Sustainable (Green) Aviation and Aerospace Education

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ASEE Midwest Section Meeting, Lawrence, KS

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Sustaining the Future

Washington University in St. Louis

Gro Harlem Brundtland

Sustainable Development:

“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

The Brundtland Report: *Our Common Future*, 1987, World Commission on Environment and Development

Sustainability

- "The effort to frame social and economic policy so as to preserve earth's bounty – its resources, inhabitants, and environments – for the benefit of both present and future generations. The old Native American proverb ---- We do not inherit the earth from our ancestors, we borrow it from our children."

Frank. H.T. Rhodes, President Emeritus, Cornell University, in Chronicle of higher Education, 20 October 2006

Global Warming Could Devastate World Economy

Washington University in St. Louis

- "Unchecked Global Warming will devastate the world economy on the scale of World Wars and the Great Depression. It is no doubt that, if the science is right, the consequences for our planet are literally disastrous. This disaster is not set to happen in some science fiction future many years ahead, but in our lifetime." Tony Blair, British P.M. commenting on a report by Sir Nicholas Stern

Associated Press, 30 October 2006

Also IPCC Report, Brussels, April 2007

Sustainable Aviation

Washington University in St. Louis

Aircraft with Minimal Environmental Impact

(Low Noise, Fuel Burn and Emissions)

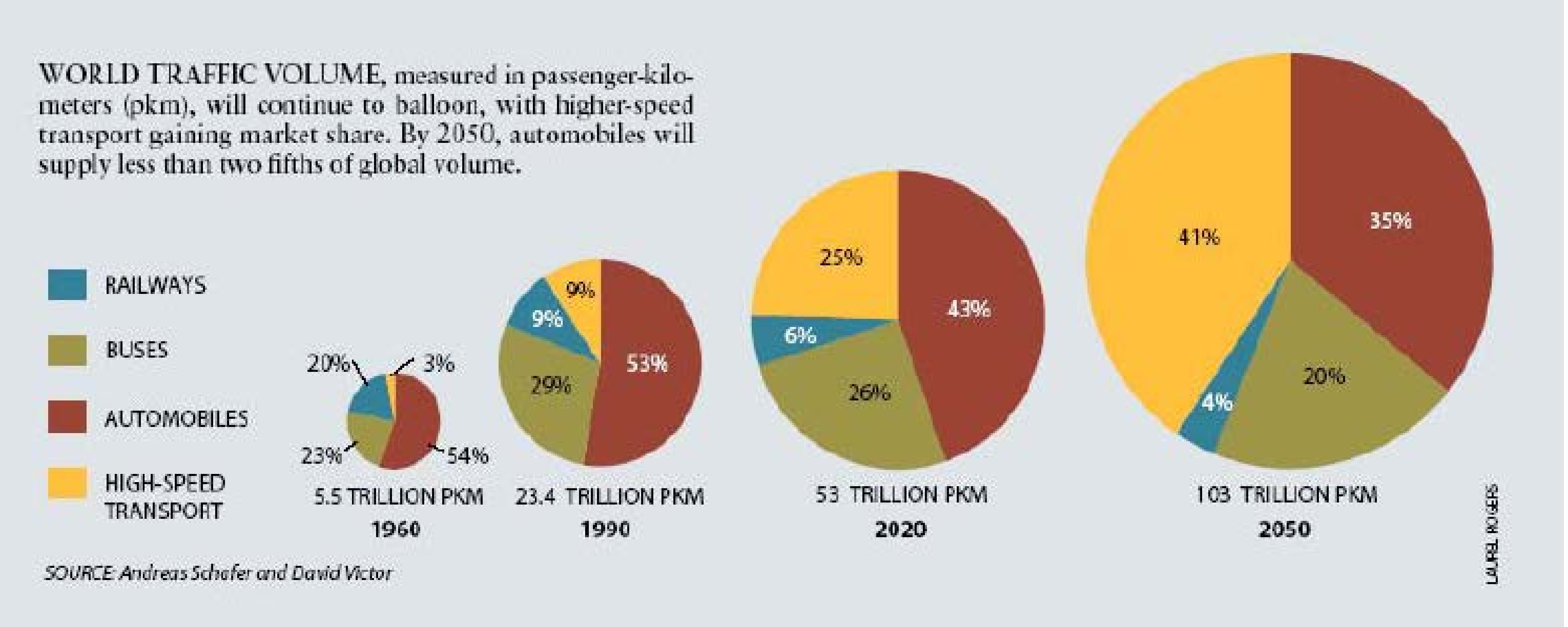
Sustainable Green Airports

(Low Noise and Carbon Neutral)

Global Mobility Trends

Source: Schafer et al. (2009)

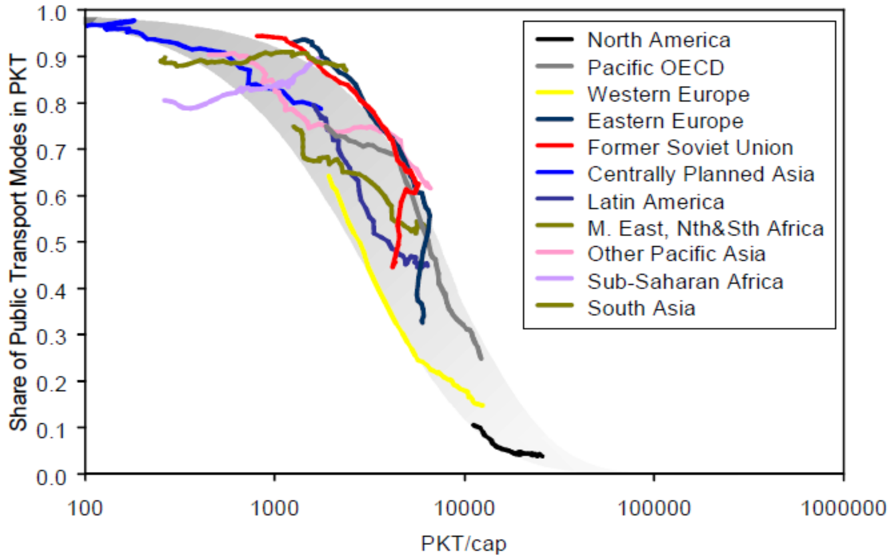
- Currently, air and ground vehicles are responsible for 50% of petroleum (oil) consumption and 60% of all greenhouse gas (GHG) emissions worldwide.
- There are approximately 500,000 air vehicles and 750 million ground vehicles in service worldwide. These numbers are forecasted to double by 2050.



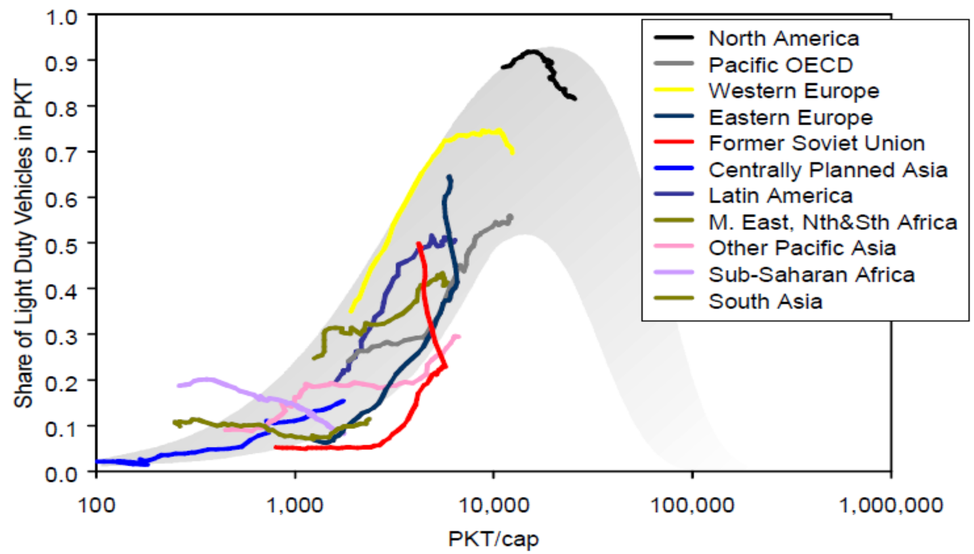
Global Mobility Trends

Source: Schafer et al. (2009)

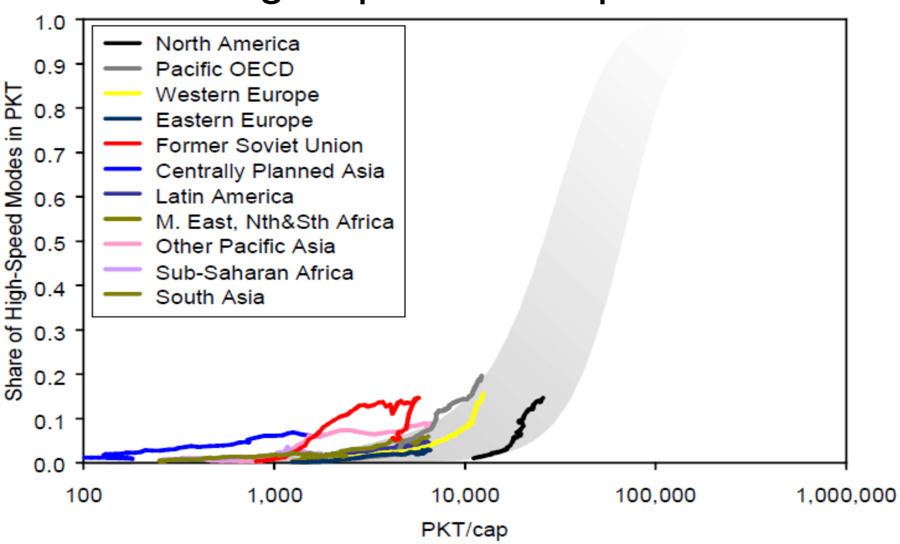
Public Transport



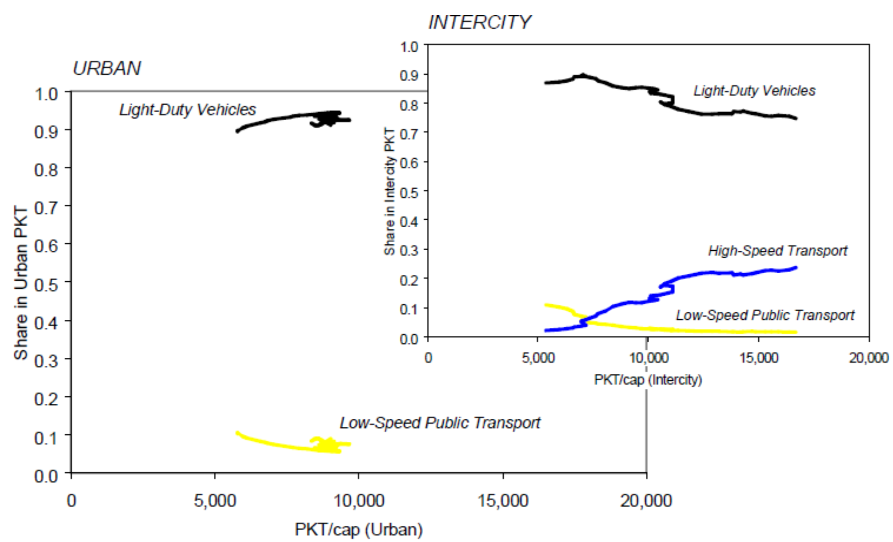
Light-Duty Vehicle Transport



High Speed Transport



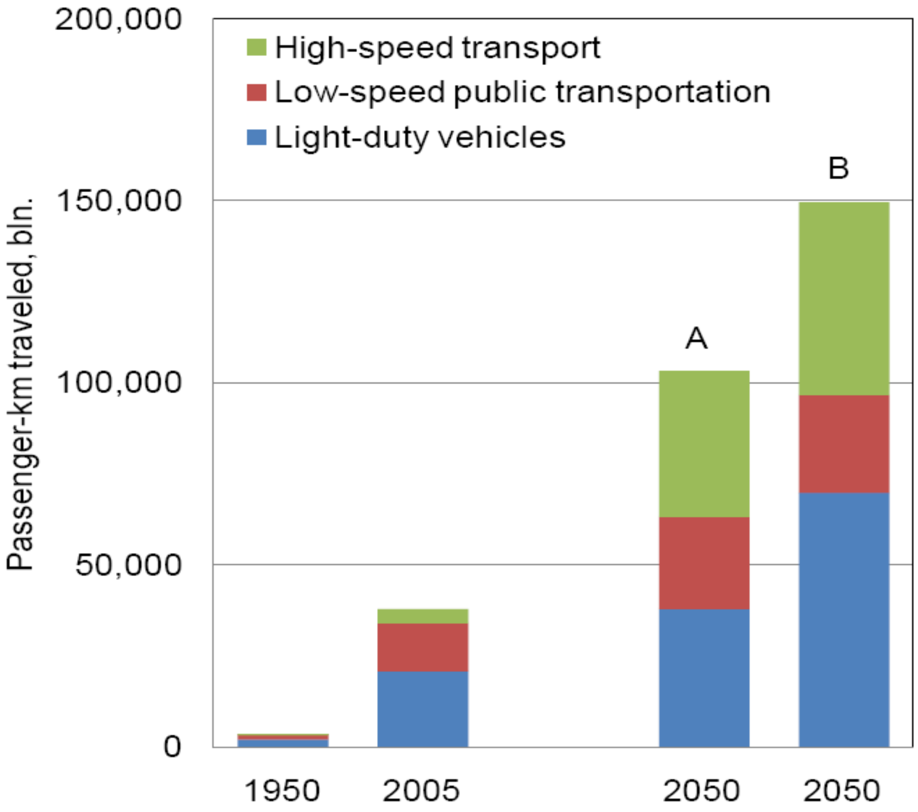
Intercity Travel (U.S)



