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Review of Technologies to Achieve Sustainable (Green) Aviation

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1. Introduction

Among all major modes of transportation, people travel by airplanes and automobiles continues to experience the fastest growth. As shown in Figure 1 [1], the travel as measured by Passenger - Kilometers (PKM) is forecasted to more than double from the current 2010 level of ~ 40 trillion PKM to approximately 103 trillion PKM by 2050. Among these two modes of transportation, air travel is experiencing the faster growth. The number of Passenger – Kilometers Travelled (PKT)/ capita by various modes of transportation in different countries is shown in Figures 2(a) - 2(d) [1]. Figures 2(a) and 2(c) also show that the use of personal vehicles compared to public transport (in PKT) is highest in U.S. followed by the wealthier nations. Furthermore, as the per capita income of a nation increases, the travel demand will increase (Figure 3) [1] resulting in greater demand for personal vehicles as well as for air transportation as shown in Figure 1. 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. Only major policy changes and intervention by governments through development of infrastructure for public transportation is likely to slow down these trends shown in Figure 1. Most of the energy for transportation is currently provided by the fossil fuels (primarily petroleum). Figure 4 shows the oil consumption for transportation in U.S. and its forecast for the future [2]. Figure 5 shows the relative percentage of fuel consumption by various categories of vehicles in U.S [2]. The consequence of burning fossil fuels is well established in their long term impact on climate and global warming due to Greenhouse Gas (GHG) emissions, primary being the CO_2 and NOx. Table I gives the current level of CO_2 emissions worldwide by ground and air transportation [3] and Figure 6 shows the forecast for the future if the current Business as Usual (BAU) scenario continues [3]. The reduction in GHG emissions due to the burning of fossil fuels is the major goal of "Green Transportation." The "Sustainability" goal is to explore both the technological solutions to increase the efficiency of transportation as well as the alternative carbon neutral fuels (e.g. biofuels among others).

2. Sustainable (green) air transportation

Most of the material presented in this section has been taken from the author's William Littlewood Award Lecture [4]. This section provides an overview of issues related

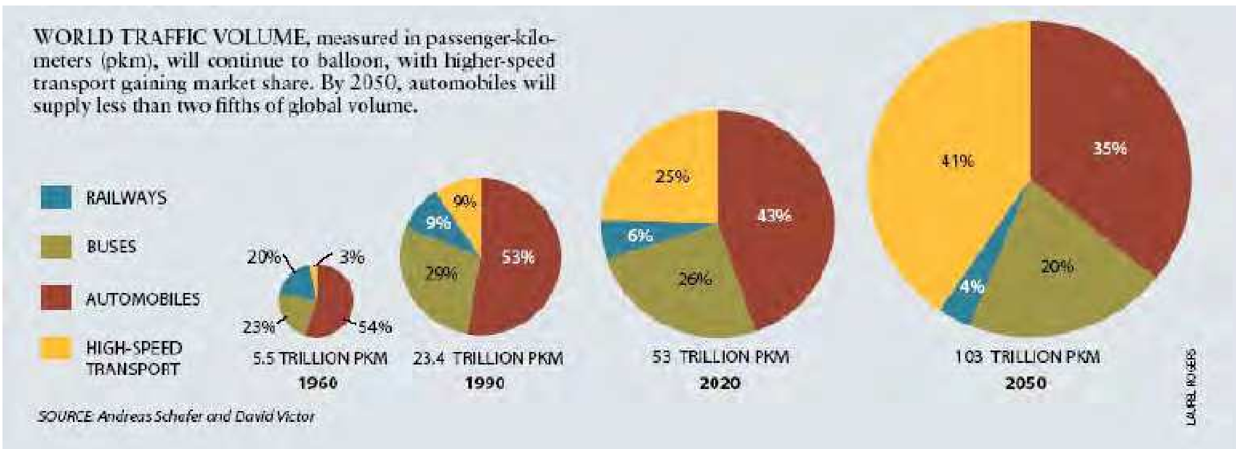
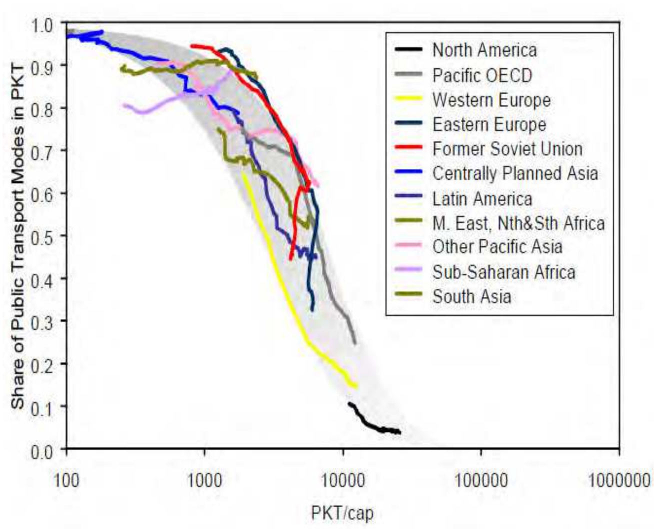
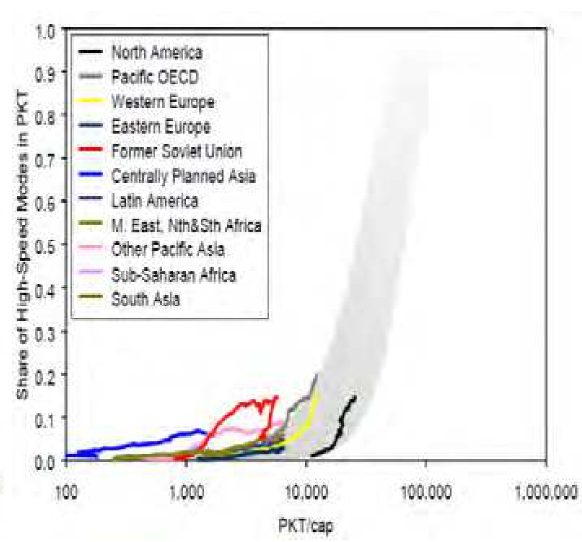


Fig. 1. Global mobility trends from various modes of transportation [1].



(a)



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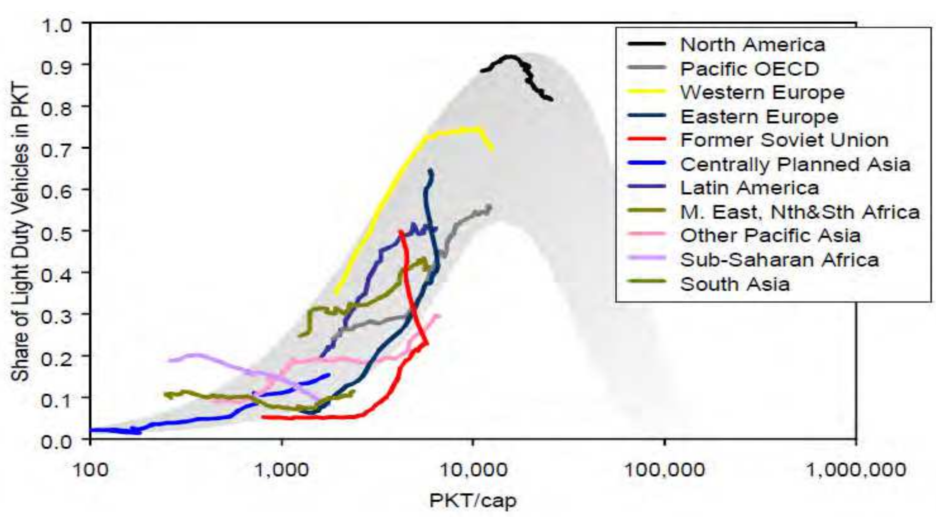

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Fig. 2. a: % share of public transport in various countries; b: % share of high speed transport in various countries; c: % share of light-duty vehicle transport in various countries [1].

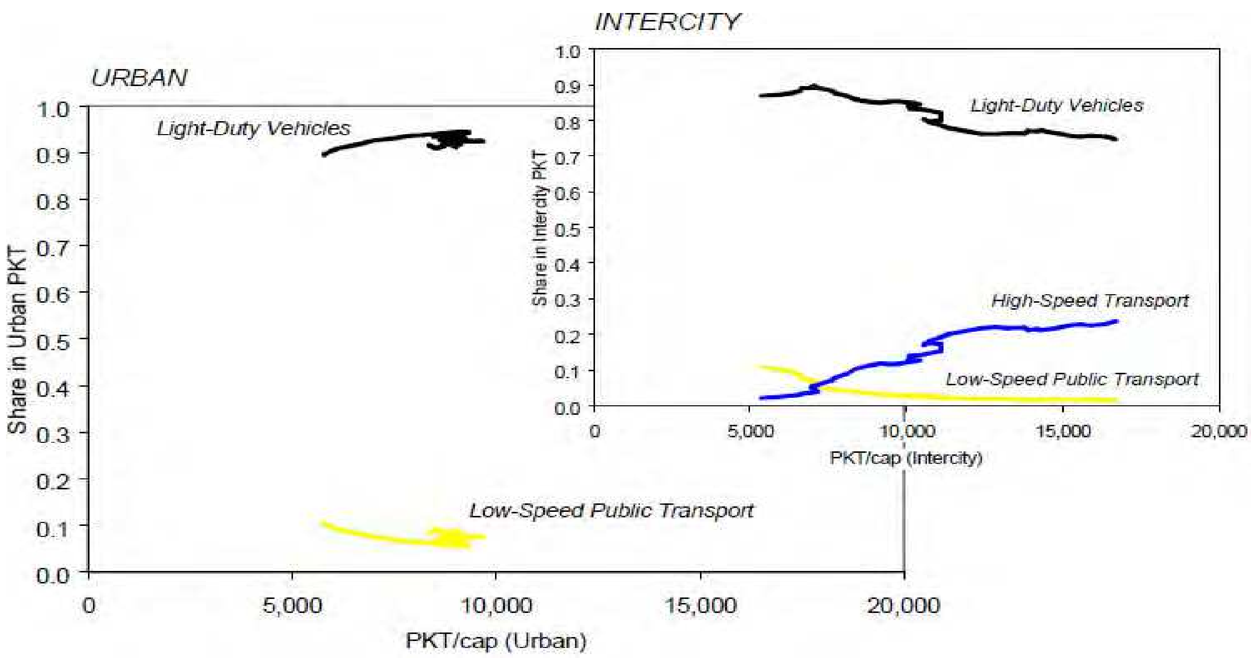

Fig. 2(d). % share of various modes of transportation for inter-city travel in U.S. [1].

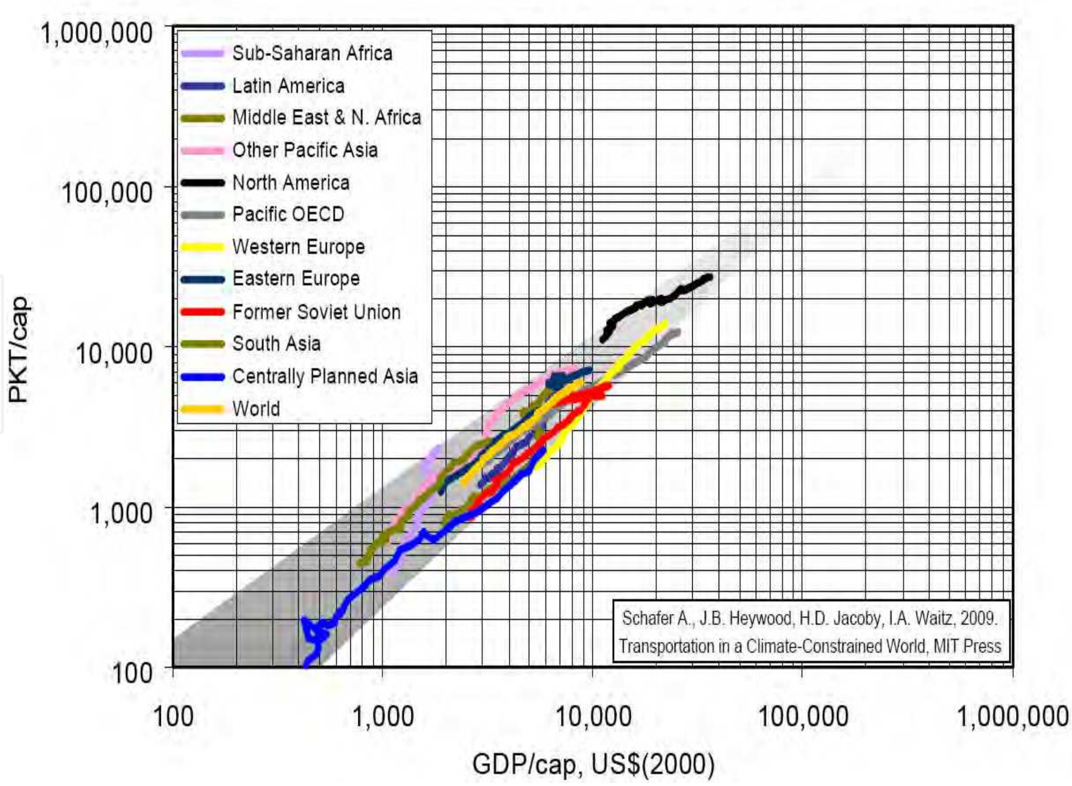

Fig. 3. Travel demand/capita with increase in GDP/capita of nations [1].

