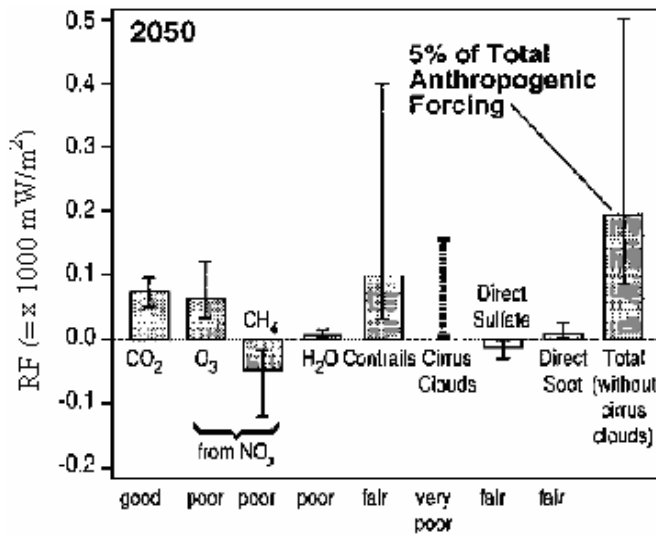


Figure 13: IPCC Estimated Radiative Forcing (RF) due to Emissions - 2050 [13]

It should be noted that the RF estimates for 2050 in Figure 13 are based on several assumptions about the growth in aviation, state of technology etc. which are most likely to change. Based on the RF estimates shown in Figures 12 and 13, aviation is expected to account for 0.05K of the 0.9K global mean surface temperature rise expected to occur between 1990 and 2050 [12]. However, RF is not a good metric for weighing the relative importance of short-lived and long-lived emissions. Most importantly, the range of uncertainty about the climate impact of contrails and cirrus cloud remains substantial. According to recent IPCC report, the best estimates for RF in 2005 from linear contrails were 10 (3-30)mW/m² and 30(10-80)mW/m² from total aviation induced cloudiness, the numbers in bracket give the range of the 2/3 confidence limit [14]. As noted in Reference [14], "the tradeoff estimate of the CO₂ RF in 2000 was 23.5mW/m². Despite the growth in CO₂ RF between 2000 and 2005, aviation induced cloudiness remains the greatest contributor to RF according to these estimates. Because of doubts of RF as a metric as well as data spread in cloudiness related RF, the relative contribution of the two (CO₂ and cloudiness) to climate change can not be ascertained with confidence at present time. However, the atmospheric conditions under which an aircraft will generate a persistent contrail – the Schmidt-Appleman criterion [15] – are well understood and can be predicted accurately for a particular aircraft.

Currently there is no technological fix to prevent contrail formation if the atmospheric conditions and engine exhaust characteristics satisfy the Schmidt-Appleman criterion. One assured way of reducing the persistent contrail formation is to reduce aircraft traffic through regions of supersaturated air in which the persistent contrail can form, by flying under, over or around these regions. However, this approach may not be acceptable commercially because of increase in fuel burn, disruption in airline schedule, added ATM workload, and

additional operating costs as well as increase in CO₂ and NO_x emissions. Because contrail reduction involves an increase in CO₂ and NO_x emissions, the best environmental solution is not the complete avoidance of contrails, but a balanced result that minimizes climate impact. This requires a better understanding of the relationship between the properties of the atmosphere (temperature, humidity etc.), the size of the aircraft, the quantity of its emissions (water and particulates), and extent of the persistent contrail and subsequent cirrus formation that results.

The adoption of synthetic kerosene produced by Fischer-Tropsch or some similar process offers the prospect of substantial reduction in sulfate and black carbon particulate emissions. This is likely to reduce the extent of contrail and cirrus formation, but the extent of reduction as well as to what extent it would reduce the fuel burn penalty of operational avoidance measures requires further research. Based on the current status, it appears that fuel additives do not offer a significant reduction in contrail formation. The contrail avoidance measures e.g. making modest changes in altitude can reduce contrail formation appreciably with a small penalty in additional fuel burn."

Increasing the cruise altitude and higher engine pressure ratio can reduce CO, HC, and CO₂ emissions as well as decrease the fuel burn (improve the fuel efficiency) and facilitate noise reduction. Since higher pressure ratio requires higher flame temperature, the NO_x formation rate increases. On the other hand, decreasing the cruise altitude and reducing the engine overall pressure ratio can reduce the NO_x but increase the CO₂ emissions. This should be an important consideration in the optimization of future aircraft and engine designs. Research is needed in understanding the impact of cruise altitude on climate. *In addition, there is a need for new optimized aircraft and engine designs that provide a compromise between minimizing the fuel burn and reducing the climate impact.* The lower NO_x emissions can possibly be achieved by new combustor concepts such as flameless catalytic combustor and technological improvements in fuel/air mixers using alternative fuels (biofuels), aided by active combustion control. These concepts/technologies should make it possible to meet the N+1 and N+2 generation goals (Figure 5) of achieving the LTO NO_x reductions by 60% and 75% respectively below the ICAO standard adapted at CAEP 6 (Committee on Aviation Environmental Protection). It should result in reducing the steepness of the trade-off between NO_x and CO₂ emissions and should therefore also help in making a significant contribution to the aircraft performance goal by reducing the fuel burn by 33% and 40% for the N+1 and N+2 generation aircraft respectively.

Thus, there are three key drivers in emissions reductions as shown in Figure 14 [16]: (a) innovative engine technologies and aircraft designs, (b) the improvement in ATM and operations, and (c) the alternative fuels etc.