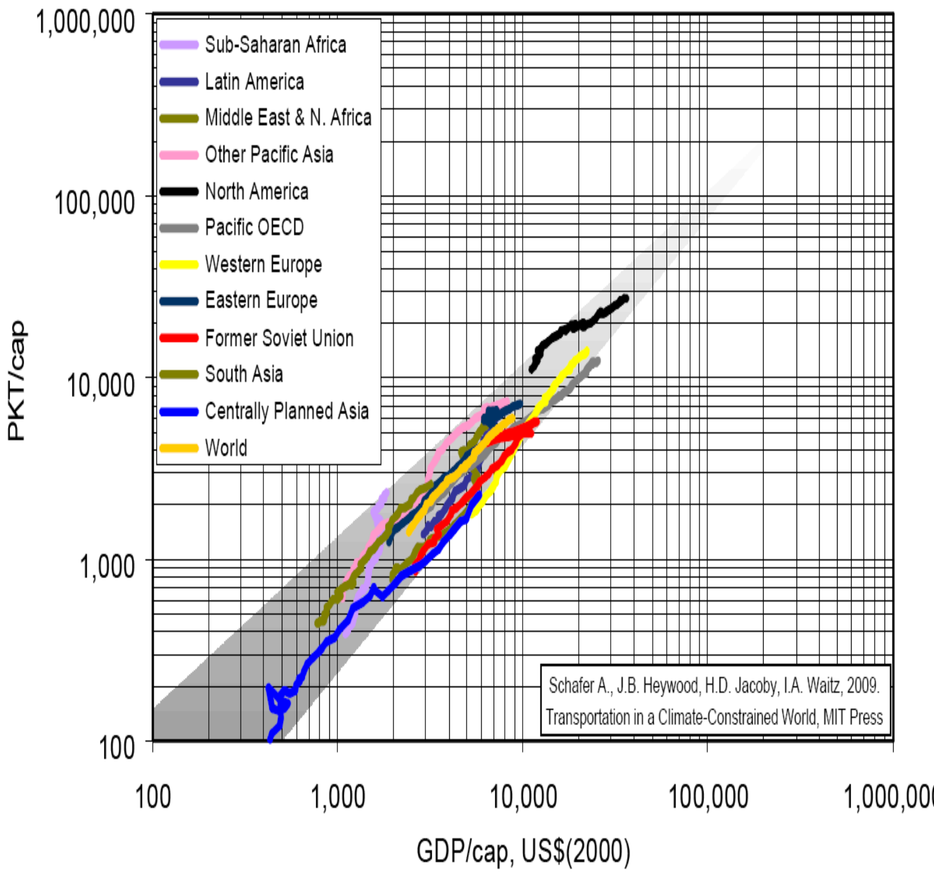
Air Travel Forecast

- 1% of world passenger traffic in 1950, 10% in 2005 , projected to be 36-40% by 2050 (assuming 3% growth in GDP, 5.2% growth in passenger traffic and 6.2% increase in Cargo) Source: Schafer et al. (2009)

Projected Growth in World Passenger-Kilometers Traveled (PKT)

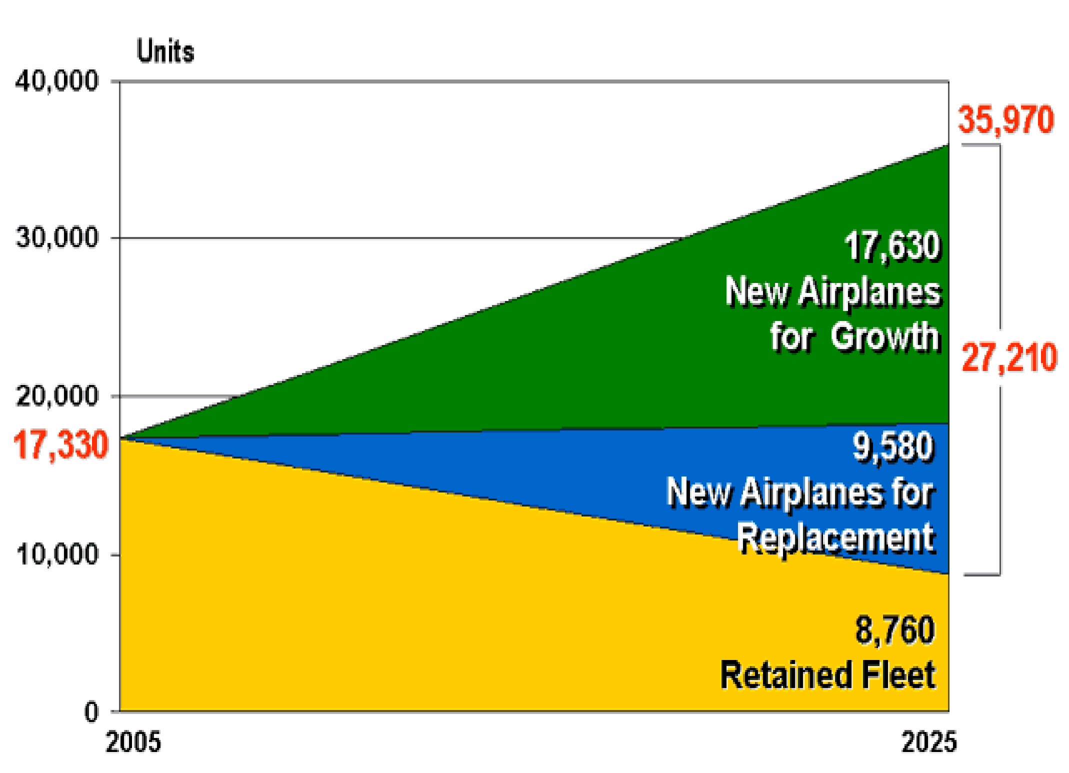


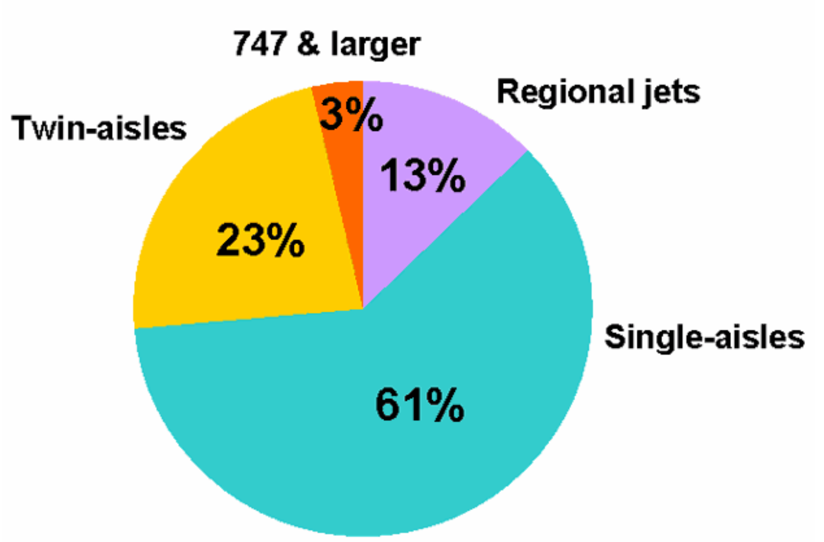
Travel Demand/Capita with Increase in GDP/Capita



Boeing Market Forecast for New Airplanes

- Total market value of new airplanes is estimated to be $2.6 trillions.
- Maximum need would be for single-aisles plane.



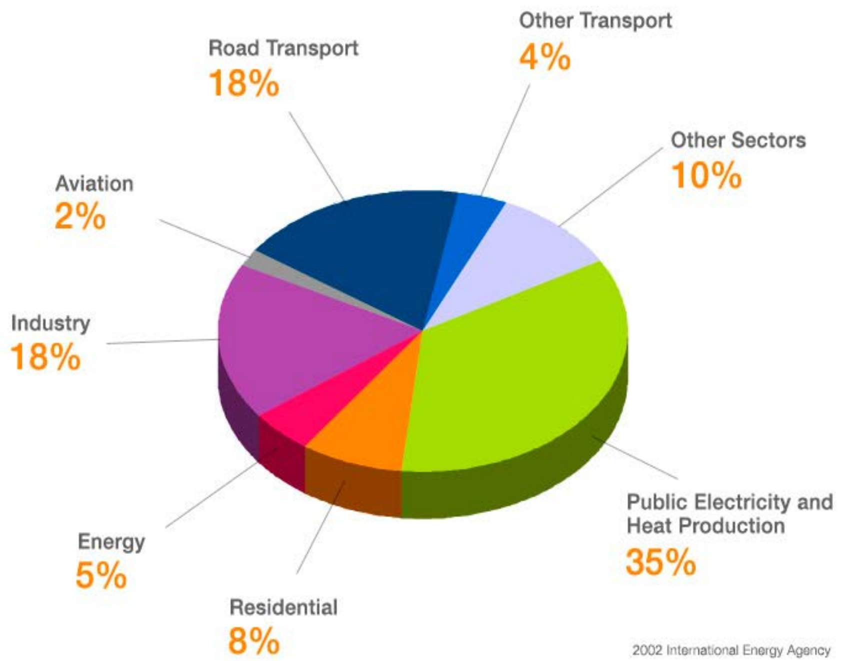


http://www.boeing.com/randy/archives/2006/07/in_the_year_202.html

Environmental Impact of Aviation
(Current Scenario)

- 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. However, it contributes 9% relative to the entire transportation sector. With 2050 forecast of air travel to become 40% of total PKT, it will become a major contributor to GHG emissions.

CO_2 Emissions Worldwide Contributed by Various Economic Sectors
Source: IEA



Environmental Impact of Growth in Aviation

- 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.
- 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, 0.5% are NOx, HC, CO, SOx and soot particulates.
- Formation of contrails and cirrus clouds is unique to aviation which contribute significantly to Radiative Forcing (RF), which contributes to climate change.
- The impact of burning fossil fuels at 9-13 km is twice that of burning the same fuel at ground.
- Based on RF, aviation is expected to account for ~ 0.05K of the 0.9K global mean surface temperature rise by 2050.