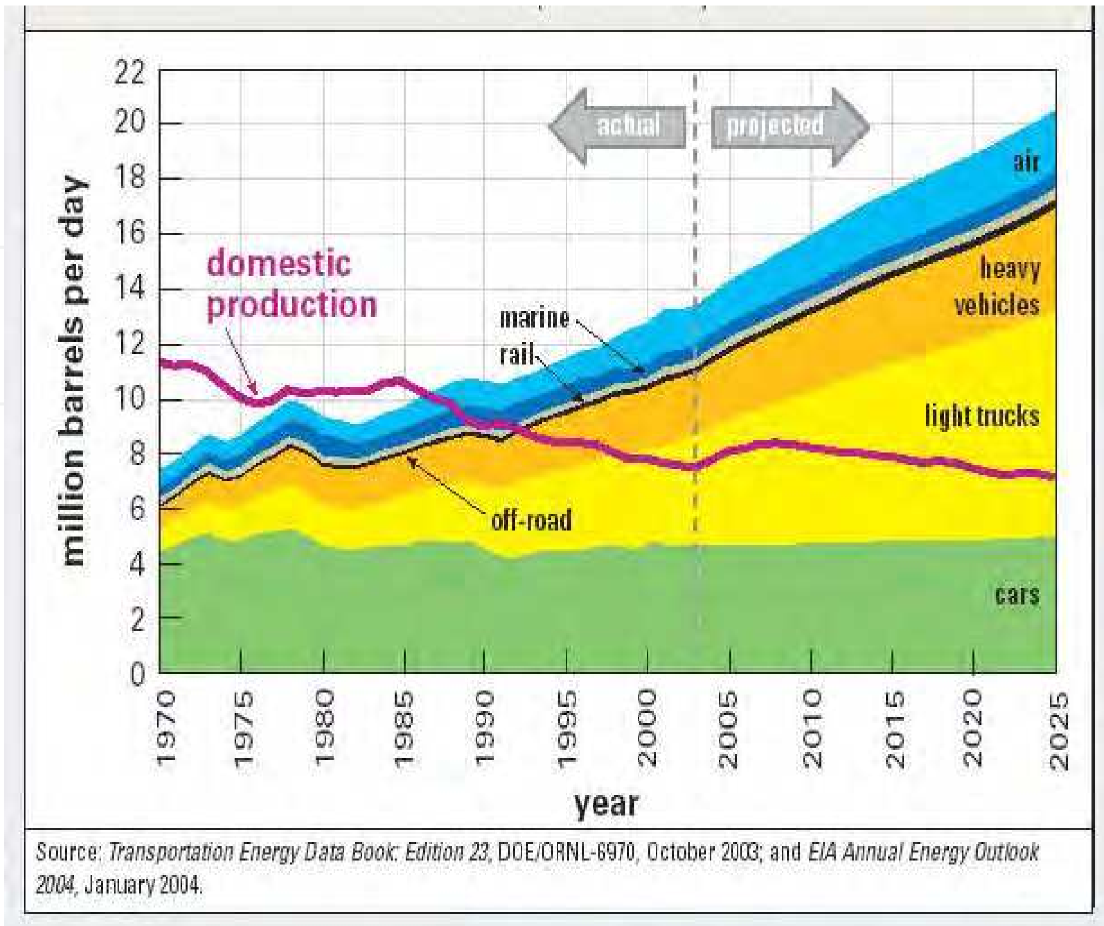

Fig. 4. Fuel consumption in U.S by transport vehicles [2].

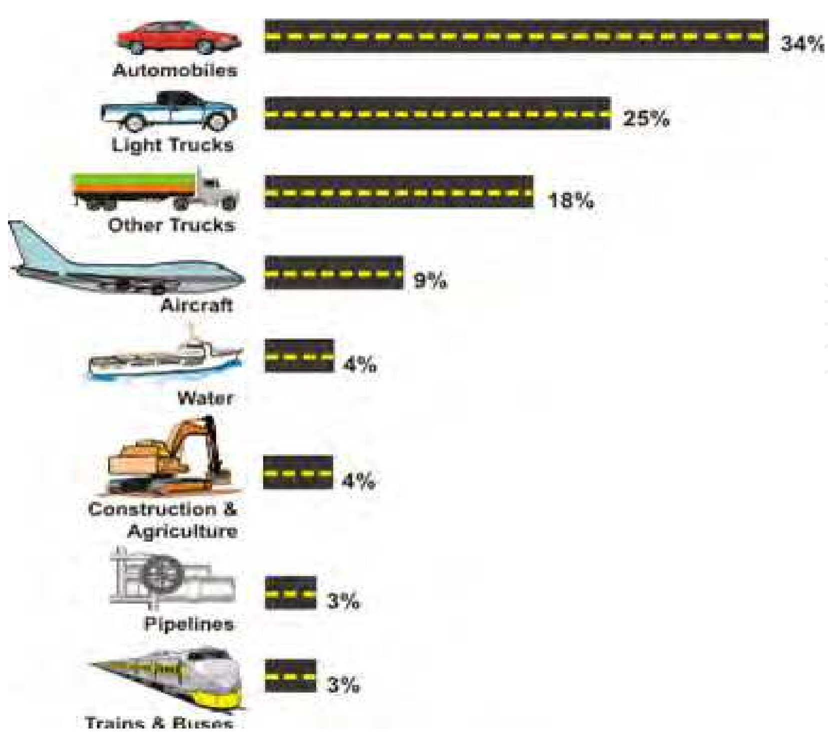

Fig. 5. Relative fuel consumption in U.S by various categories of vehicles [2].

- World Total CO_2 Emissions = 28.4 x 10^9 tonnes (100%)
- US Total CO_2 Emissions = 5.75 x 10^9 tonnes (20.2%)
- China Total CO_2 Emissions = 6.10 x 10^9 tonnes (21.5%)
- World Total from All Transportation = 5.99 x 10^9 tonnes (21.0%)
- World Total from Road Transportation = 3.69 x 10^9 tonnes (13.0%)
- World Total from Air Transportation = 5.68 x10^8 tonnes (2.0%)
- US Total from Road Transportation ~ 4.46 x 10^9 tonnes (15.6%)
- US Total from Air Transportation ~ 1.39 x 10^9 tonnes (0.5%)

Table 1. Current level of CO_2 emissions from air and ground transportation [3].

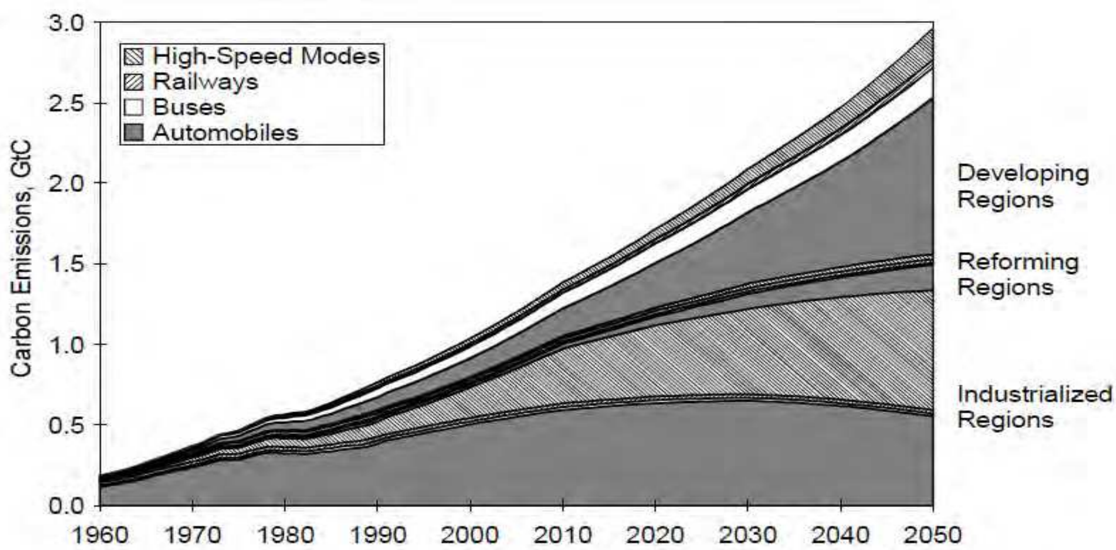

Fig. 6. CO_2 emissions due to world passenger travel in Business as Usual (BAU) scenario [3].

to air transportation and its impact on environment. The environmental issues such as noise, emissions and fuel burn (consumption), for both airplane and airport operations, are discussed in the context of energy and environmental sustainability. They are followed by the 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.

As mentioned in the '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. Based on these demands for air travel, Boeing has determined the outlook for airplane demand by 2025 as shown in Figure 7 [5]. Figure 8 shows various categories of 27,200 airplanes that would be needed by 2025 [5]. 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 CO_2 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.

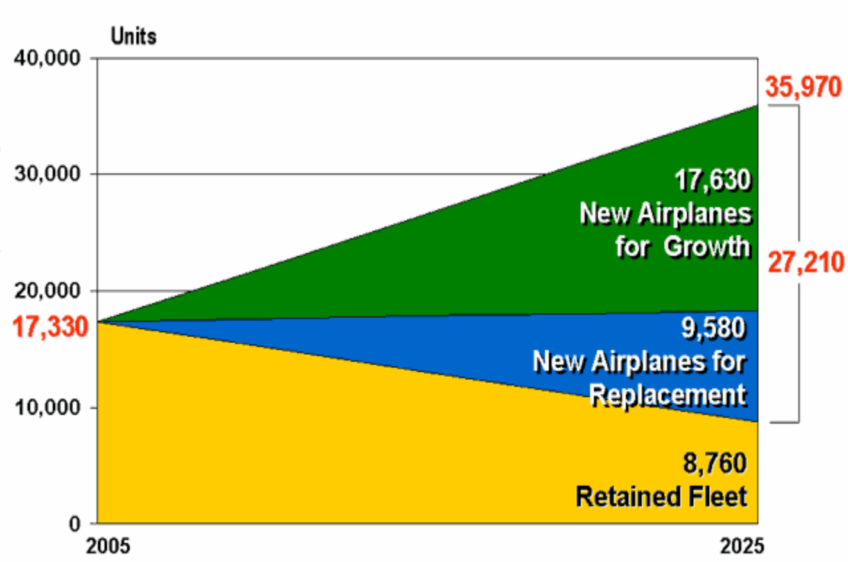

Fig. 7. Boeing market forecast for new airplanes [5].

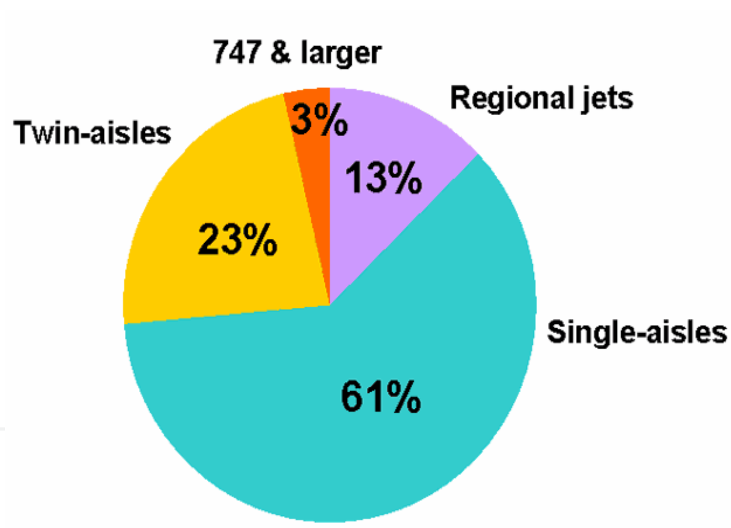

Fig. 8. Boeing demand forecast for various types of Airplanes by 2025 [5].

2.1 Environmental 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 CO_2 emissions per passenger kilometer (PKM) by 50%, and (c) reduce the NOx emissions by 80% relative to 2000 reference [6]. NASA has similar objectives for 2020 as shown in Figure 9 for N+2 generation aircraft [7]. 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 [8]. 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

Fig. 9. NASA subsonic fixed wing system level metric for improving noise, emission and performance using technology & operational improvements [7].

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."

2.2 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 operational improvements that may make air travel one of the greenest industries by 2050 [9]. These 25 green technologies/concept areas are listed below from Reference [9].

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, CO_2 and NOx emissions due to air transportation and possible strategies for their mitigation to achieve the ACARE and NASA goals.

2.3 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 10 [10]. 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. 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 11 [11]. 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.

In recent years, the joint MIT/Cambridge University project on "Silent Aircraft" has produced an innovative aircraft/engine design, shown in Figure 12 that has imperceptible noise outside an urban airport [12]. 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 13 in the chart by Reynolds [13]. 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.