Goals for Environmentally Responsible Aviation - ERA

- **Reduction in Energy Requirements**
  - Reduce the Vehicle Mass Using High Strength Low Weight Materials (Advanced Composites)
  - Innovative Aircraft Designs (e.g. BWB) and Technologies (e.g. high L/D)
  - Innovative Engine Designs (e.g. P&W PurePower)
  - NextGen Air Traffic Management (ATM)
  - Changes in Aircraft Operations (Reduce MTOW and Range)
    - Air-to-Air Refueling, Close Formation Flying, Tailored Arrivals
- **Reduction in GHG Emissions**
  - Alternative Fuels (Bio-fuels, Synthetic Kerosene)
  - Innovative Aircraft Designs (e.g. BWB) and Open Rotor Engines, Low NOx Combustors
- **Reduction in Noise**
  - Innovative Aircraft Designs (e.g. Silent Aircraft SAX-40)
  - Innovative Engine Designs (e.g. P&W PurePower)
  - Airport Operations

ACARE and NASA Goals for Environmentally Responsible Aviation (ERA)

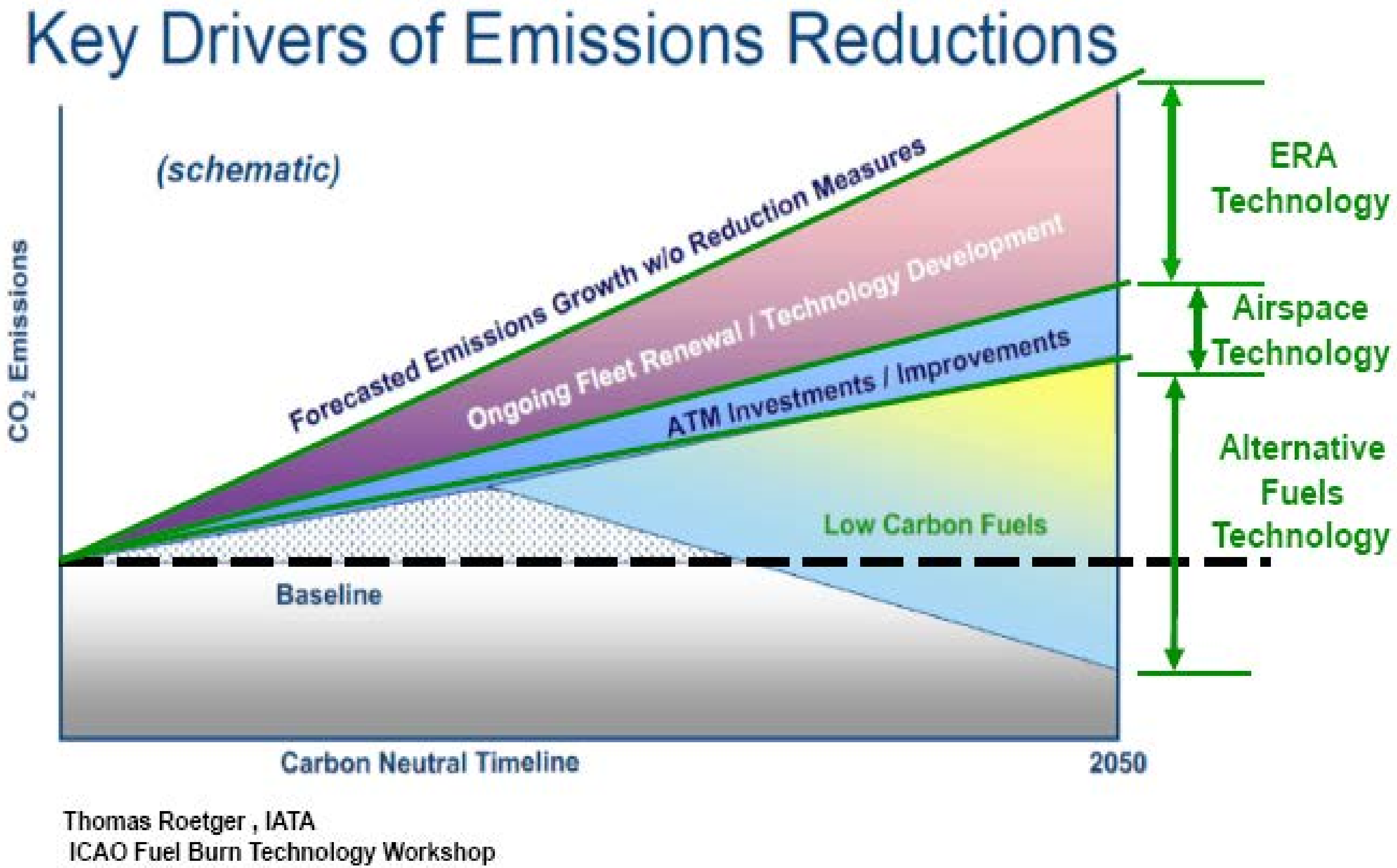
ACARE = Advisory Committee for Aeronautical Research in Europe

- ACARE Goals for 2020 relative to 2000 reference (Source: RAeS Greener by Design Report - 2008)
  - Reduce the perceived noise to one-half of current average levels
  - Reduce the CO_2 emissions per passenger km (PKM) by 50%
  - Reduce the NOx emissions by 80%
- NASA Goals (Source: F. A. Collier, NASA Langley)

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 percent may be possible through improved operational capability

Technology Impact on Environmental Footprint



Source: F. Collier, NASA Langley

Green Technologies for Aviation - 1

Aerospace International, March 2009, Royal Aeronautical Society, U.K.

- *Biofuels* – These are already showing promise; the third generation biofuels may exploit fast growing algae to provide a drop-in fuel substitute.
- *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.
- *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.
- *Wireless cabins* – The use of Wi-Fi for IFE systems will save weight by cutting wiring - leading to lighter aircraft.
- *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%.
- *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.

Green Technologies for Aviation - 2

Aerospace International, March 2009, Royal Aeronautical Society, U.K.

- *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.
- *Microwave dissipation of contrails* – Using heating condensation behind the aircraft could prevent or reduce contrails formation which leads to cirrus clouds.
- *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.
- *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.
- *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.
- *Metal composites* - New metal composites could result in lighter and stronger components for key areas.

Green Technologies for Aviation - 3

Aerospace International, March 2009, Royal Aeronautical Society, U.K.

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

Green Technologies for Aviation - 4

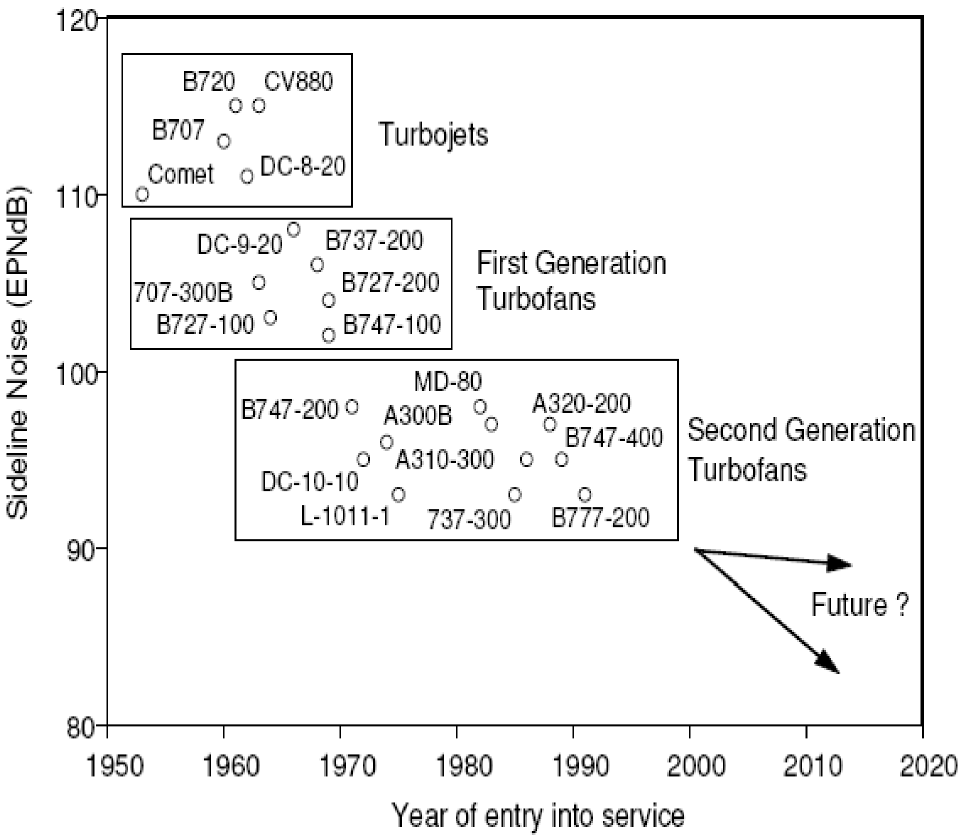
Aerospace International, March 2009, Royal Aeronautical Society, U.K.

- *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.
- *Morphing aircraft* - Already being researched for UAVs, morphing aircraft that adapt to every phase of flight could promise greater efficiency.
- *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.
- *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.
- *Sustainable power for airports* - Green airports of 2050 could draw their energy needs from wave, tidal, thermal, wind or solar power sources.
- *Greener helicopters* - Research into diesel powered helicopters could cut fuel consumption by 40%, while advances in blade design will cut the noise.
- *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.

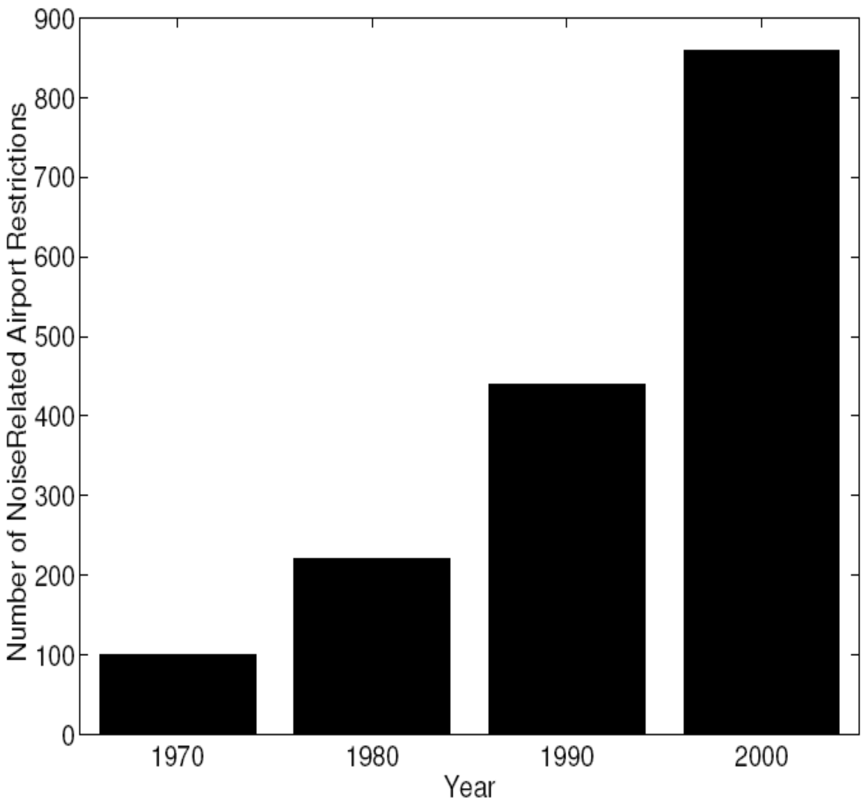
Noise Abatement

- Significant progress in reducing the aircraft noise (airframe, engine, undercarriage etc.) in past five decades by technological innovations and changes in operations at airports.
- FAA has invested over $5 billion in airport noise reduction.