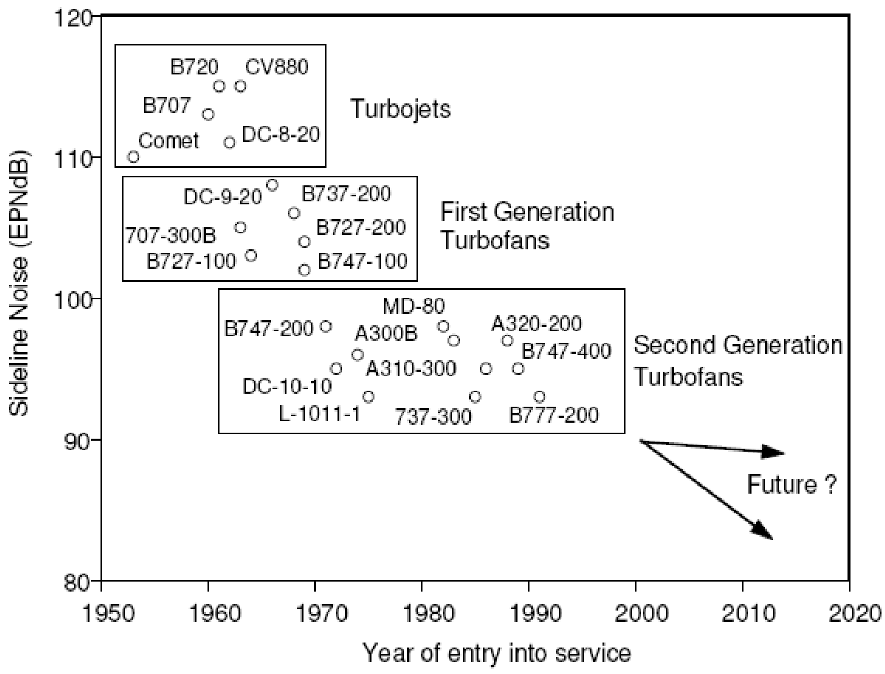

Fig. 10. Reductions in noise levels of aircrafts in past thirty years [11].

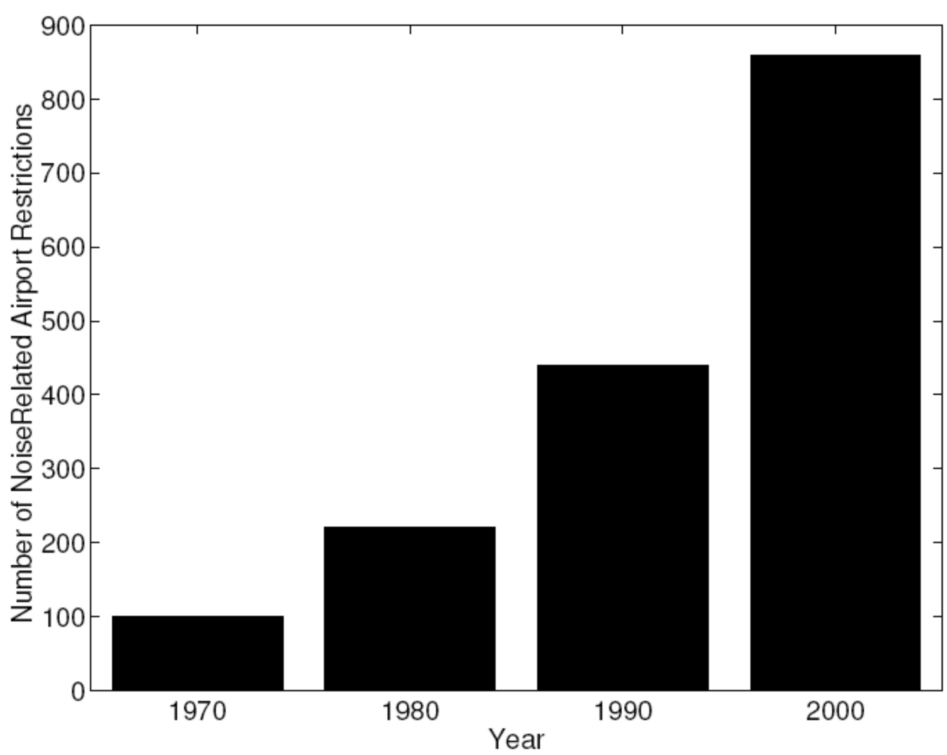

Fig. 11. Number of airports with noise related restrictions in past fifty years [10].

Fig. 12. Silent aircraft SAX – 40: (joint MIT/Cambridge University design) [12].

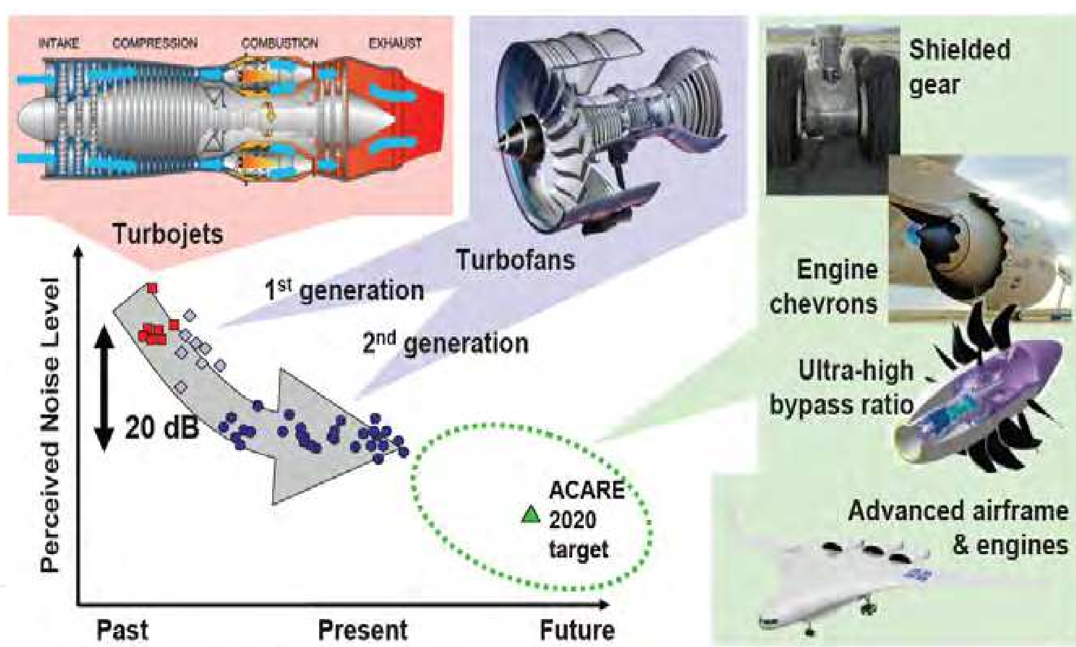

Fig. 13. Evolution of noise reduction technologies [13].

2.4 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 CO_2 emissions worldwide [14] as shown in Figure 14. 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.

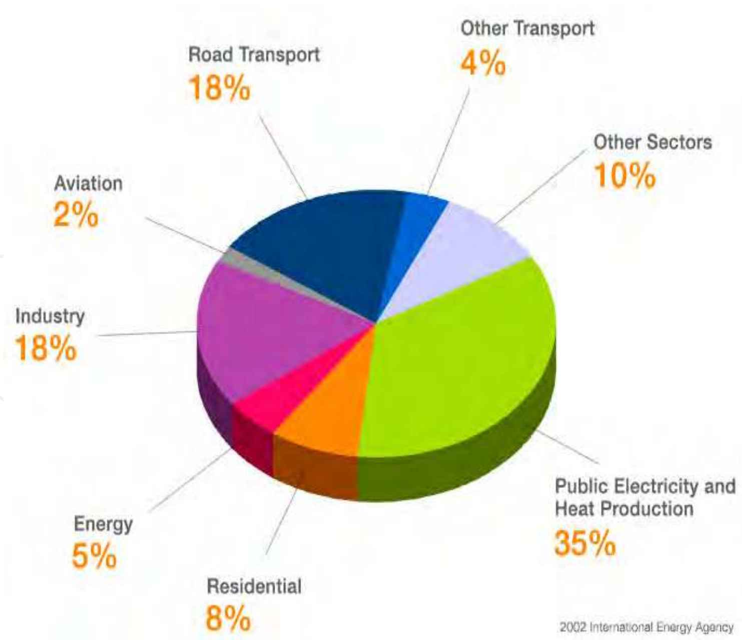

Fig. 14. CO_2 emissions worldwide contributed by various economic sectors [14].

Fig. 15. Contrails & Cirrus Clouds.

Of the exhausts emitted from the engine core, 92% are O_2 and N_2, 7.5% are composed of CO_2 and H_2O with another 0.5% composed of NOx, HC, CO, SOx and other trace chemical species, and carbon based soot particulates. In addition to CO_2 and NOx emissions, formation of contrails and cirrus clouds (Figure 15) contribute significantly to radiative forcing (RF) which impacts the climate change. This last effect is unique to 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 [15]. 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 16 and 17 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 [16]. It should be noted that in Figures 16 and 17, RF scale is given in W/m[2]. It is usually given in mW/m[2]; then the numbers in Figures 16 and 17 should be multiplied by 1000 as shown. The horizontal line in Figures 16 and 17 is indicative of the current level of scientific understanding of the impact of each exhaust species.

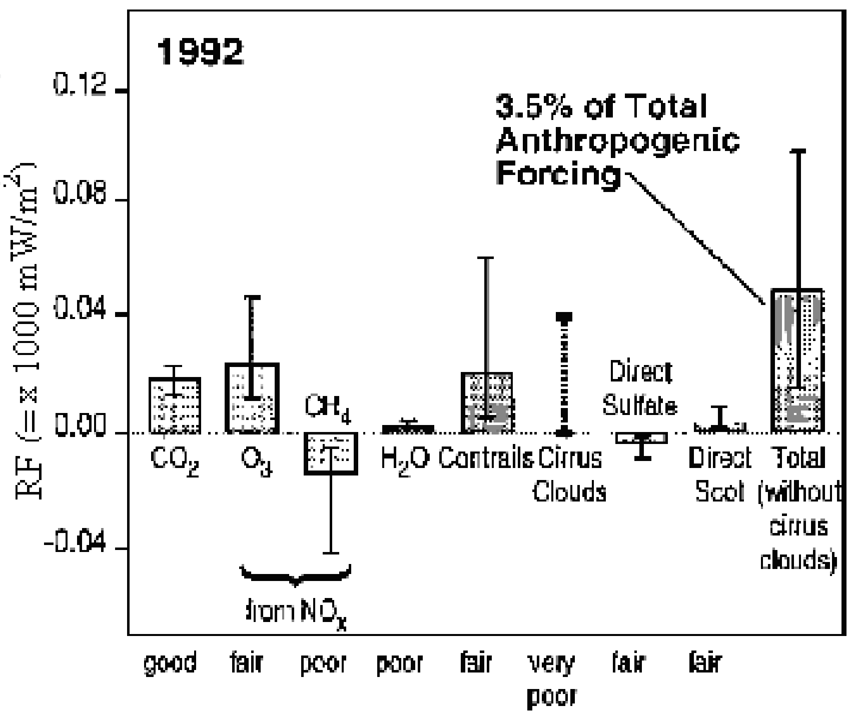

Fig. 16. IPCC estimated Radiative Forcing (RF) due to Emissions – 1992 [16].

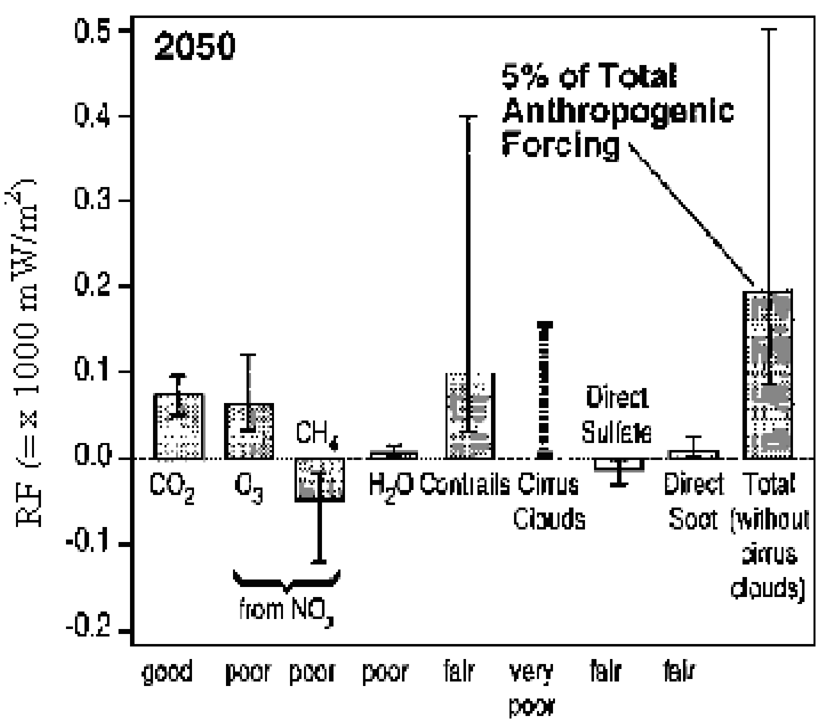

Fig. 17. IPCC estimated Radiative Forcing (RF) due to emissions – 2050 [16].

It should be noted that the RF estimates for 2050 in Figure 17 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 16 and 17, aviation is expected to account for 0.05K of the 0.9K global mean surface temperature rise expected to occur between 1990 and 2050 [15]. 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/m^2 and 30(10-80)mW/m^2 from total aviation induced cloudiness, the numbers in bracket give the range of the 2/3 confidence limit [17]. As noted in Reference [17], "the tradeoff estimate of the CO_2 RF in 2000 was 23.5mW/m^2. Despite the growth in CO_2 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 (CO_2 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 [18] – 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 CO_2 and NOx emissions. Because contrail reduction involves an increase in CO_2 and NOx 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 CO_2 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 NOx formation rate increases. On the other hand, decreasing the cruise altitude and reducing the engine overall pressure ratio can reduce the NOx but increase the CO_2 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 NOx 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 9) of achieving the LTO NOx 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 NOx and CO_2 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 18 [19]: (a) innovative engine technologies and aircraft designs, (b) the improvement in ATM and operations, and (c) the alternative fuels e.g. biofuels. The three-prong approach can achieve the goals enunciated by ACARE and NASA by 2020 and beyond. These are discussed in next few sections.