Reductions in Aircraft Noise in Past Fifty Years (Source: Smith)



Number of Airports with Noise Restrictions (Source: Erickson)



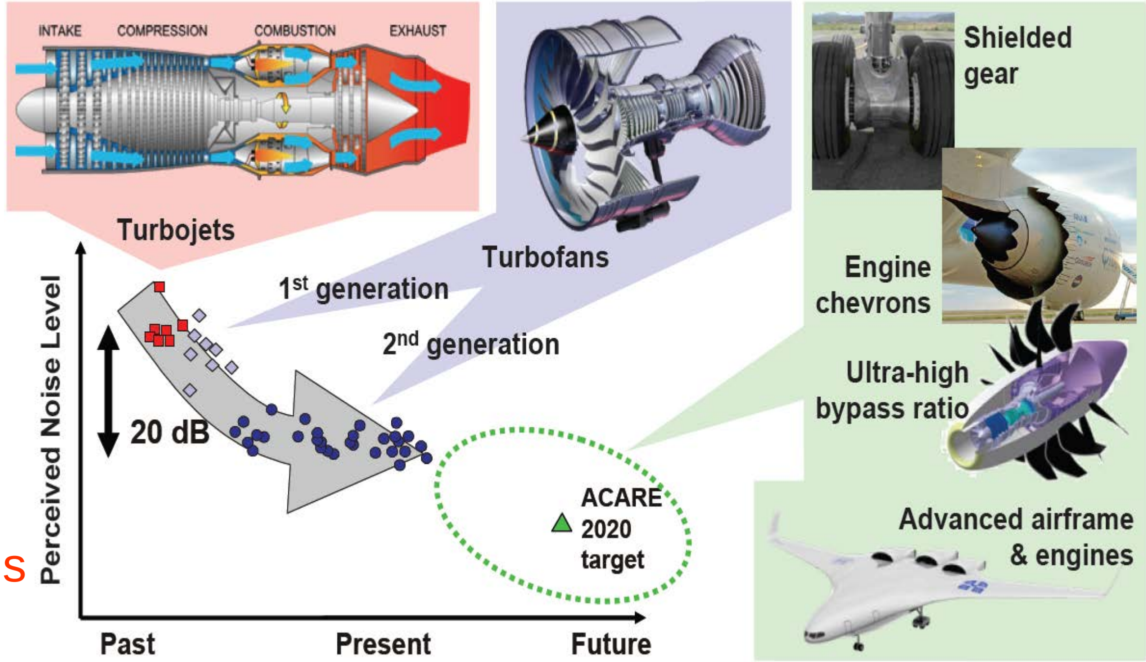
Noise Abatement – Future

Goal: Reduction by 50% in Perceived Noise Levels by 2020

- New Aircraft Designs (Hybrid Wing-Body)
  - MIT/Cambridge University Silent Aircraft SAX-40
- New Engine Technologies
  - Chevron Nozzles, Shielded Landing Gears, UHB engines with improved fan (geared fan and contra fan), fan-exhaust duct-liner technology
- New flight paths in ascent and descent flight

Silent Aircraft SAX -40
Source: http://silentaircraft.org

Engine Noise Reduction Technologies

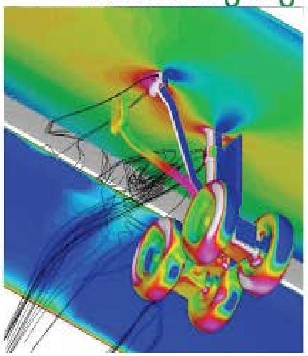


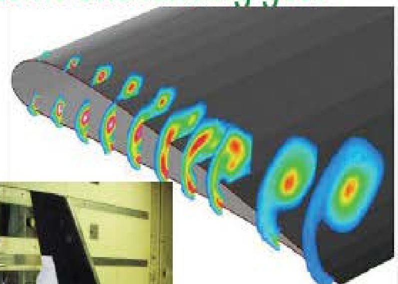
Source: Reynolds

Addressing Noise Reduction Goals

Airframe Noise

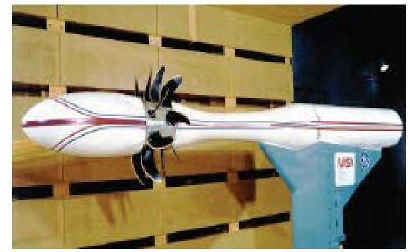
Addressing high-lift systems and landing gear





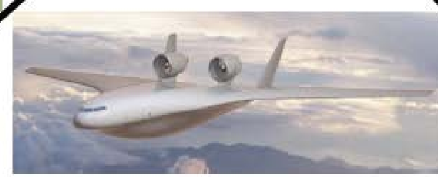
Propulsion Noise

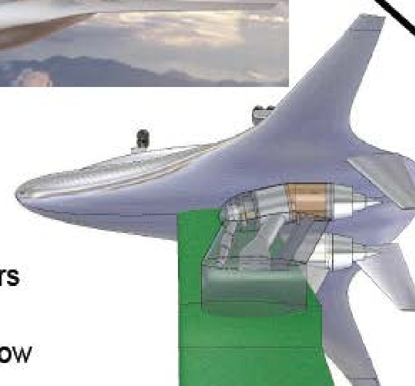
Addressing fan, core, and jet noise



Open Rotor

UHB Turbofans





- Twin High Bypass Ratio Jet Simulators
- Simplified Fan Noise Simulator
- Instrumentation and Processing for Low Noise Levels

Propulsion Airframe Aeroacoustics

Addressing airframe/propulsion interaction - shielding

Source: F. Collier, NASA Langley

Innovative Aircraft Concepts/ Designs

- Increase the *L/D* ratio: It is one of the most powerful means of reducing the fuel burn. There are three ways to increase *L/D*:

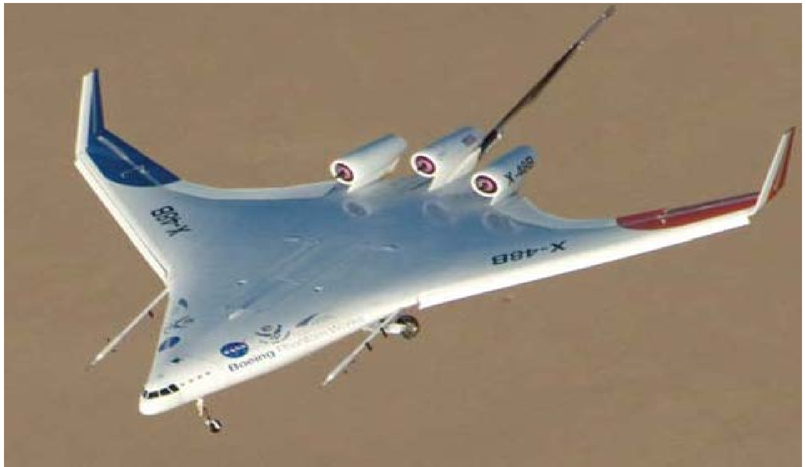
  (a) increase the wing span

  (b) reduce the vortex drag factor

  (c) reduce the profile drag

- Reducing the profile drag has the greatest mid- to long-term potential – (1) The adoption of hybrid wing-body (BWB) type layout reduces the profile drag by ~30% providing an increase of about 15% in *L/D*, (2) The laminar flow control – natural, hybrid or full LFC can reduce the profile drag.

Boeing/NASA X-48B BWB



Honda Jet, Laminar Flow Wing

Alternate Configuration Concepts

(Source: Richard A. Wahls, NASA LaRC)


Airbus
Aviation Week 1/15/01


Boeing NRA
FAP Annual Mtg 10/08


Boeing/MIT/UCI NRA
Aviation Week 2/2/09


Airbus
Aviation Week 1/15/01


NASA VSP
2003


Cambridge/MIT SAX-40
1/07

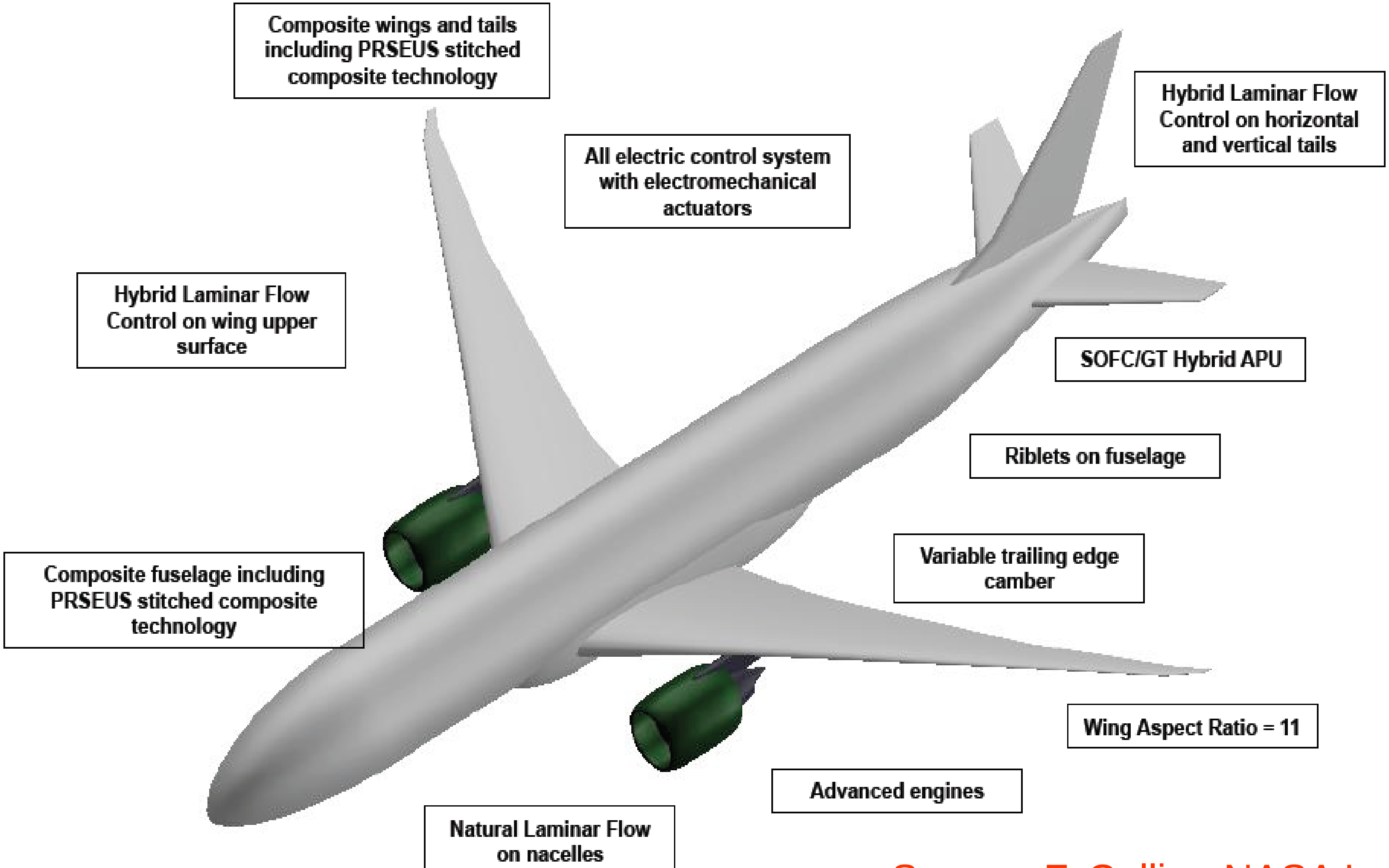

easyJet ecoJet
Reuters 6/14/07


NASA- M Moore
2009


RAeS Concept
Greener By Design, 2006

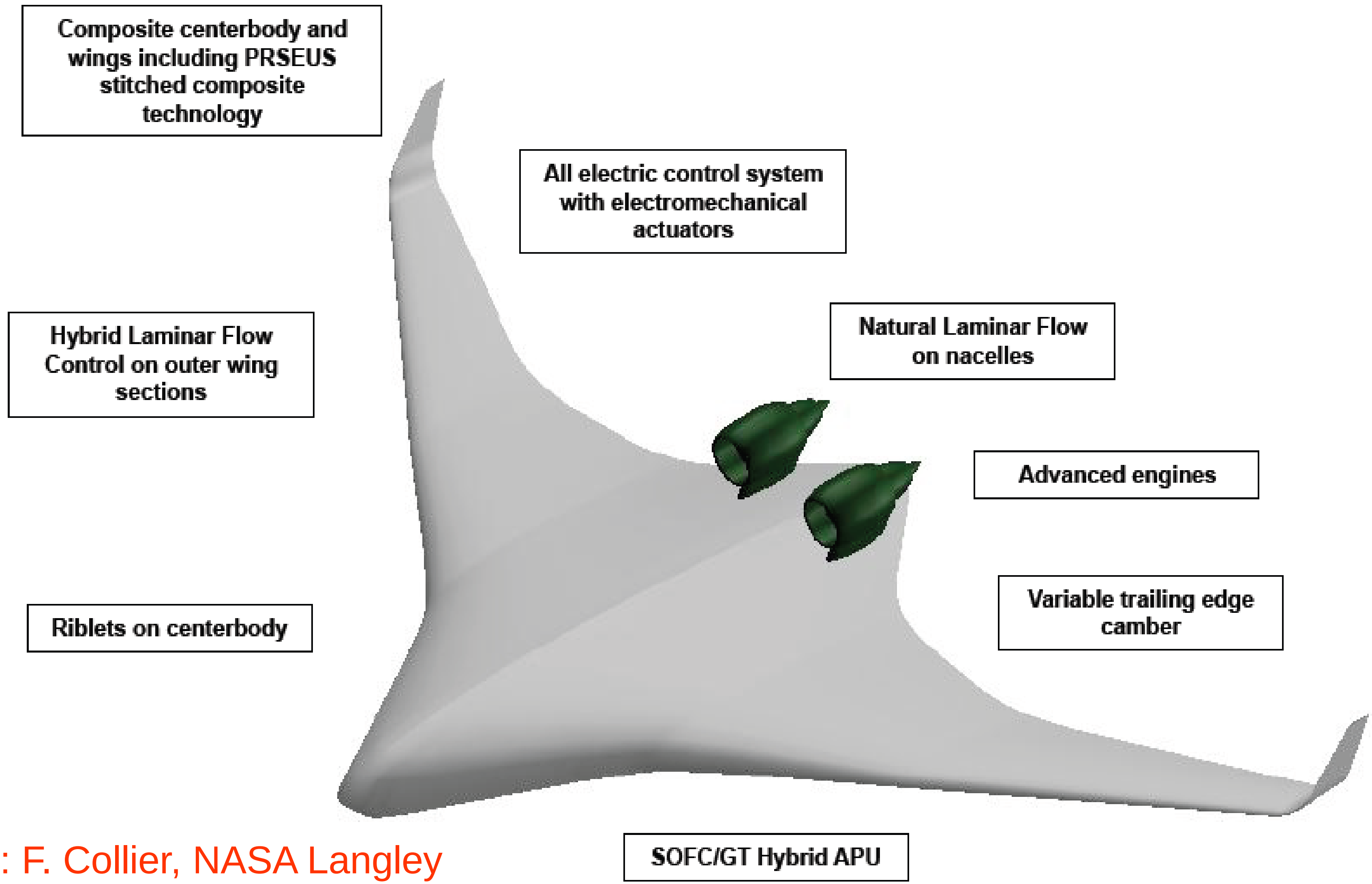
-What combination of configuration and technology can meet the goals?
-What is possible in N+2 timeframe?