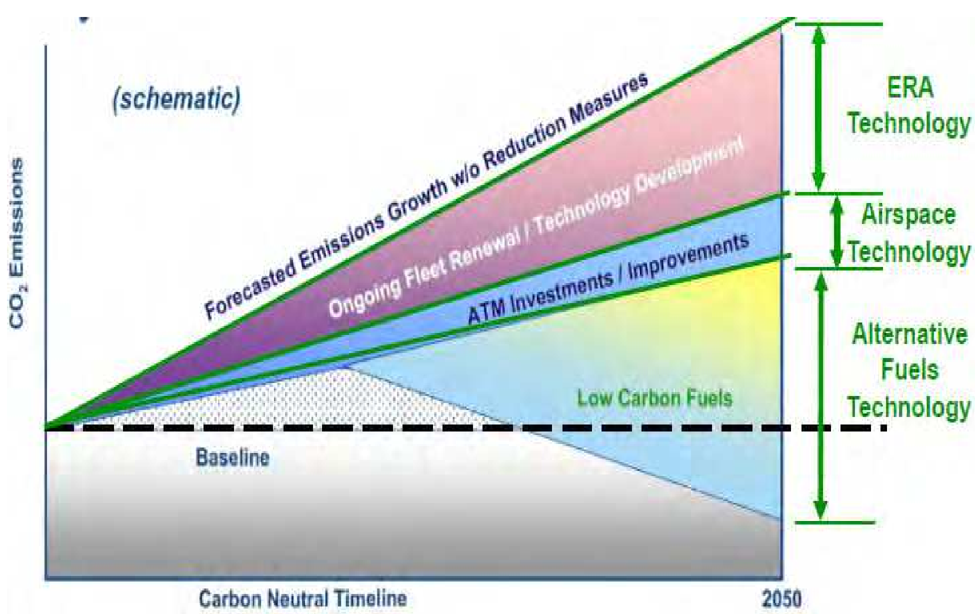

Fig. 18. Key drivers for emissions reductions [19].

2.5 Innovative engine technologies

In cruise condition, the amount of fuel burn varies in inverse proportion to propulsion efficiency and lift-to-drag ratio. Aircraft and engine manufacturers in U.S. and Europe along with several research organizations are developing new engine technologies aimed at improving the propulsion efficiency to reduce the fuel burn and also to simultaneously reduce NOx emissions and noise. The greatest gains in fuel burn reduction in the past sixty years (since the appearance of jet engine) have come from better engines. The earliest engines were turbojets in which all the air sucked in at the front is compressed, mixed with fuel and burned, providing thrust through a jet out the back (see Figure 13). Afterwards, more efficient turbofans were designed when it was realized that greater engine efficiency could be achieved by using some of the power of the jet to drive a fan that pushes some of the intake air through ducts around the core (see Figure 13). Other boosts in efficiency have come from better compressors and materials to let the core burn at higher pressure and temperature. As a result, according to International Airport Transport Association (IATA), new aircraft are 70% more fuel efficient than they were forty years ago. In 1998, passenger aircraft averaged 4.8 liters of fuel/100km/passenger; the newest aircraft – Airbus A380 and Boeing B787 use only three liters. Figure 19 shows the relative improvement in fuel efficiency of various aircraft engines since 1955 [20]. The current focus is on making turbofans even more efficient by leaving the fan in the open. Such a ductless “open rotor” design (essentially a high-tech propeller) would make larger fans possible; however one may need to address the noise problem and how to fit such engines on the airframe. In the short-to-medium-haul market, where most fuel is burned, the open rotor offers an appreciable reduction in fuel burn relative to a turbofan engine of comparable technology, but at the expense of some reduction in cruise Mach number. It is worth noting here that in mid 1980’s GE invested significant effort in advanced turbo-prop technology (ATP). The un-ducted fan (UDF) on a GE36 ultra high bypass (UHB) engine on MD-81 at Farnborough air show in 1988 (Figure 20 [21]) created enormous buzz in the air transportation industry. The author of this paper was at McDonnell Douglas during that period and played a small role in the airframe – engine integration study of MD81 with GE36 ATP. However, in spite of its potential for 30% savings in fuel consumption over existing turbofan engines with comparable performance at speeds up to Mach 0.8 and altitudes up to 30,000 ft, for a variety of technical and business reasons, the advanced turboprop concept never quite got-off the ground [22].

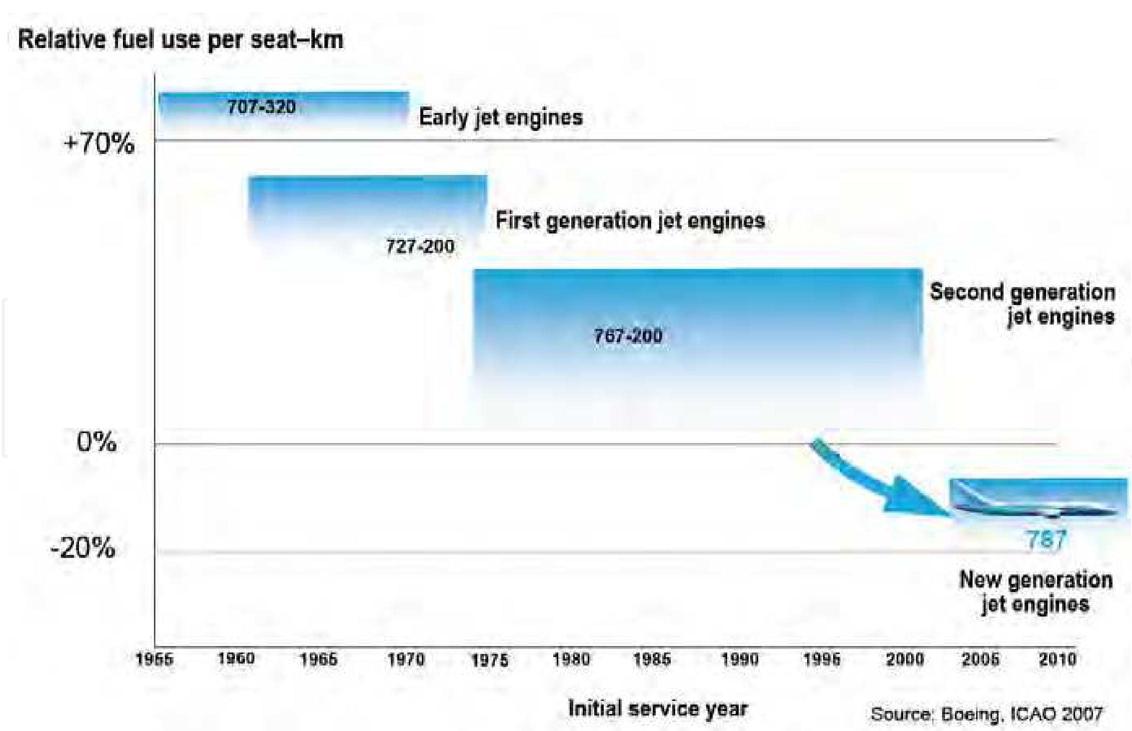

Fig. 19. Relative improvement in fuel efficiency of various aircraft engines from 1955 to 2010 [20].

Fig. 20. GE36 Turbo-Prop demonstrator engine on MD-81 aircraft [21].

At present in Europe, under the auspices of NACRE (New Aircraft Concept Research Europe), Rolls-Royce and Airbus are making a joint study of the open rotor configurations (Figure 21), including wind-tunnel investigations of power plant installation effects. A key issue in future engine design is how to balance the conflicting aims of reducing fuel burn and NOx emissions (along with the other conflicting aims of reducing noise, weight, initial investment cost and maintenance cost). The results of these types of current and future projects should provide a sounder basis for making decisions between turbofan and open rotor engines for future aircraft. They should also take engine technology well towards its contribution to the goal of a 20% improvement in the installed engine fuel efficiency by 2020.

Fig. 21. Open-Rotor version of pro-active Green Aircraft in NACRE study [17].

Fig. 22. Turbofan version of pro-active Green Aircraft in NACRE study [17].

2.6 Innovative aircraft designs

As noted in Reference [17], “the classic swept-winged aircraft with a light alloy structure has been evolving for some sixty years and the scope for increasing its lift-to-drag ratio (L/D), if its boundary layers remain fully turbulent, is by now exceedingly limited. Nevertheless, it is well established that increasing L/D is one of the most powerful means of reducing fuel burn. The three ways of increasing L/D are to (a) increase the wing span, (b) reduce the vortex drag factor κ and (c) reduce the profile drag area. The vortex drag factor is a measure of the degree to which the span-wise lift distribution over the wing departs from the theoretical ideal. Current swept-wing aircraft are highly developed and there is little scope for further improvement. A flying wing may enable some additional small reduction in κ, however realistically; there is no real prospect of a significant reduction in fuel burn by altering span-wise loading distributions. Furthermore, increasing the wing span increases wing weight. Current long-range aircraft are optimized to minimize the fuel burn at current cruise Mach numbers. In a successful design the balance between the wing span and wing weight is close to optimum. However, the change to advanced composite materials for the wing structure should result in an optimized wing of greater span; both the B787 and Airbus A350 reflect this. If cruise Mach number is reduced, reducing wing sweep also enables the wing to be optimized at a greater span. The turbofan version of Pro-Active Green Aircraft (Figure 22) included in the NACRE study features a slightly forward swept wing optimized at a significantly higher than usual span. This aircraft is aimed at an appreciable increase in L/D at the expense of some reduction in cruise Mach number. The third option for increasing L/D is to reduce the profile drag of the aircraft. This is seen as the option with the greatest mid-term and long-term potential. For large aircraft, the adoption of a blended wing-body (BWB) layout reduces profile drag by about 30%, providing an increase of around 15% in L/D (estimates of 15% - 20% have been published).” The work on such configurations, both by Boeing (the X-48B, wind tunnel and flight tested at model scale by NASA [Figure 23]) and by Airbus within the NACRE project are proceeding. At present, the first applications of the Boeing BWB are envisaged to be in military roles or as a freighter, with 2030 suggested as the earliest entry to service date for a civil passenger aircraft.

Fig. 23. Boeing/NASA X-48B BWB technology demonstrator aircraft [23].

Fig. 24. Honda Jet [24].

The other well known approach of reducing the profile drag is by the use of laminar flow control in one of its three forms - natural, hybrid or full. Natural laminar flow control was applied with great success in World War II on the P-51 Mustang fighter to give it an exceptional range. As a result there was significant effort devoted to the development of laminar flow airfoils after the end of World War II. In these airfoils, the reduction in friction drag was achieved by moving the transition farther back on the airfoil. In addition, the location of the maximum airfoil thickness was at about 60% of the chord which moved the shock system farther back and reduced the effects of boundary layer thickening and separation caused by it. However in spite of a large number of studies, the success in the laboratory in reducing the drag was never realized on medium size aircraft with swept wings. Therefore, its application has been restricted by a combination of size and wing sweep either to small aircraft with swept wings or medium-sized aircraft with zero or very little sweep. The Pro-Active Green Aircraft in the NACRE project (Figures 21 & 22) is designed to exploit natural laminar flow control and has slightly swept forward wings, to avoid contamination of the flow over the wing by the turbulent boundary layer on the fuselage. "Hybrid laminar flow control employs suction over the forward upper surface of the wing to stabilize the boundary layer. This enables the drag reducing principles that underlie natural laminar flow control to be applied to larger, swept-winged aircraft up to typically the size of the A310. The use of suction to maintain laminar flow over the first half of an airfoil surface has been successfully demonstrated in flight on a B757 wing and an A320 fin. The aerodynamic principles are well understood but the engineering of efficient, reliable, lightweight suction systems requires further work. Thereafter, demonstration of the practicality of the system and assessment of the maintenance and other operational problems that it may encounter will require an extended period of operational validation. The application of suction to maintain laminar flow over the entire surface of a flying wing airliner was proposed by Handley Page in the early 1960s. The proposal was based on the substantial body of research into full laminar flow control, including flight demonstrations, over the preceding decade. Full laminar flow control may have potential to double L/D relative to current standards [17]." Recently unveiled "Honda Jet" (Figure 24) has combined several innovative aircraft and engine design features, namely a combination of over the wing (OTW) engine mount design, natural laminar flow wing (NLF), all composite fuselage, HF – 120 turbofan engine, which give it a 30-35% more fuel efficiency and higher cruise speed than conventional light business jets. This is the range of efficiency that can be achieved for the N+1 generation conventional tube and wing aircraft by 2015. Saeed et al. [25] have recently conducted the conceptual design study of a Laminar Flying Wing (LFW) aircraft capable of carrying 120 passengers. They have estimated that, subject to the constraint of a low cruise Mach number of 0.58, LFC has the potential to reduce aircraft fuel-burn by just over 70%, to about 6 gram per passenger-km (PKM), with a trans-Atlantic range of 4125 nautical miles. Studies of this nature do show the promise of innovative aircraft designs to reduce the fuel burn.