Advanced Configuration 1
N+2 Advanced Tube and Wing
2025 Timeframe



Source: F. Collier, NASA Langley

Advanced Configuration 2A
N+2 Advanced HWB
2025 Timeframe



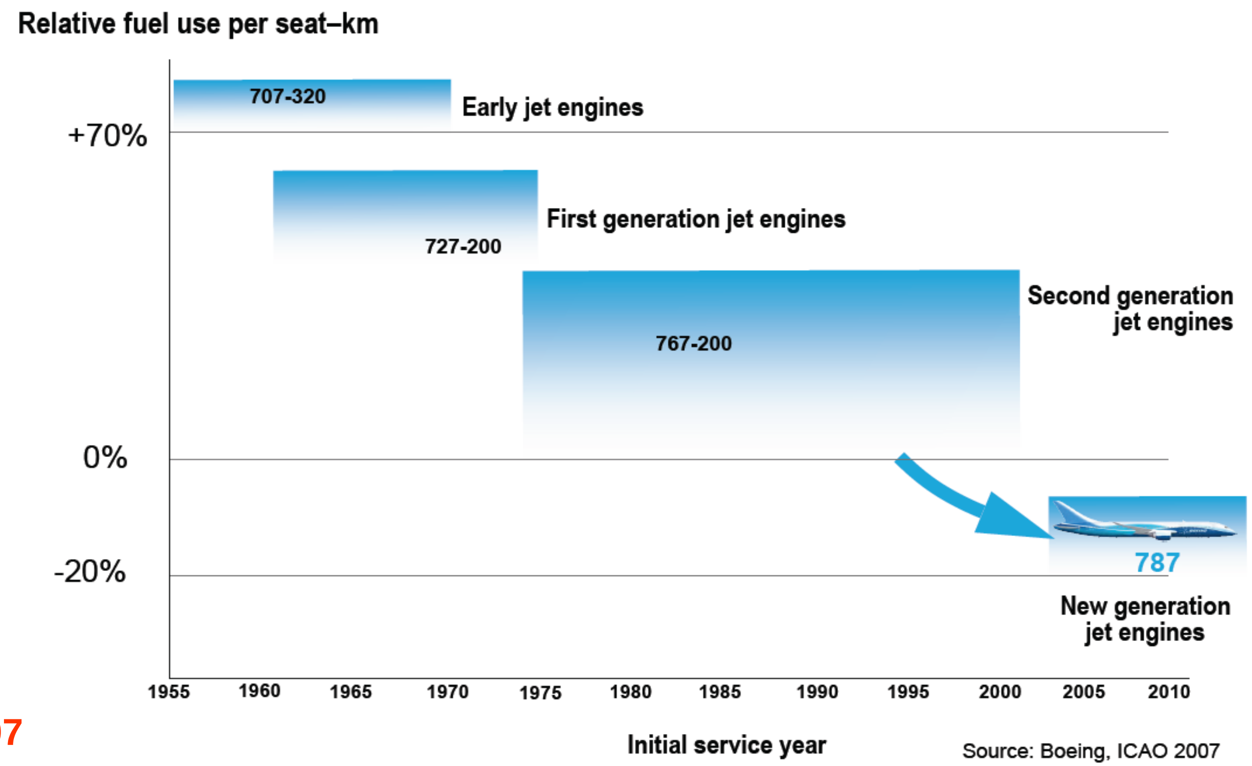
Source: F. Collier, NASA Langley

MIT's D "Double Bubble" Aircraft Design

70% Less Fuel Burn than Current Planes (B737-800), Less Noise and NOx

Innovative Engine Technologies

- The greatest gain in fuel burn reduction in past sixty years have come from better engines (turbojets to turbofans to turboprop(?)).
- There has been boost in efficiency with better compressors and materials to let the core burn at higher pressure and temperature.
- The newer aircraft are 70% more fuel efficient than they were forty years ago. In 1998, passenger aircraft averaged 4.8 liters of fuel/100km/passenger; A380 and B787 use only 3 liters.



**Source:
Boeing, ICAO 2007**

Innovative Engine Technologies

- Make Turbofans more efficient by "open rotor" design
- In mid-eighties, significant effort by GE in advanced turboprop technology (ATP). ATP has the 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.
- Issues related to noise, weight, integration with airframe, maintenance cost etc. need to be addressed.

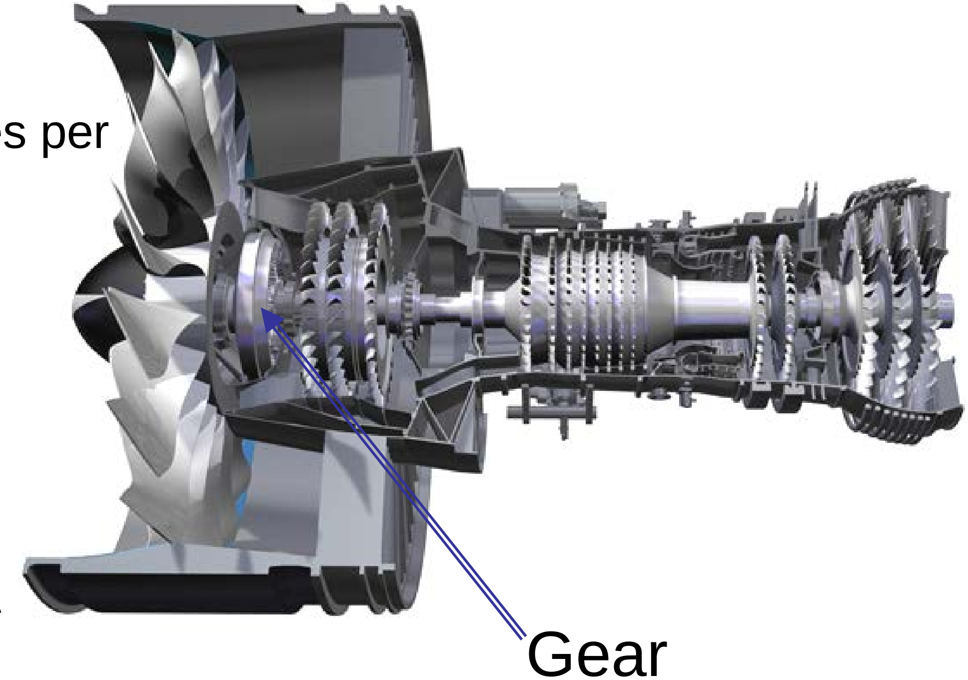
GE36 Turboprop Demonstrator on MD 81 at Farnborough (1988)
Source: www.b-domke.de/Aviation

Open-Rotor Version of Pro-Active Green Aircraft in NACRE Study
Source: RAeS Greener by Design Report

Innovative New Engine Designs

PurePower® Engine benefits

- Fuel burn improvement 12-15%
- CO_2 emissions reduced by 3000 Tonnes per aircraft per year
- NOx emissions cut in half
- Noise levels of Stage 4 minus 20 dB
- 1,500 fewer airfoils
- Lower maintenance cost
- $1.5M annual cost savings per aircraft*

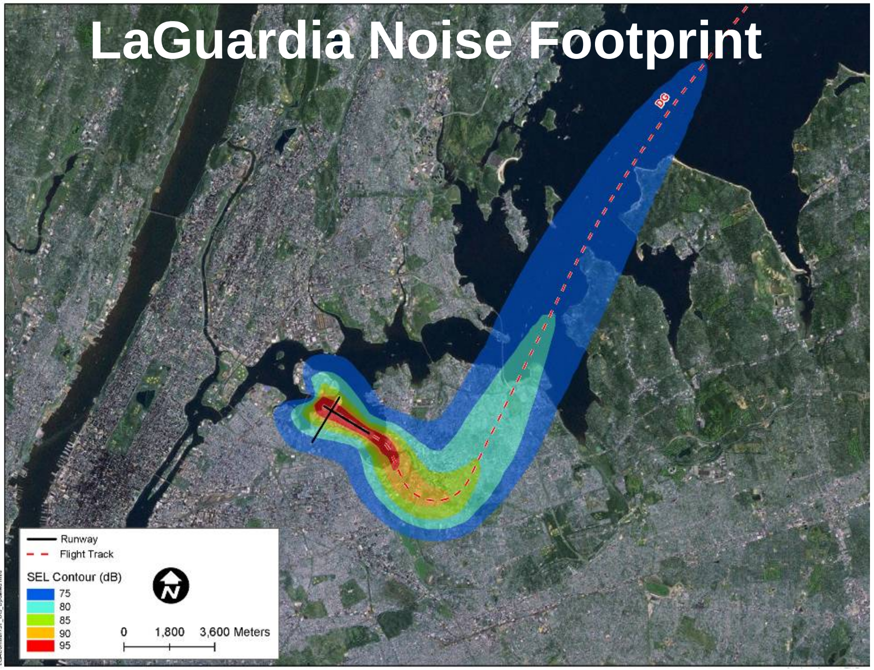


The Comprehensive Approach to Economic and Environmental Operation

Source: D. Parekh, UTRC

*At $2.50 gal fuel price, 500 nm trip

PurePower® Engine Significantly Reduces Noise



Current Modern Aircraft

P&W PurePower® Engine (77% reduction)

Noise contours for a B-737/A-320 type 150 passenger aircraft

Source: D. Parekh, UTRC

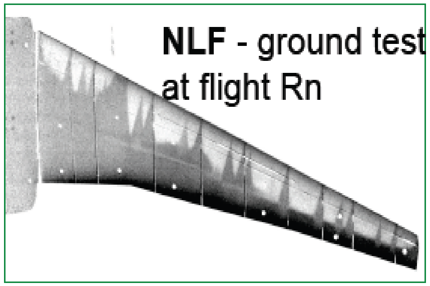
Addressing Fuel Burn (CO_2 Emissions)

DRAG REDUCTION via Laminar Flow

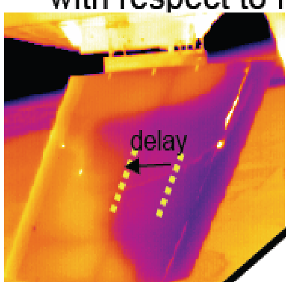
Addressing concepts & barriers
to achieving practical laminar flow on transport a/c

HLFC - revisit crossflow expt
- understand system weight

NLF - ground test
at flight Rn



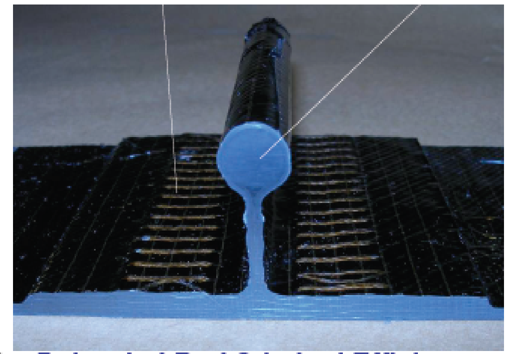
DRE - exploring the limits
with respect to Rn