Figure 9 shows the NASA goals of achieving a 33% and 40% reduction in fuel burn for N+1 and N+2 generation aircrafts respectively by using the advanced propulsion technologies, advanced materials and structures, and by improvements in aerodynamics and subsystems. Collier [26] from NASA Langley has provided a detailed outline as to how such savings in fuel burn can be achieved. He has estimated that for a N+1 generation conventional small twin aircraft (162 passengers and 2940nm range), 21% reduction in fuel burn can be achieved by using advanced propulsion technologies, advanced materials and structures, and by improvements in aerodynamics and subsystems. For an advanced small twin, additional 12.3% savings in fuel burn can be achieved by using hybrid laminar flow control as shown in Figure 25.

For a N+2 generation aircraft (300 passengers and 7500 nm range) flying at cruise Mach of 0.85, 40% saving in fuel burn relative to baseline B777-200ER/GE90 can be achieved by a combination of hybrid wing-body configuration (with all composite fuselage), advanced engine and airframe technologies, embedded engines with BLI inlets and laminar flow as shown in Figure 22 [24]. For the baseline aircraft, the fuel burn at Mach 0.85 with 300 passengers for a 7500nm mission range is 237,000 lbs. The N+2 generation aircraft should require 141,100lbs of fuel. As discussed in next few sections, additional savings of 10% in fuel burn can be achieved by operational improvements.

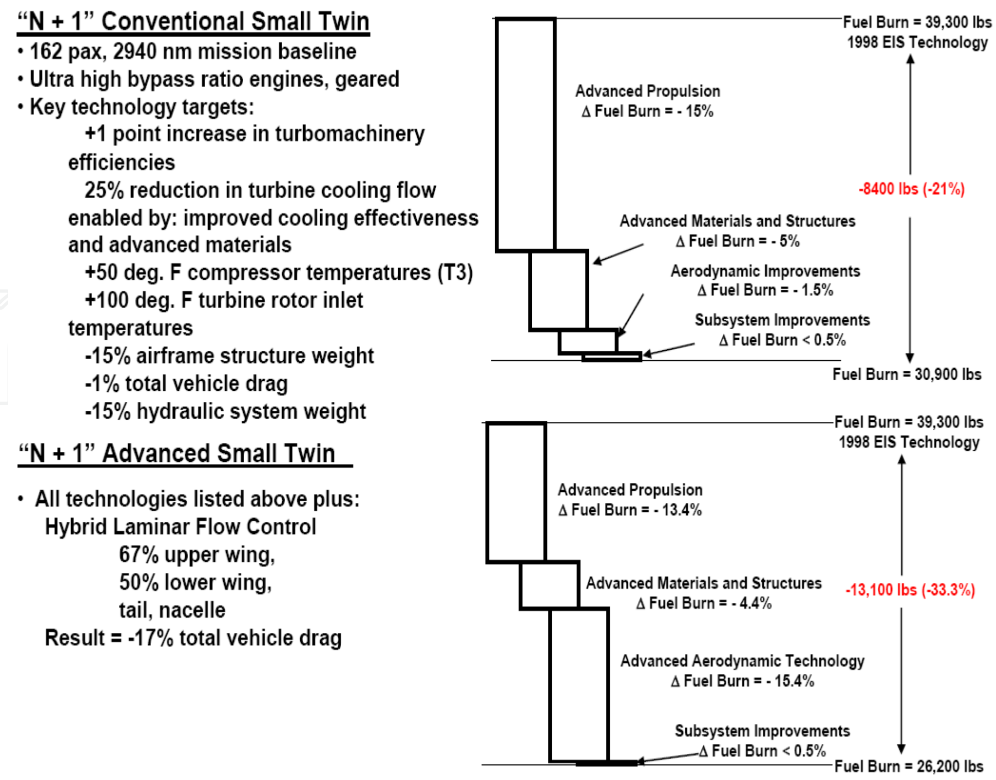

Fig. 25. Reduction in fuel burn for N+1 generation aircraft relative to baseline B737/CFM56 using advanced technologies [26].

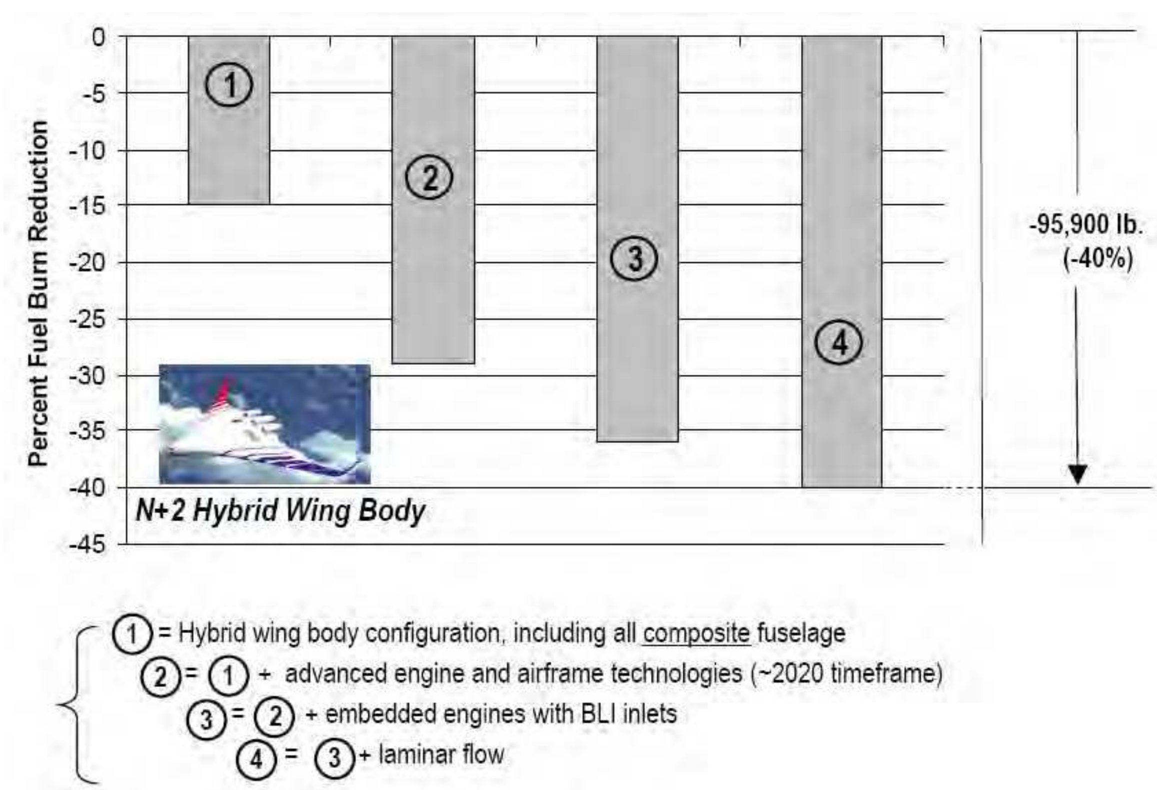

Fig. 26. Reduction in fuel burn for N+2 generation aircraft relative to baseline B777-200ER/GE96 using advanced technologies [26].

2.7 Operational improvements/changes

2.7.1 Improvement in air traffic management (atm) infrastructure

There are many improvements in operations that are being introduced, or will be introduced in the relatively near future that can reduce CO_2 emissions significantly. Foremost among these is the reduction of inefficiencies in ATM, which give rise to routes with dog-legs, stacking at busy airports, queuing for a departure slot with engines running, etc. U.S. Next Generation Air Transportation System (NextGen) architecture and the European air traffic control infrastructure modernization program, SESAR (Single European Sky ATM Research Program), are an ambitious and comprehensive attack on this problem. As described in the U.S. National Academy of Science (NAS) report [27], "NextGen is an example of active networking technology that updates itself with real time-shared information and tailors itself to the individual needs of all U.S. aircraft. NextGen's computerized air transportation network stresses adaptability by enabling aircraft to immediately adjust to ever-changing factors such as weather, traffic congestion, aircraft position via GPS, flight trajectory patterns and security issues. By 2025, all aircraft and airports in U.S. airspace will be connected to the NextGen network and will continually share information in real time to *improve efficiency, safety, and absorb the predicted increase in air transportation.*" Here it is worth noting that operational measures, which can apply to almost the entire world fleet, can have a greater impact, sooner, than the introduction of new aircraft and engine technologies, which can take perhaps 30 years to fully penetrate the world fleet.

2.7.2 Air-to-air refueling (aar) with medium range aircraft for long-haul travel

One particular operational measure that has been advocated is the use of medium-range aircraft, with intermediate stops, for long-haul travel. It has been estimated, using a simple parametric analysis, that undertaking a journey of 15,000km in three hops in an aircraft with design range of 5,000km would use 29% less fuel than doing the trip in a single flight in a 15,000km design. Hahn [28] and Creemers & Slingerland [29] have performed analyses to address this issue using sophisticated aircraft design synthesis methods. Hahn [28], analyzing the assessment for a 15,000km journey in one stage or three, predicted a fuel saving of 29%. Creemers & Slingerland [29], considering a B747-400 (range 13,334km) as the baseline long-range aircraft, designed an aircraft with the same fuselage and passenger capacity (420) but for half the design range (6,672km). This aircraft was predicted to do the long-haul journey in two hops with a 27% fuel saving and at a fuel cost of $70 per barrel, a DOC saving of 9%. Nangia [30] has shown that fuel burn savings of as much as 50% were achievable by using a 5,000km design for a 15,000km journey, since a medium range aircraft can carry a much higher share of their maximum payload as passengers. This difference — which appears essentially to be the difference between medium-range single and long-range twin-aisle aircraft — was not a feature of either the study of Hahn [28] or Creemers & Slingerland [29], which used the same fuselage for both long and medium range designs. This highlights the importance of cabin dimensions and layouts in considering future designs in which, both environmentally and commercially, seat-kilometers per gallon becomes an increasingly important objective. The full system assessment of this proposition, using optimized medium-range aircraft needs further investigation. In order to avoid the intermediate refueling stops, air-to-air refueling (AAR) (Figure 27) has been suggested as a means of enabling medium-range designs to be used on long-haul operations. Nangia has now published a number of papers reporting his work on AAR, which indicate substantial fuel burn savings even after the fuel used by the tanker fleet is taken into account [30, 31].

Fig. 27. Air-to-Air Refueling [30].

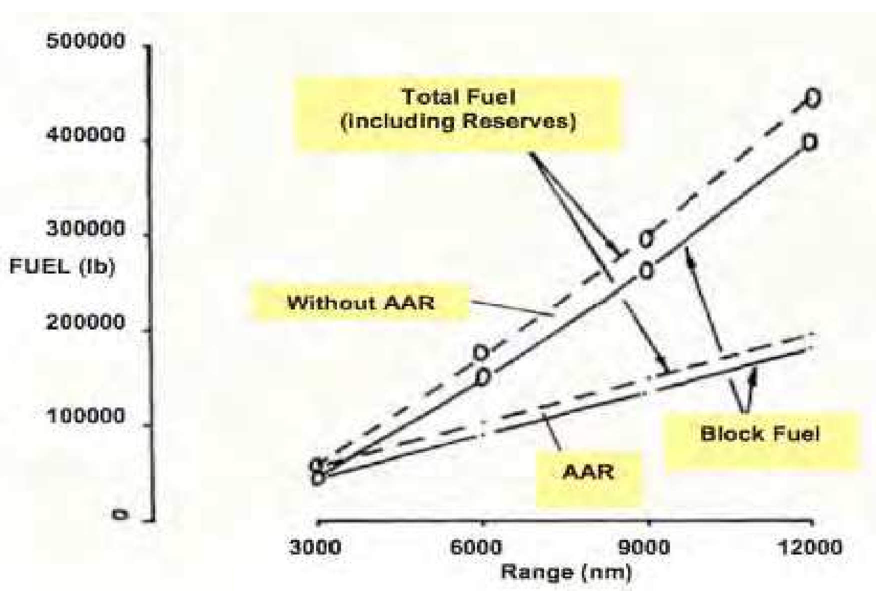

Fig. 28. Savings in fuel burn with Air-to-Air Refuelling (AAR) for long haul flights [31].

Nangia [31] has shown (Figure 28) that an aircraft with *L/D* = 20, would require 46,147 lbs, 161,269 lbs, and 263,073 lbs of fuel to cover a range of 3,000, 6,000 and 9,000 nautical miles (nm) respectively. With AAR, it will require 92,294 lbs and 138, 441 lbs of fuel for a range of 6,000 and 9,000 nm respectively indicating a savings of 43% and 47% in fuel burn relative to that required without AAR. Accounting for the fuel required by the air tanker – 9,000 lbs for one refueling for a range of 6,000nm and 18,000 lbs for two refueling for a range of 9,000nm, the net savings in fuel burn with AAR are 37% and 41% for a range of 6,000nm and 12,000 nm respectively. However it is paramount that with AAR, the absolute safety of the aircraft is assured.

2.7.3 Close Formation Flying (CFF)

The possibility of using CFF to reduce fuel burn or to extend range is well known. As stated by Nangia [31], “aircraft formations (Figure 29) occur for several reasons e.g. during displays or in AAR but they are not maintained for any significant length of time from the fuel efficiency perspective.” The reason is that flying in formation will require extreme safety measures by use of sensors coupled automatically to control systems of individual aircrafts. Furthermore, flying a close formation through clouds or in gusty environment may not be practical. The obvious benefit of flying in formation is a more uniform downwash velocity field, which minimizes the energy transferred into it from propulsive energy consumption. Another benefit is the cancellation of vortices shed from the wing-tips of individual airplanes, except the two outermost ones. How effective this cancellation will be would depend upon the practicality of achievable spacing among the aircrafts. There would also be a substantial benefit in elimination of vortex contrails and cirrus clouds. Recently, NASA conducted tests on two F/A-18 aircraft formations [32]. It was shown that the benefits of CFF occur at certain geometry relationships in the formation, namely the trailing aircraft should overlap the wake of the leading aircraft by 10-15% semi-span in this case. Jenkinson [33] suggested that the CFF of several large aircrafts is more efficient in comparison with flying a very large aircraft. The aircrafts could take-off from different airports and then fly in formation over large distances before peeling off for landing at required destinations. Bower at al. [34] have recently investigated a two aircraft echelon formation and a three aircraft formation of three different aircraft and analyzed the fuel burn. Their study determined the fuel savings and difference in flight times that result from applying CFF to missions of different stage lengths and different spacing between the cities of origin. For a two aircraft formation, the maximum fuel savings were 4% with a tip-to-tip gap between the aircraft equal to 10% of the span and 10% with a tip overlap equal to 10% of the span. For the three aircraft inverted-V formation, the maximum fuel savings were about 7% with tip-to-tip gaps equal to 10% of the span and about 16% with tip overlaps equal to 10% of the span.

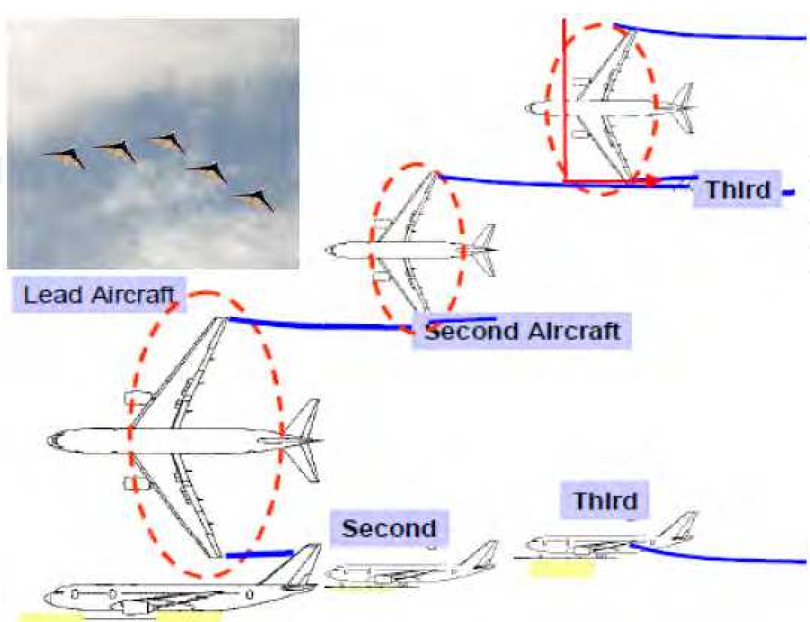

Fig. 29. Three different aircraft type in CFF [31].

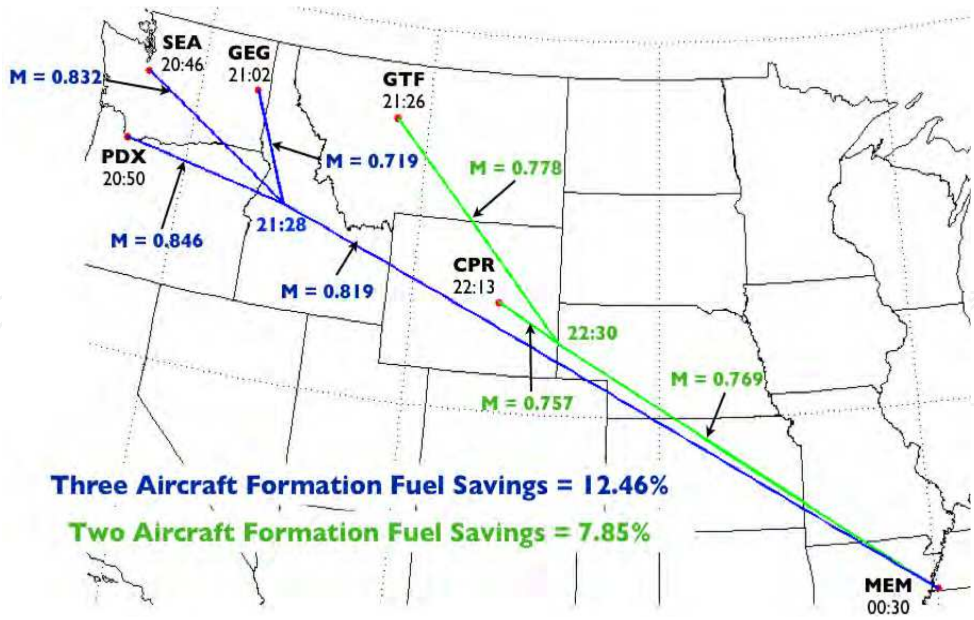

Fig. 30. Five FedEx aircraft in Formation Flight enroute from Pacific Northwest to Memphis [34].

Bower et al. [34] conducted a case study to examine the effect of formation flight on five FedEx flights from the Pacific Northwest to Memphis, TN. The purpose of this study was to quantify the fuel burn reduction achievable in a commercial setting without changing the flight schedule. With tip-to-tip gaps of about 10% of the span it was shown that fuel savings of approximately 4% could be achieved for the set of five flights. With a tip-to-tip overlap of about 10% of the span the overall fuel savings were about 11.5% if the schedule was unchanged. This translated into saving of approximately 700,000 gallons of fuel per year for this set of five flights. Figure 30 shows the three types of aircrafts employed in the study – two Boeing B 727-200, two DC 10-30 and one Airbus A300 – 600F. It should be noted that in CFF, each aircraft will experience off-design forces and moments. It is important that these are adequately modeled and efficiently controlled. Simply using aileron may trim out the induced roll but at the expense of drag. But as Bower et al. [34] have shown, it is possible to realize savings in fuel burn by using the existing aircraft by suitably tailoring the formation.

2.7.4 Tailored arrivals

Boeing [35] is working with several airports, airlines and other partners around the world in developing tools for "tailored arrivals" which can reduce fuel burn, lower the controller workload and allow for better scheduling and passenger connections (Figure 31). To optimize tailored arrivals, additional controller automation tools are needed. Boeing completed the trial of Speed and Route Advisor (SARA) with Dutch air traffic control agency (LVNL) and Eurocontrol in April/May 2009. SARA delivered traffic within 30 seconds of planned time on 80% of approaches at Schiphol airport in Netherlands compared to within 2 minutes on a baseline of 67%. At San Francisco airport, more than 1700 complete and partial tailored arrivals have been completed between December 2007 and June 2009 using the B777 and B747 aircraft. It has been found that tailored arrivals save an average of 950 kg of fuel and approximately $950 per approach. Complete tailored arrivals saved approximately 40% of the fuel used in arrivals. For one year period, four participating airlines saved more than 524,000 kg of fuel and reduced the carbon emissions by 1.6 million kg.

Fig. 31. Airports and Partners participating in the concept of Tailored Arrivals [35].

2.8 Savings in fuel burn by aircraft weight reduction

It is well known that substantial savings in fuel burn can be achieved by reducing the ratio of the empty weight to payload of an aircraft. It can be accomplished by the development and use of lighter and stronger advanced composites, and by reducing the design range and cruise Mach number.

2.8.1 Aircraft weight reduction by use of advanced composites

Reducing the weight of an aircraft is one of the most powerful means of reducing the fuel burn. Boeing and Airbus, as well as other Business and General Aviation aircraft manufacturers are investing in advanced composites which have the prospects of being lighter and stronger than the present carbon fiber composites (CFC). The replacement of structural aluminum alloy with carbon fiber composite is the most powerful weight reducing option currently available to the aircraft designer working towards a given payload-range requirement. The Boeing B787 and Airbus A350 have both taken this step, having wings and fuselage made with CFC. Most new designs are likely to take this path.

2.8.2 Aircraft weight reduction by reducing the design range

Although the historic trend has been in the opposite direction, another powerful means of reducing the weight of an aircraft is to reduce its design range. The study by Hahn [28] has shown that by reducing the design range from 15,000km to 5,000km, with the fuselage and passenger accommodation fixed, it is possible to reduce the operational empty weight (OEW) by 29%. The study by Creemers & Slingerland [29] noted a 17% reduction in OEW by halving the design range from 13,334km to 6,672km. Nangia [30, 31] has also shown that, with the fuselage and number of passengers fixed, wing area increases rapidly to contain the fuel needed and to maintain C_L as the design range increases. Figure 32 shows the aircraft designs and maximum take-off weight MTOW for design range from 3,000 to 12,000 nm. From Nangia's study [31], it is clear that 3,000nm aircraft can provide substantial savings in fuel burn by having less weight and can be used for long range flight by using AAR. In past twenty years, each new aircraft type has achieved 10-15% gain in fuel efficiency. Additional achievements in fuel efficiency by improvements in airframe and engine design will take some time, however, several studies have shown that it is possible to reduce fuel burn significantly by instituting operational measures such as more efficient Air-Traffic Management (ATM), Air-to-Air Refueling (AAR), Close Formation Flying (CFF), Tailored Arrivals, and by reducing the ratio of empty weight to payload.

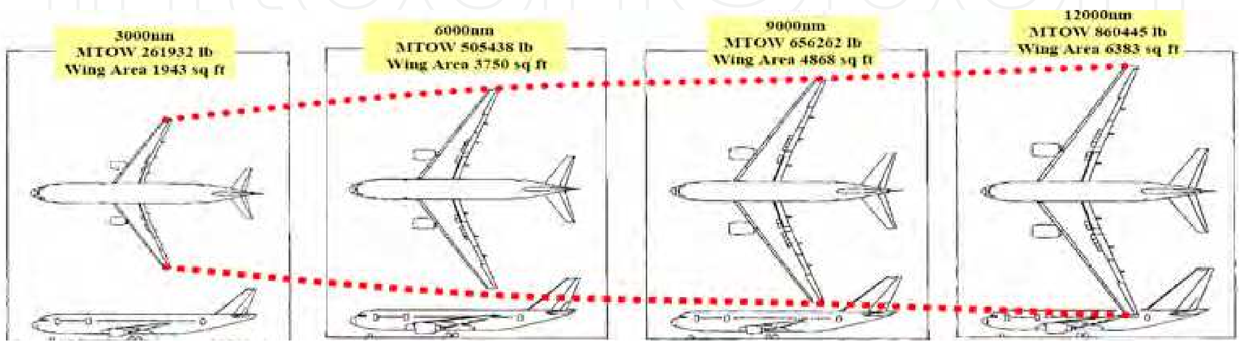

Fig. 32. Aircraft designs, with fixed fuselage, 250 passengers and $C_{L,}$ for different ranges of operation [30, 31].

2.9 Alternative fuels

All forms of powered ground and air transportation are experiencing the pressure of the need to mitigate greenhouse gas (GHG) emissions to arrest their impact on climate change. In addition the high price of fuel (oil reaching $149/barrel during summer of 2008) as well as the need for energy security are driving an urgent search for alternative fuels, in particular the biofuels. There is emphasis on both the improvements in energy efficiency and new alternative fuels. Aviation is particularly sensitive to these pressures since, for many years, no near term alternative to kerosene has been identified. Until recently, biofuels have not been considered cost competitive to kerosene. An important much desired characteristic of an alternative fuel is whether it can be used without any change to the aircraft or engines. The attractions of such a *drop-in fuel* are clear: it does not require the delivery of new aircraft but the environmental impact of all aircraft flying today can be significantly reduced. Non-drop-in fuels, such as hydrogen or methane hydrates, are unlikely to be used before 2050. The key criteria in identifying that a new alternative fuel would be beneficial in reducing CO_2 emissions should be based on the life cycle analysis of CO_2; the life-cycle CO_2 generation must be less than that of kerosene. Many first generation biofuels have performed poorly against this criterion, though second generation biofuels appear to be far more promising. Furthermore, it is important that there are no adverse side-effects arising from production of the feedstock for biofuel generation, such as adverse impact on farming land, fresh-water supply, virgin rain-forests and peat-lands, food prices, etc. Algae and halophytes (salt-tolerant plants irrigated with sea/saline water) are emerging as potential sustainable feedstock solutions. The alternative fuels need to meet specific aviation requirements and essentially should have the key chemical characteristics of kerosene, that is they won't freeze at flying altitude and they would have a high enough energy content to power an aircraft's jet engine. In addition, the alternative fuel should have good high-temperature thermal stability characteristics in the engine and good storage stability over time.

Interest in biofuels for civil aircraft has increased dramatically in recent years and the focus of the aviation industry on what is and what is not credible in this arena has sharpened. It is clear that a *'drop-in'* replacement for kerosene i.e. the synthetic kerosene appears to be the only realistic possibility in the foreseeable future. The potential of such bio-derived synthetic paraffinic kerosene (Bio-SPK) to reduce the net CO_2 emissions from aviation may well match or exceed that of advances in airframe and engine technologies, and perhaps may achieve reductions across the world fleet sooner than new technologies. In addition, since synthetic kerosene produces substantially less black carbon and sulphate aerosols than kerosene from oil wells, there is a possibility that its use will reduce contrail and cirrus formation as well.