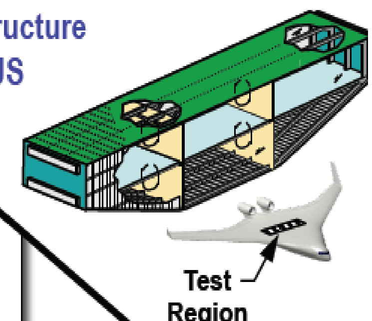
WEIGHT REDUCTION via Advanced Structures

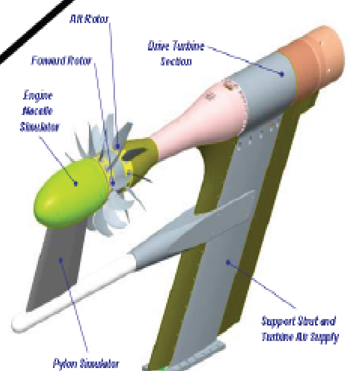
Moving from "safe-life" to "fail-safe" design
with a lightweight composite structure

Stitches Rod

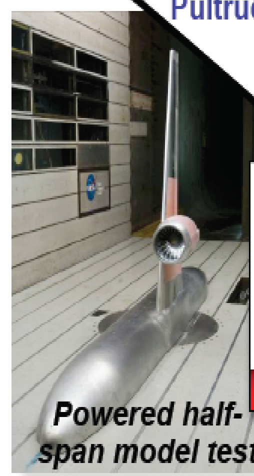


Pultruded Rod Stitched Efficient
Unitized Structure
PRSEUS

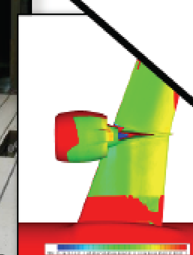




Open Rotor Propulsion Rig



Powered half-span model test



PSP Results

SFC REDUCTION via UHB

Addressing multidisciplinary challenges from subcomponent to installation
to achieve ultra-high by-pass ratio

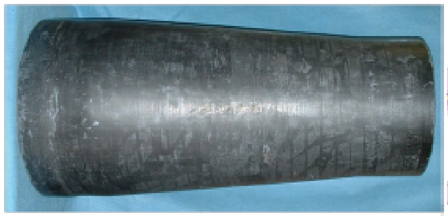
Source: F. Collier, NASA Langley

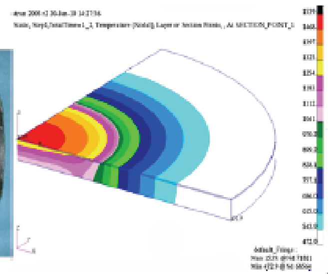
Addressing Reduced LTO NOx Emissions

ERA CMC Combustor Liner

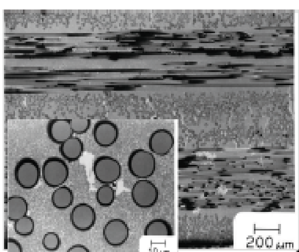
CMC combustor liner enables new engine designs incorporating higher engine temperatures and reduced cooling air flows

CMC combustor liner



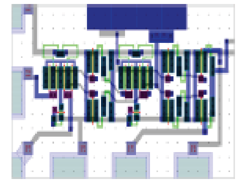


SIC CMC – enable higher temperature engine



Active Combustion Instability Control

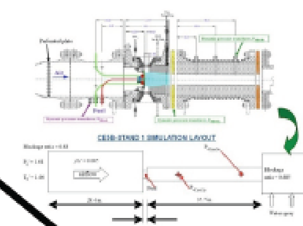
Demonstrating the capability to suppress combustor instabilities for low emission combustors

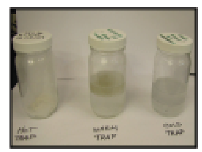


High Temperature SiC electronics circuits and dynamic pressure sensors

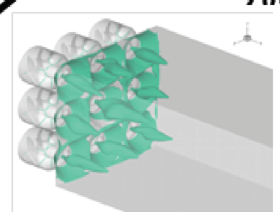
Fuel Modulation – high frequency fuel delivery systems

Instability Models and Control Methods

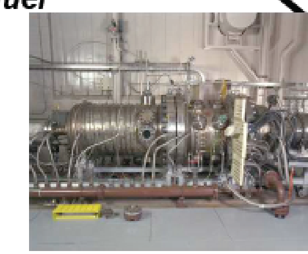




Alternative fuel



Innovative Injector Concept



ASCR Combustion Rig

Low Nox, Fuel-Flexible Combustor

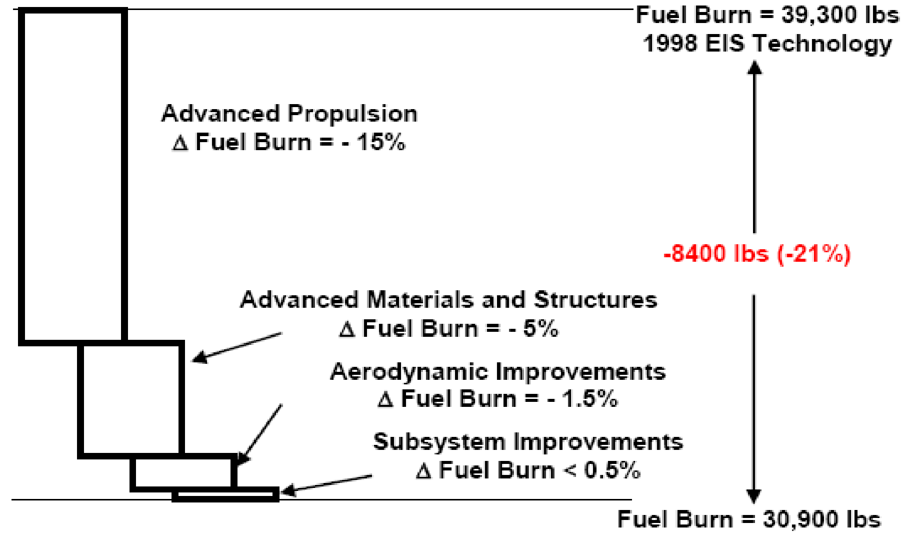
- High Bypass Ratio/High Pressure Combustor
- Superior Alternative Fuel properties
- Enhance Fuel/Air Mixing
- Advanced Ignition

Source: F. Collier, NASA Langley

Reduction in Fuel Burn for N+1 Generation Aircraft Relative to Baseline B737/CFM56 Using Advanced Technologies

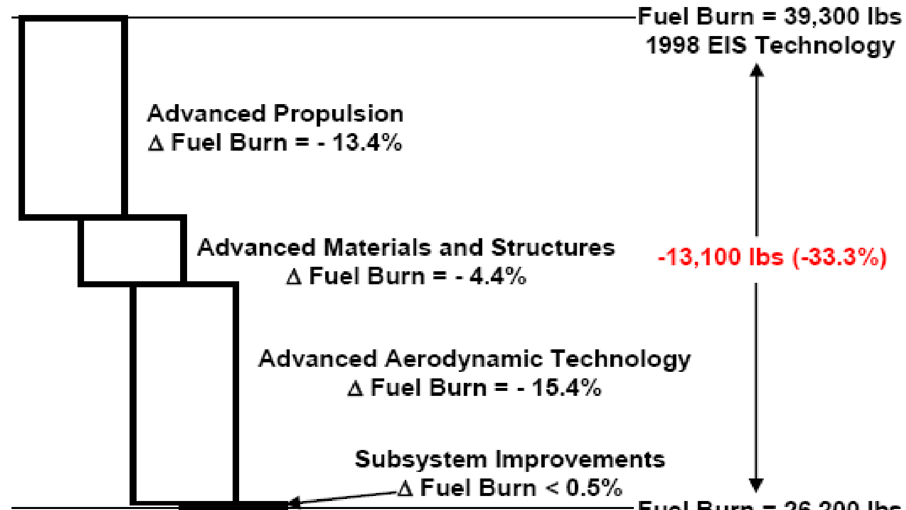
<u>"N + 1" Conventional Small Twin</u>

- 162 pax, 2940 nm mission baseline
- Ultra high bypass ratio engines, geared
- Key technology targets:
  - +1 point increase in turbomachinery efficiencies
  - 25% reduction in turbine cooling flow enabled by: improved cooling effectiveness and advanced materials
  - +50 deg. F compressor temperatures (T3)
  - +100 deg. F turbine rotor inlet temperatures
  - -15% airframe structure weight
  - -1% total vehicle drag
  - -15% hydraulic system weight



<u>"N + 1" Advanced Small Twin</u>

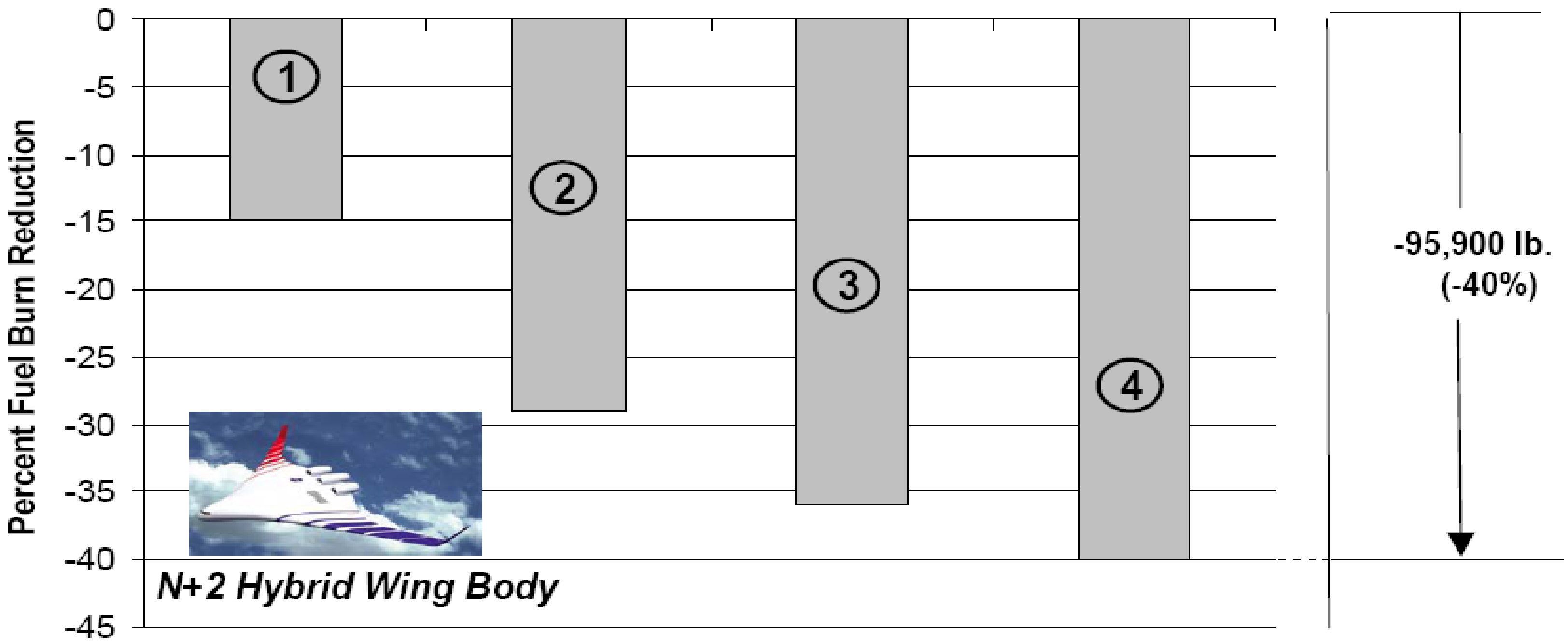
- All technologies listed above plus:
  - Hybrid Laminar Flow Control
    - 67% upper wing,
    - 50% lower wing,
    - tail, nacelle
  - Result = -17% total vehicle drag



Source: F. Collier, NASA Langley

Reduction in Fuel Burn for N+2 Generation Aircraft Relative to Baseline B777-200ER/GE96

Using Advanced Technologies



① = Hybrid wing body configuration, including all <u>composite</u> fuselage

② = ① + advanced engine and airframe technologies (~2020 timeframe)

③ = ② + embedded engines with BLI inlets

④ = ③ + laminar flow

Source: F. Collier, NASA Langley

Operational Improvements/Changes

- Improvement in Air Traffic Management (ATM) Infrastructure

- CO_2 emissions can be reduced significantly by reducing the inefficiencies in ATM which result in dog-legs, stacking at busy airports, queuing for departure slots with engines running etc. U.S. NextGen and European SESAR are aimed at addressing these problems. According to NAS report,

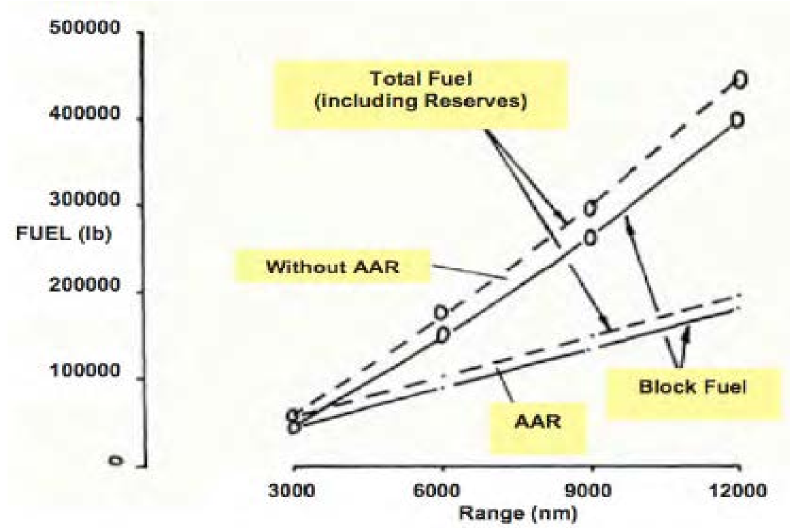
"NextGen will be an example of active networking technology that updates itself with real time-shared information and tailors itself to the individual needs of all U.S. aircraft. NextGen's computerized air transportation network stresses adaptability by enabling aircraft to immediately adjust to ever-changing 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.*"

Operational Improvements/Changes

- Air-to-Air Refueling (AAR) with Medium Range Aircraft for Long – Haul Travel
- The use of medium-range aircraft, with intermediate stops, for long-haul travel can result in significant saving in fuel consumption. For example, undertaking a journey of 15,000 km in three hops in an aircraft with a design range of 5,000 km would require 29% less fuel than doing the trip in a single flight with a 15,000km design. Furthermore, since a medium range aircraft can carry a much higher share of their maximum payload as passengers, fuel savings of as much as 50% are achievable.
- In order to avoid the intermediate refueling stops, AAR has been suggested. However, safety issues for a passenger aircraft must be addressed.

AAR

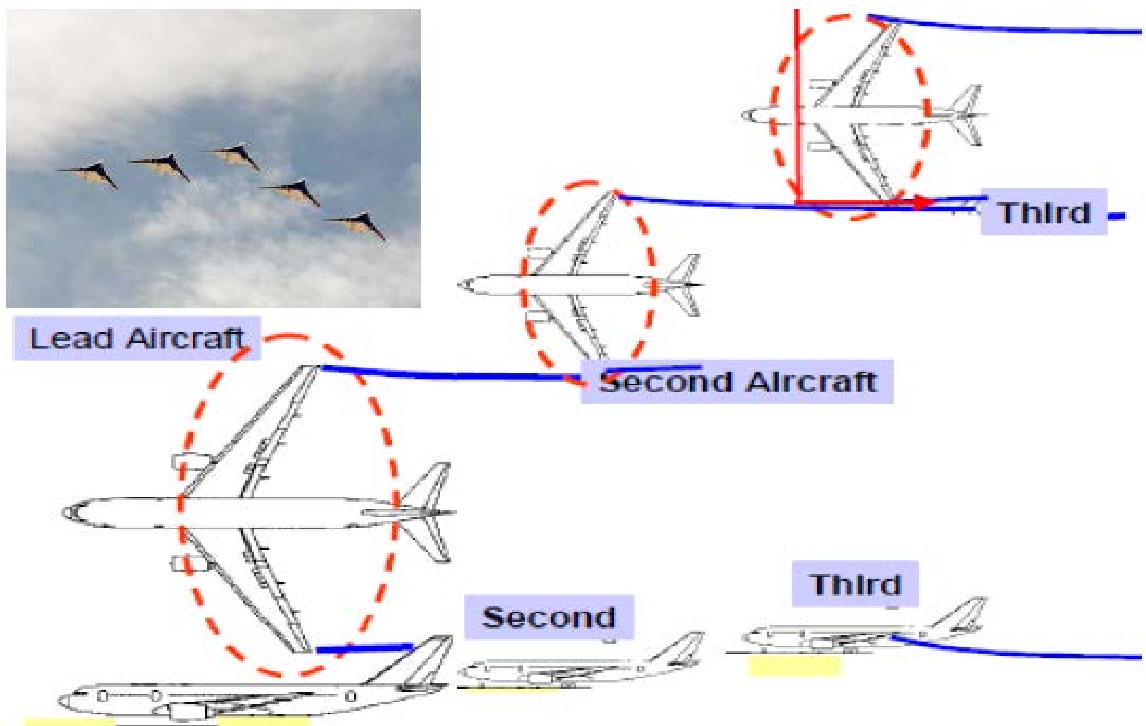
Savings in Fuel Burn with AAR Source: Nangia



Operational Improvements/Changes

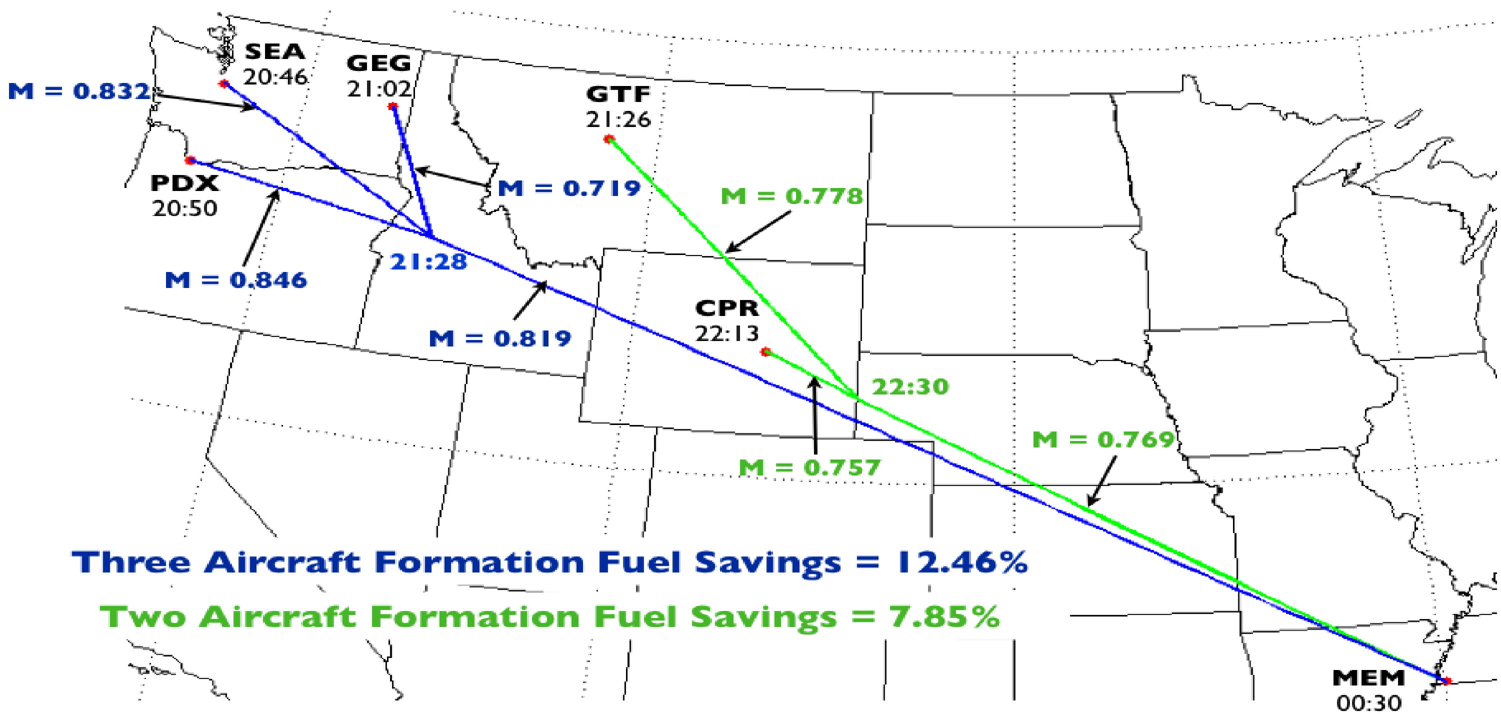
- Close Formation Flying (CFF)
- CFF can be used to reduce the fuel burn or extend the range.
- The aircraft could take-off from different airports and then fly in formation over large distances before peeling-off for landing at required destinations.
- CFF would require extreme safety measures by use of sensors coupled automatically to control systems of individual aircraft.

Three Different Aircraft Type in CFF
Source: Nangia



Operational Improvements/Changes

- Close Formation Flying (CFF) – Study by Bower et al. (2009)
- Examined the effect of CFF on five FedEX flights from Pacific Northwest to Memphis without changing the flight schedule
- Two B727-200, two DC 10-30 and one A300-600F were employed in the study. With tip-to-tip gaps of about 10% of the span, the fuel savings were ~ 4%; with a tip-to-tip overlap of 10% of the span, the overall fuel savings were ~ 11.5%. This translated into savings of 700,000 gallons of fuel/year for set of five flights.



Operational Improvements/Changes

- Tailored Arrivals
- Tailored arrivals can reduce fuel burn, lower the controller workload and allow for better scheduling and passenger connections.
- Boeing is working with several airports, airlines and other partners in developing tools such as SARA (Speed & Route Advisor) for "tailored arrivals".
- SARA delivered traffic within 30 seconds of planned time on 80% approaches at Schiphol airport in Holland compared to within two minutes on a baseline of 67%.
- At San Francisco Airport, more than 1700 complete and partial tailored arrivals were completed between December 2007 and June 2009 using the B777 and B747 aircraft. The tailored arrivals saved an average of 950kg of fuel and ~ $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.

Operational Improvements/Changes

- Tailored Arrivals

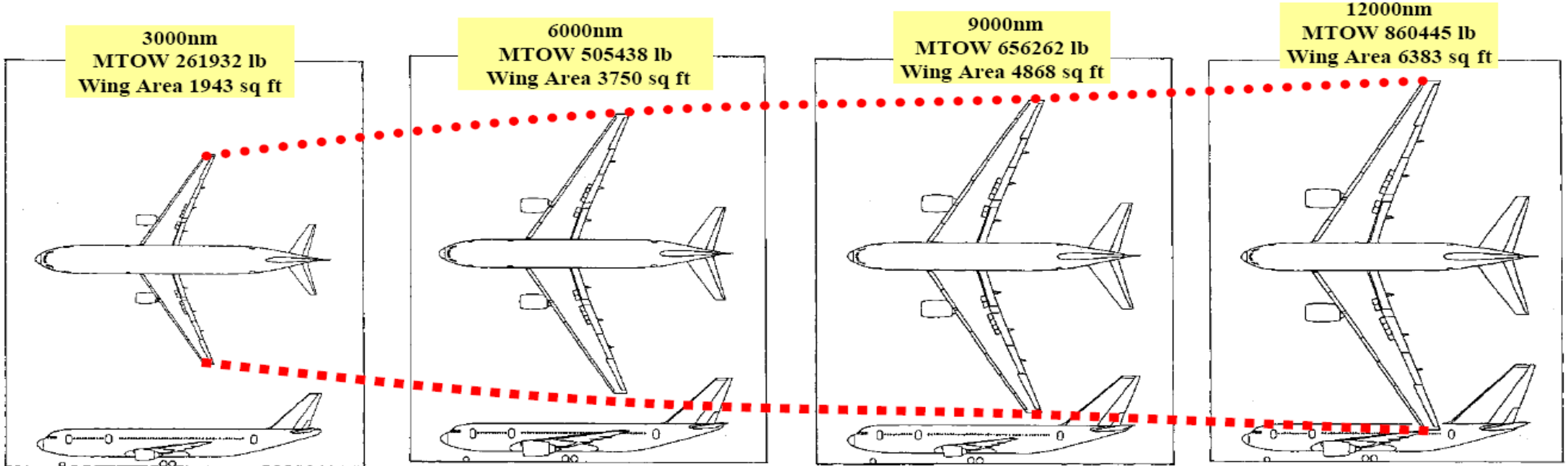
Airports and Partners Participating in Tailored Arrival Concept
Source: Glover (Boeing)

Savings in Fuel Burn by Weight Reduction

- Reducing the weight of an aircraft is one of the most powerful way of reducing the fuel burn. It can be accomplished by:
- (a) use of lighter and stronger advanced composites than the present carbon fiber composites (CFC). Replacement of structural aluminum alloy with CFC. B787 and A350 have wings and fuselage made with CFC.
- (b) reducing the design range and cruise Mach number.