Boeing, Airbus and the engine manufacturers believe that the present engine technology can operate on biofuels (tests are very promising) and that within 5 to 15 years, the aviation industry can convert to biofuels. On 19 June 2009, Billy Glover of Boeing made a presentation to the press at the Paris air show [35] describing the Boeing's "Sustainable Biofuels Research and Technology Program." Tables I and II show the comparisons of key fuel properties of currently used Jet A/Jet A-1 fuel with those with Bio-SPK fuel derived from three different feed-stocks (Jatropha, Jatropha/Algae, and Jatropha/Algae/Camelina) for neat fuel and blends respectively. All Bio-SPK blends met or exceeded the aviation jet fuel requirements. In this presentation, Boeing declared that they are preparing a comprehensive report on Bio-SPK fuels for submittal to ASTM International and expect an approval in 2010. Boeing is working across the industry on regional biofuel commercialization projects. There have already been a few experimental flights operated by several airlines using the biofuel blends and many more are planned in the near future.

Property		Jet A/Jet A-1	ANZ Jatropha	CAL Jatropha/Algae	JAL Jatropha/Algae/Camelina
Freeze Point °C	Max	-40 Jet A -47 Jet A-1	-57.0	-54.5	-63.5
Thermal Stability JFTOT (2.5 hrs. at control temperature) Temperature °C	Min	260	340	340	300
Viscosity -20°C, mm^2/s	Max	8.0	3.663	3.510	3.353
Contaminants Existent gum, mg/100mL	Max	7	<1	<1	<1
Metals ppm.	Max	0.1 per metal	<0.1	<0.1	<0.1
Net Heat of Combustion MJ/kg	Min	42.8	44.3	44.2	44.2

Table I. Key Biofuel (Neat) and Jet/Jet A-1 Fuel properties comparison [35].

Property		Jet A/Jet A-1	ANZ Jatropha	CAL Jatropha/Algae	JAL Jatropha/Algae/Camelina
Freeze Point °C	Max	-40 Jet A -47 Jet A-1	-62.5	-61.0	-55.5
Thermal Stability JFTOT (2.5 hours @control temperature)	Min	260	300	300	300
Viscosity -20°C mm2/s	Max	8.0	3.606	3.817	4.305
Contaminants Existent gum, mg/100mL	Max	7	1.0	<1	<1
Net Heat of Combustion MJ/kg	Min	42.8	43.6	43.7	43.5

ANZ = Air New Zealand, CAL = Continental Airline, JAL = Japan Airline

Table II: Key Biofuel (Blend) and Jet/Jet A-1 fuel properties comparison [35].

On 24 February 2008, Virgin Atlantic operated a B747-400 on a 20% biofuel/80% kerosene blend on a short flight between London-Heathrow and Amsterdam. This was the first time a commercial aircraft had flown on biofuel and it was the result of a joint initiative between Virgin Atlantic, Boeing and GE. On 30 December 2008, Air New Zealand (ANZ) conducted a two hour test flight of a B747-400 from Auckland airport with one-engine powered by 50-50 blend (B50) of biofuel (from Jatropha) and conventional Jet-A1 fuel. B50 fuel was found to be more efficient. ANZ has announced plans to use the B50 for 10% of its needs by 2013. The test flight was carried out in partnership with Boeing, Rolls-Royce and Honeywell's refining technology subsidiary UOP with support from Terasol Energy. On January 7th, Continental Airline (CAL) completed a 90-minute test flight using biofuel derived from algae and Jatropha. B737-800 flew from Houston with one engine operating on a 50-50 blend of biofuel and conventional fuel (B50) and the other using all conventional fuel for the purpose of comparison. The biofuel mix engine used 3,600 lbs of fuel compared to 3,700 lbs used by the conventional engine. On January 30, 2009, Japan Airline (JAL) became the fourth airline to use B50 blend of Jatropha (16%), algae (<1%) and Camelina (84%) on the third engine of a 747-300 in one-hour test flight. It was again reported that biofuel was more fuel efficient than 100% jet-A fuel. It should be noted that in all the above demos, biofuel came from sustainable feedstocks (see Tables I and II), sources that neither compete with staple food crops nor cause deforestation. It is worth mentioning that on 1 February 2008, Airbus A380 flew from Filton, U.K. to Toulouse, France with one of its Rolls-Royce engines powered by an alternative, synthetic gas-to-liquid (GTL) jet fuel. Airbus and Qatar Airways are now partners in a GTL consortium which also includes Shell International Petroleum to investigate the use of GTL neat/blend vis-à-vis conventional jet fuel. From an environmental standpoint, it is encouraging and very hopeful that both major manufacturers – Boeing and Airbus are positioning themselves to be at the forefront of alternative and bio-jet fuels. It is surmised that by 2050, with the use of synthetic kerosene derived from biomass, the world fleet CO_2 emissions per passenger-kilometer (PKM) could be lower at least by a factor of three, NOx emissions lower by a factor of 10 and contrail and contrail-induced cirrus formation lower by a factor of 5 to 15.

2.10 Electric, solar or hydrogen powered green aircraft

For many years, there have been several exploratory studies in academia and industry to build and fly aircraft using sources of energy other than Jet-kerosene or synthetic kerosene (biofuels). There have been several success stories in recent years. In March 2008, Boeing successfully conducted a test flight of a manned aircraft powered by PEM hydrogen fuel cells [36], shown in Figure 33. Since fuel cells convert hydrogen directly into electricity and heat without the products of combustions such as CO_2, they use a clean or green source of energy. Fuel cells propelled aircraft is also often called as "an all electric aircraft."

Fig. 33. Boeing PEM Fuel Cell Powered Electric Aircraft [36].

Fig 34. Solar Power Aircraft HB-SIA from SOLAR IMPULSE [37].

Recently in June 2009, the prototype of a new solar-powered manned aircraft was unveiled in Switzerland by the company SOLAR IMPULSE [37]. The airplane is designed to fly both day and night without the need for fuel. The aircraft has a wing span equal to that of a Boeing 747 but weighs only 1.7 tons. It is powered by 12,000 solar cells mounted on the wing to supply renewable solar energy to the four 10HP electric motors. During the day, the solar panels charge the plane's lithium polymer batteries, allowing it to fly at night. To be sure, the fuel-cell propelled electric aircraft and the solar energy driven aircraft are not likely to become feasible for mass air transportation. However, they can become viable for recreation and personal transportation, and possibly as business aircraft in not too distant future. The idea of using liquid hydrogen as a propellant has been around for many decades, but is unlikely to become feasible for commercial aircraft, at least before 2050, because of many challenges that would have to be overcome. Figure 35 shows the artist's rendering of a hydrogen-powered version of A310 Airbus [38]. It is also called a "Cryoplane" because of the very visible cryogenic hydrogen tank located above the passengers. Cryogenic hydrogen is the only possibility for the airplane since the high pressure tanks would be too heavy. The physical properties of the liquid hydrogen determine the appearance of the Cryoplane. Liquid hydrogen occupies 4.2 times the volume of jet fuel for the same energy; therefore the tanks will have to be huge. Jet fuel weighs 2.9 times more than liquid H_2 for the same energy. The reduced weight partly compensates for the increased aerodynamic drag of the tanks. The Cryoplane would have less range and speed than A310. It will have higher empty weight. Furthermore, whatever energy source is used, 30% will be lost in hydrogen liquefaction. In addition, the cost, infrastructure and passenger acceptance issues would have to be addressed. The main advantage of using a hydrogen powered airplane is the reduced emissions as shown in Figure 36 from Penner [39]. Since the use of H_2 does not produce any CO_2, it is dubbed as clean fuel.

Fig. 35. Artist's rendering of a Hydrogen powered version of A310 Airbus [38].

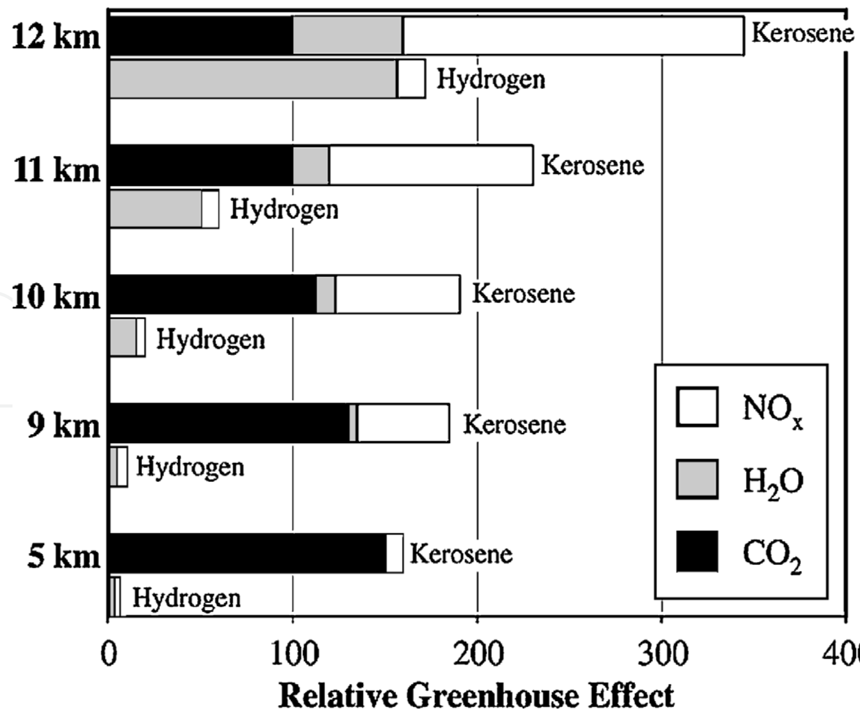

Fig. 36. Relative emissions from Jet-kerosene and Hydrogen at various altitudes [39].

2.11 Modeling environmental & economic impacts of aviation

2.11.1 Cambridge university aviation integrated modeling project (AIM)

Institute for Aviation and the Environment at Cambridge University in U.K. has developed one of the most comprehensive projects – called the Aviation Integrated Modeling (AIM) project to develop a policy assessment capability to enable comprehensive analyses of aviation, environment and economic interactions at local and global levels. It contains a set of inter-linked modules of the key elements which include models of aircraft/engine technologies, air transport demand, airport activity and airspace operations, all coupled to global climate, local environment and economic impact blocks. A major benefit of AIM architecture is the ability to model data flow and feedback between the modules allowing for the policy assessment to be conducted by imposing policy effects on upstream modules and determining the implications through down stream modules to the output metrics, which can then be compared to the baseline case [40].

These modules include: (a) an *Aircraft Technology and Cost Module* to simulate aircraft fuel use, emissions production and ownership/operating costs for various airframe/engine technology evolution scenarios which are likely to have an effect during the period of the forecast; (b) an *Air Transport Demand Module* to predict passenger and freight demand into the future between origin-destination pairs within the global air transportation network; (c) an *Airport Activity Module* to investigate the air traffic growth as a function of passenger and freight growth, to calculate delays and future airline response to them, and to model ground and low altitude operations and congestion to determine LTO emissions as a function of growth in air traffic operations within the vicinity of the airport; (d) an *Aircraft Movement Module* to simulate airborne trajectories between city-pairs, accounting for airspace inefficiencies and delays for given Air Traffic Control (ATC) scenarios and to identify the locations of emissions release from aircraft in flight; (e) a *Global Climate Module* to investigate global environmental impact of aircraft movements in terms of multiple emissions species and contrails; (f) a *Local Air Quality and Noise Module* to investigate local environmental impacts from dispersion of critical air pollutants and noise from landing and take-off (LTO) operations; and (g) a *Regional Economics Module* to investigate positive and negative economic impacts of aviation in various parts of the world, including the increase in direct and indirect employment opportunities in the region. The schematic of the AIM general architecture is shown in Figure 37 [40].

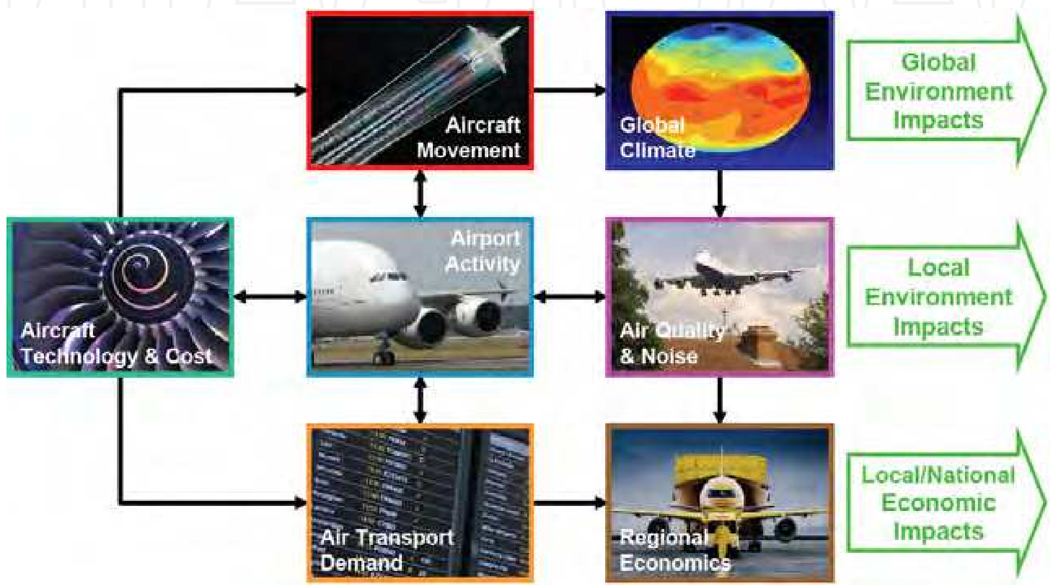

Fig. 37. AIM Architecture [40].

The details of the seven modules and interaction among them are not given here but can be found in many papers listed on the website of the Institute for Aviation and the Environment of Cambridge University in U.K (http://www.iae.damtp.cam.ac.uk/ innovation.html). Here we briefly describe the power of the AIM architecture by reproducing some results from Reynolds et al. [40]. Employing the AIM architecture, Reynolds et al. [40] have performed a case study of the U.S. transportation system, which provides a forecast of air transport passenger demand between 50 major airports in U.S. from 2000 to 2030. The flights between these 50 airports represent over 40% of U.S. scheduled domestic departures in 2000 and nearly 20% the world's scheduled flights. Reynolds et al. [40] conducted simulations under three scenarios: 1. Unconstrained/No Feedback (air transport passenger demands and resulting operations were assumed to grow unconstrained), 2. Feedback of Delay Effects (a simplified airline response to delay is modeled by assuming that the 50% of the cost incurred by the airlines due to delays are passed directly to passengers in the form of higher fares), and 3. Feedback of Delay Effects Plus Per-Km Tax Policy (This is same as scenario 2 , but with a per-Km tax applied to tickets from 2020 onwards with the objective of reducing the Revenue Passenger Km (RPKM) demand in 2020 to 2000 levels, so that the resulting delays and emissions can be directly compared). *Reynolds et al.* [40] *state that these three scenarios, their associated forecasts and environmental impact results are for illustrative purposes only to show the capabilities of AIM; they do not represent realistic evolutions of the U.S. air transportation system.* The main focus of the scenarios is on interactions between the Air Transport Demand and the Airport Activity Modules. However, one can calculate the en route and local emissions utilizing the capabilities of other modules in AIM integrated structure as given in [40]. Details of the data and assumptions used in the simulation are not presented here. The reader is referred to the paper by Reynolds et al. [40].

Forecasts from 2000 to 2030 for annual demand in terms of Revenue Passenger-Km (RPKM) from the Air Transport Demand Module; and total system aircraft operations, system average arrival delay and local NOx emissions at Chicago O'Hare (ORD) from the Airport Activity Module for the above three scenarios are presented in Figures 38 – 41 from Reynolds et al. [40]. The demand forecasts in Figure 38 include those from Airbus (for U.S market), and Boeing, ICAO and AERO-MS for the North American (NA) market for the purpose of comparison. Since they apply to different route groups and time periods, the start year total RPKM value in each case has been normalized to the historical value for the 50 airports extracted from U.S department of transportation T100 data. Figure 38 shows that for scenario 1, the demand growth measured by increase in RKPM will be 3.5 times the 2000 level by 2030. This is higher than the published estimates as expected given the unconstrained nature of the scenario 1. In scenario 2, the relatively modest feedback of 50% of the increased operating cost to the passenger has a significant effect, particularly over longer time frames. Demand forecast shows a 20% reduction (Figure 38), annual systems operations show a 15% reduction (Figure 39) and average arrival delays show a 50% reduction (Figure 40). Under scenario 3, Figures 38-40 show the effects of distance-based tax; in order to reduce the RPKM demand to 2000 levels in 2020, a 7.7 cents/km charge is required, equating to an additional $300 on a ticket from New York to Los Angeles. Figure 41 shows the annual local emissions at Chicago O'Hare (ORD); all scenarios show an initial gradual increase in emissions which can be explained in conjunction with Figures 38-40 accounting for the increase in RPKM, aircraft operations and arrival delays. The sharp decrease in emissions in scenario 3 in 2020 is due to the reduced operations caused by the introduction of distance-tax policy. The Local Air Quality and Noise Module of AIM architecture can provide results for local air quality at ORD e.g. the annual average NOx concentration at ORD as well as en route CO_2 emissions and global radiative forcing. These results demonstrate that significant insights about environmental and economic impact of aviation can be gained by AIM architecture. It should be noted that many improvements and enhancements to AIM architecture are currently under development at Cambridge.

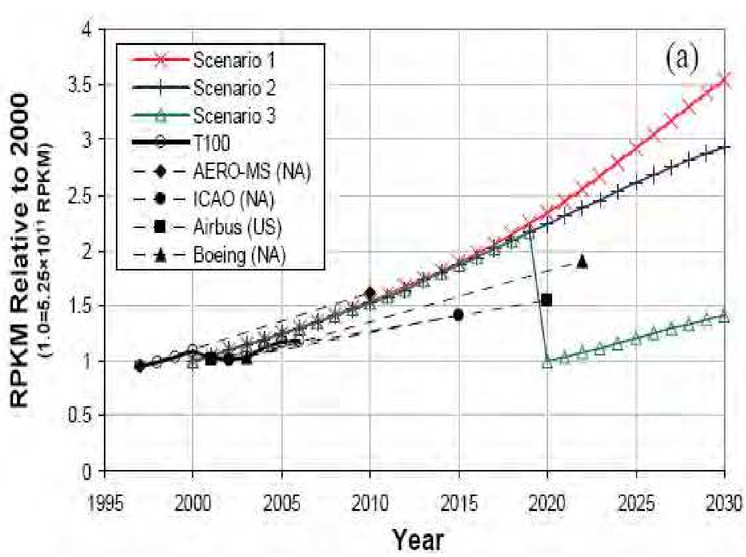

Fig. 38. Forecast of system Revenue Passenger – Km (RPKM) growth at O'Hare [40].

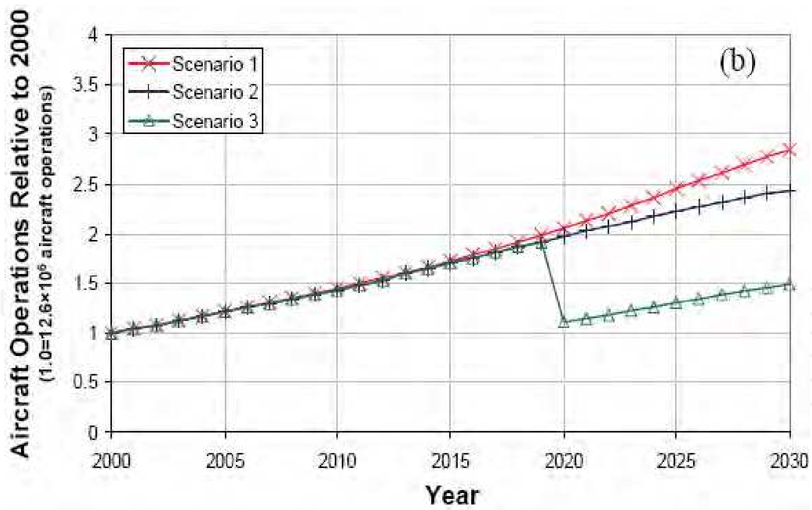

Fig. 39. Forecast of total system aircraft operations at O'Hare [40].

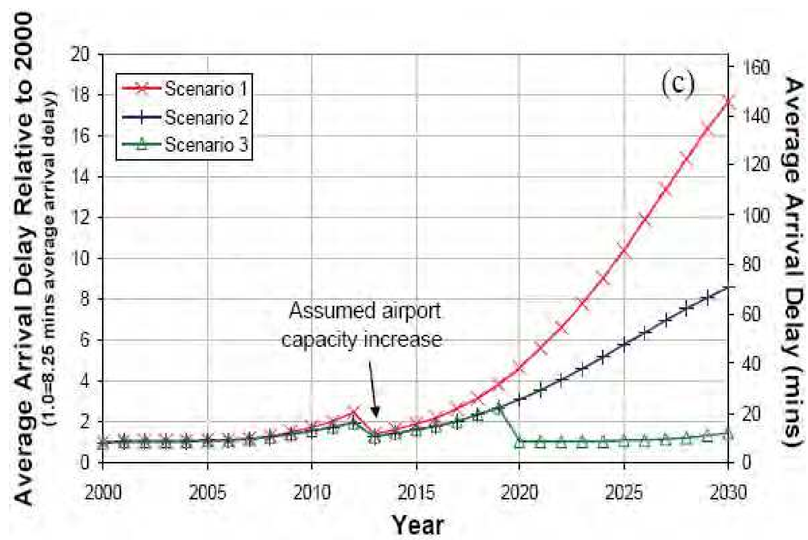

Fig. 40. System average arrival delays at O'Hare [40].

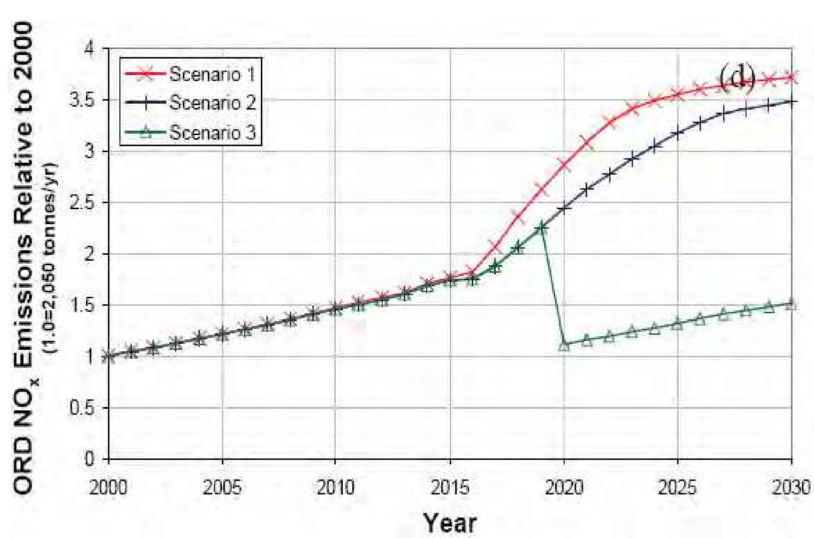

Fig. 41. LTO NOx emissions at O'Hare [40].

2.12 Sustainable airports

The airports and associated ground infrastructure constitute an integral part of Green Aviation. To address the issues of energy and environmental sustainability, the Clean Airport Partnership (CAP) was established in U.S. in 1998 [41] and is the only not-for-profit corporation in the U.S devoted exclusively to improving environmental quality and energy efficiency at airports. CAP believes "that efficient airport operations and sound environmental management must go hand in hand. This approach can reduce costs and uncertainty of environmental compliance; facilitate growth, while setting a visible leadership example for communities and the nation." The airport expansion and the development of new airports should include both the environmental costs and life-cycle costs. Sustainable growth of airports requires that they be developed as inter-modal transport hubs as part of an integrated public transport network. The ground infrastructure development should include low emission service vehicles; LEEDS certified green buildings with low energy requirements, and recyclable water usage. There should be effective land use planning of the area around the airports (including securing land for future development) with active investments into the surrounding communities. Airport expansion must also consider the issue of noise and its impact on the surrounding communities, and should be involved in its mitigation by engaging in the flight path design. The air quality near the airports should be monitored and measures for its continuous improvement should be put in place. In addition, there should be regulatory requirements to set risk limits.

3. Opportunities and future prospects

It is clear that the expected three fold increase in air travel in next twenty years offers enormous challenge to all the stakeholders – airplane manufacturers, airlines, airport ground infrastructure planners and developers, policy makers and consumers to address the urgent issues of energy and environmental sustainability. The emission and noise mitigation goals enunciated by ACARE and NASA can be met by technological innovations in aircraft and engine designs, by use of advanced composites and biofuels, and by improvements in aircraft operations. Some of the changes in operations can be easily and immediately put into effect, such as tailored arrivals and perhaps AAR. Some innovations in aircraft and engine design, use of advanced composites, use of biofuels, and overhauling of the ATM system may take time but are achievable by concerted and coordinated effort of government, industry and academia. They may require significant investment in R&D. It is now recognized by the industry (airlines and manufacturers) as well the relevant government agencies and the policy makers that there is urgent need for action to meet the challenges of climate change; aviation is becoming an important part of it. It is worth noting that in July 2008 in Italy, G8 countries (U.S, Canada, Russia, U.K., France, Italy, Germany and Japan) called for a global emission reduction target of "at least 50%" by 2050, which is in line with goal established by IATA members at their June 2009 Annual General Meeting in Kuala Lumpur, Malaysia. IATA further committed to carbon-neutral traffic growth by 2020. These challenges provide opportunities for breakthrough innovations in all aspects of air transportation.

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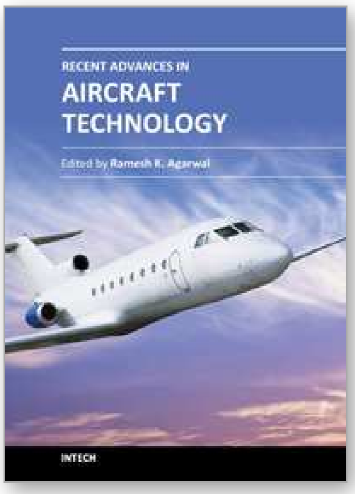

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The book describes the state of the art and latest advancements in technologies for various areas of aircraft systems. In particular it covers wide variety of topics in aircraft structures and advanced materials, control systems, electrical systems, inspection and maintenance, avionics and radar and some miscellaneous topics such as green aviation. The authors are leading experts in their fields. Both the researchers and the students should find the material useful in their work.