For example, 3000 nm aircraft can provide substantial fuel savings by having less weight and can be used for long range flight using AAR

Aircraft designs with fixed fuselage, 250 passengers and CL for different ranges of operation; Source: Nangia



Alternative Fuels - Biofuels

- The desirable alternative to Jet Kerosene is "*drop-in fuel*" requiring no change to aircraft or engines, but should have similar efficiency and reduce CO_2 emissions (the life-cycle CO_2 generation must be less than that of kerosene).
- The alternative fuel should meet the aviation requirements – it should not freeze at flying altitude and should have high enough energy content to power the engines. It should have high-temperature thermal stability in the engine and good storage stability over time.
- Many first-generations biofuels have performed poorly against this criteria. Second generation biofuels appear to be promising.
- Biofuel generation should not adversely affect the farming land, fresh water supply, virgin rain forests and peat-lands, food prices etc. Algae and halophytes are emerging as sustainable feedstocks.
- The bio-derived synthetic paraffinic kerosene (Bio-SPK) is considered to be the most promising "*drop-in-fuel* " in the foreseeable future to reduce CO_2 emissions as well contrails & cirrus. Boeing, Airbus and engine manufacturers believe that the present engines can operate on biofuels blends and biofuels.

Key Biofuel (Neat) and Jet/Jet A-1 Fuel Properties Comparison

Source: Glover (Boeing)

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

Key Biofuel (Blend) and Jet/Jet A-1 Fuel Properties Comparison

Source: Glover (Boeing)

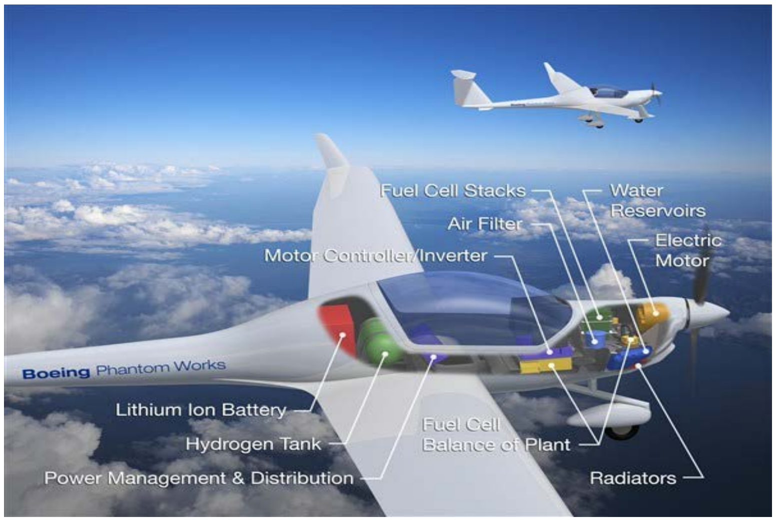
Property		Jet A/Jet A-1	ANZ Jatropha	CAL Jatropha/Algae	JAL Jatropha/Algae/Camelina
Freeze Point °C	Max	-40 Jet A -47 Jet A-1	-62.5	-61.0	-55.5
Thermal Stability JFTOT (2.5 hours @control temperature)	Min	260	300	300	300
Viscosity -20°C mm2/s	Max	8.0	3.606	3.817	4.305
Contaminants Existent gum, mg/100mL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

Experimental Flights Using Biofuels

- On 24 February 2008, Virgin Atlantic operated a B747-400 on a 20% biofuel/80% kerosene blend on a flight between London-Heathrow and Amsterdam (first for a commercial aircraft, 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 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 of B737-800 from Houston using biofuel (derived from algae and Jatropha) 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 is surmised that by 2050, the use of synthetic kerosene derived from biomass should reduce the CO_2 emissions per PKM by a factor of 3, NOx by a factor of 10 and cirrus by a factor of 5-15, for the world fleet.

Electric, Solar and Hydrogen Powered Green Aircraft

Boeing PEM Fuel Cell Powered



SOLARIMPULSE Solar Powered HB-SIA

Artist's Rendering of Hydrogen Powered A310

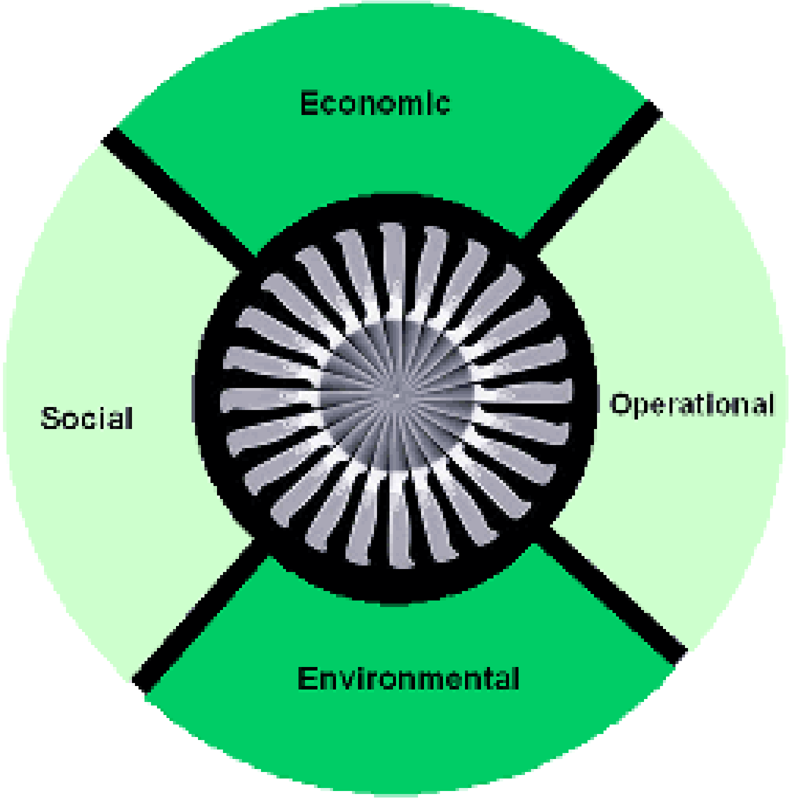
Challenges:

- Requires cryogenic hydrogen
- Liquid H_2 occupies 4.2 times the volume of jet fuel for same energy; needs huge tanks which will increase aero-drag
- It will have less range and speed than A310, also higher empty weight.
- Cost, infrastructure and passenger acceptance issues

Advantage: Reduced Emissions

Sustainable Airport Planning

Clean Airport Partnership (CAP)



- Land use planning
- House purchases
- Infrastructure alignment (low emission ground and air transportation, green buildings with low energy and recyclable water usage)
- Flight path design (low noise)
- Regulatory requirements to set risk limits

Sustainable Growth of Airports

- Inter-modal transport hub
- Recognition that environmental issues are critical capacity constraints and business risk and therefore must be included in expansion as well as new airport designs
- Planning for long term (+30years)
- Infrastructure development should include environmental costs and lifecycle costs
- Strategy towards carbon neutrality
- Securing adequate land for future development
- Effective land use planning of the area around the airports
- Airport and its service partners must adopt an integrated approach
- Multi-stakeholder corporate responsibility program
- Active investment in surrounding communities

Aerospace Courses at WUSTL

- Aerospace Minor

MEMS 2701 – Introduction to Aerospace Vehicles
MEMS 5700 - Aerodynamics
MEMS 5701 – Aerospace Propulsion
MEMS 4302 – Aircraft Stability and Control
MEMS 321 – Structural Behavior and Analysis
MEMS 411 – Mechanical/Aerospace Design

Inclusion of Sustainability in Aerospace Courses

- MEMS 2701: the issues of environmental challenges such as noise and emissions are introduced in the context of current status and projected increase in noise and emissions in next twenty five years due to three fold increase in air travel (and as a result two fold increase in flying aircraft). If no new technologies are introduced and status-quo is allowed to remain, the aircraft emissions will contribute about 17-20% to total equivalent CO_2 emissions from all sources worldwide, which will not be acceptable because of worldwide efforts to reduce greenhouse gas (GHG) emissions due to their adverse impact on climate.

Inclusion of Sustainability in Aerospace Courses

MEMS 5700: The concepts of drag reduction using active flow control and laminar flow wing are explained in the context of fuel savings and in turn in reducing the emissions. The design and performance of Honda Jet , which has natural laminar flow wings is compared with other conventional wing aircrafts in fuel efficiency. The basic concepts behind the newly emerging aircraft designs/configurations such as Blended –Wing –Body, Silent Aircraft, Hydrogen Power Aircraft, Solar Power Aircraft, and Electric Aircraft are introduced as ways of reducing noise and emissions. One can design aircrafts which can be fuel efficient and reduce emissions. The contents of this course are closely coordinated with the aircraft design course MASE 411.

Inclusion of Sustainability in Aerospace Courses

- MEMS 5701: The concepts of high bypass engines and geared turbofans for improved efficiency are introduced. The alternative technologies such as fuel cells, solar power and hydrogen for propulsion are introduced. The alternative fuels such as biofuels and syngas fuels which have reduced emissions compared to currently used jet fuels are introduced. The use of chevron nozzles can reduce noise as well as special flight paths can change the directivity of noise near airports to help mitigate its effect on people living near airports. These ideas are brought to focus in this course.

Inclusion of Sustainability in Aerospace Courses

- MEMS 321: The concepts light weight materials such as Carbon Fiber Composites (CFC) and metal composites are introduced. Structural analysis of aircraft components such as wings and fuselage using these materials is introduced.

Inclusion of Sustainability in Aerospace Courses

- MEMS 411: The concepts of innovative aircraft designs such as BWB, Double Bubble etc. are introduced. The students are encouraged to come up with their own concepts. The project involves a team of 4 - 6 students.

Conclusions

- It is increasingly recognized that the concepts of sustainability should be introduced in engineering curriculum.
- Among many facets of sustainability, environmental sustainability has become one of the most important topics because of its direct impact on human health and welfare, and climate change.
- In this paper, we have tried to show how some of the environmental sustainability ideas can be introduced in the existing undergraduate aerospace engineering courses without changing the core content of the courses.
- We will be reporting our experience in this area in future ASEE conferences which may be beneficial to other engineering schools as they contemplate introducing sustainability in the curriculum.

AIAA Short Course

- “Sustainable Aviation” by Ramesh Agarwal at AIAA Aerospace Sciences Meeting in Orlando, FL, January 2011 and other AIAA and SAE meetings
- AIAA/SAE William Littlewood Lecture, November 2009, Seattle, WA
- ASEE Distinguished Lecture, ASEE Annual Meeting, Louisville, KY, June 2010

Acknowledgements

- The material used in this presentation has been collected from a number of sources.
- Special thanks to Dr. Tom Reynolds of Cambridge University, Dr. Raj Nangia of Nangia Aviation, and Dr. Richard Wahls of NASA Langley for permission to use the material in number of slides.
- Any omission in listing a source is completely unintentional.

Opportunities and Future Prospects

- 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 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.

Goals for Environmentally Responsible Ground Vehicles - ERG

- **Reduction in Energy Requirements**
  - Reduce the Vehicle Mass Using High Strength Low Weight Materials
  - Smooth the Operational Speed Profile
  - Reduce Viscous Drag and Tires Contact Friction
  - Efficiency Improvement by Automation
  - Efficient Utilization of Infrastructure (Roads, Highways etc.)
  - Improve Engine Efficiency, Hybridization
- **Reduction in GHG Emissions**
  - Carbon - Based Fuels Synthesized from low carbon energy, e.g. Biofuels (Development of low cost catalysts capable of converting low-carbon energy into and out of forms amenable for portable storage)
  - Portable Storage of Low Carbon Electricity (Development of Batteries with high energy density and stability)
  - Hydrogen Production, Storage and Fuel Cells