Sustainable Aviation:
Future Air Transportation and the Environment
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Modern Aircraft Fuel Efficiency

Relative fuel use per seat–km

- Early jet engines
  - 707-320
  - First generation jet engines
    - 727-200
    - 767-200
  - Second generation jet engines
    - 787

New generation jet engines

Initial service year

Source: Boeing, ICAO 2007
For a flight from Seattle to Washington D.C., each passenger needs about 29 gallons of fuel.

3,709 gal / 130 pax = 29 gal/pax
(81 PMPG)

2,325 mi, 3,709 gal, 162 pax, 80% load factor
Aviation Contribution to CO$_2$

Transportation sector leads in petroleum use

Carbon emissions from global aviation exceed the total output of many countries

Source: GAO 1999
Effect of Altitude on Emissions Impact

Source: Klug et al., 1996
Sustainable Aviation — The Problem
Sustainable Aviation — The Problem

World Air Travel Continues to Grow

Revenue passenger kilometers, billions

10,000

Long-term future growth annual rate

<table>
<thead>
<tr>
<th>GDP</th>
<th>3.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger</td>
<td>5.2%</td>
</tr>
<tr>
<td>Cargo</td>
<td>6.2%</td>
</tr>
</tbody>
</table>

Boeing Current Market Outlook 2004,
Demand for Air Travel
Sustainable Aviation — The Problem

With the expected three-fold increase in global air travel over the next 30 years, the reliability and environmental impact of aviation are becoming critical issues for the future of flight.

Issues:
- Safety
- Efficiency
- Noise
- NO\textsubscript{x}
- CO\textsubscript{2}
- H\textsubscript{2}O
“Air travel is the world's fastest growing source of greenhouse gases.” --CNN Nov. 6, 2007 and Friends of the Earth. Public and political pressure is mounting.

Each long distance flight of a 747 adds approximately 400 tons of CO$_2$ to the atmosphere.
Sustainable Aviation — The Problem

Without significant action we will have major delays, large economic and environmental impact.

New government initiatives (US, Europe, Canada) are starting.
Goal: Develop technologies that will allow a \textbf{tripling} of capacity with a \textbf{reduction} in environmental impact.
Research Thrusts

- Active monitoring and managing air transportation’s environmental footprint
- Safely increase the capacity of the airspace system
- Aerospace system design for the environment
Goals: Active flight management from the vehicle level to the complete air transportation system

Critical technologies:

- Safety-critical control techniques
- Real-time, massively distributed, sensing and modeling

Example 1: Active monitoring of contrail formation and cirrus cloud formation using GPS and real-time flight path re-planning

Example 2: Real-time near-terminal area flight path planning to alleviate noise footprint
Persistent contrails formed in super-saturated and cold air
Managing Air Transportation’s Environmental Footprint
Next generation air traffic management system is vital to achieve worldwide goals:

- Improve capacity
- Reduce environmental impact
- Improve security
- Sustain safety
- Include autonomous aircraft
Safely Increase Air Transportation System Capacity

**Present:**
- dive & drive
- order aircraft into arrival lines at 200+ miles
- B-757 follows AATR-42
- acoustic noise is dispersed over large area
- 4800 foot separation for IFR approach

**Future**
- continuous descent arrival (to save 100 gallons per approach)
- feather aircraft onto arrival path based on arrival time
- tighten lateral dispersion
- 600 foot separation for IFR approach

Four Dimensional Navigation to Feather Aircraft Onto Final Approach Path
• Goal: To design, build, and fly an autonomous aircraft which can stay aloft within a three-dimensional box for as long a time as possible.

• Provides hands-on experience with aircraft design, autonomous systems, flight control, embedded software, flight testing.
Sketch to Flight in 90 Days
Research Thrust: Aerospace Design for the Environment

**Goals:** Active/intelligent aircraft design for dramatic efficiency increases

**Critical Technologies:**

- Integrated modeling of vehicles, atmospheric impact, and noise
- Optimization of new aircraft concepts and operations including environmental impact
- Distributed, adaptive sensing and control

**Example 1:** Reliable prediction of the noise radiation for novel designs, e.g. “silent aircraft”

**Example 2:** Design for dramatic reductions in regional and global environmental footprints, e.g. 50% fuel reduction
Example: Compute acoustic signature of an airplane at take-off.

To do this will require a ‘significant increase in computing capability.'
Example: Compute impact of enroute emissions on atmosphere
Aerospace Design for the Environment

- 60% laminar wing
- 20% composite weight reduction
- 10% vortex drag saving
Alternative Fuels for Aviation

*Equivalent Energy*

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Volume (BTU/ft³)</th>
<th>Weight (BTU/lb)</th>
</tr>
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<tbody>
<tr>
<td>Liquid Hydrogen</td>
<td>4.20</td>
<td>0.36</td>
</tr>
<tr>
<td>Ethanol</td>
<td>1.64</td>
<td>1.0</td>
</tr>
<tr>
<td>Jet A Syn-Jet</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Bio-Jet (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syn-Jet (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td></td>
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<tr>
<td>Ethanol</td>
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Jet-A is best per unit volume.

Hydrogen is best per unit weight.

1. Synthetic Jet fuel such as from Fisher-Tropsch process
2. Bio-derived jet fuel similar to a refined bio-diesel fuel
Hydrogen fueled airplanes face many challenges

**Advantages:**
- Reduced emissions
- Lower takeoff weight
- Better long haul fuel efficiency
- Engine design opportunities
- Oil independent fuel?
- $\text{H}_2$ works well with fuel cells

**Challenges:**
- 4X larger fuel tanks
- Higher drag
- Higher empty weight
- $\text{H}_2$ production issues
- New infrastructure
- Cost
- High technical risk
- Passenger acceptance
- Environmental effects?
Alternates to supplement jet fuel

Bio Jet Fuel
- Plants
- Oil base
- Jet fuel processing
- Bio-Jet Fuel

Gas-to-Liquid (GTL) Synthetic Jet Fuel
- Natural Gas
- GTL plant
- Jet-A Synthetic
- End Product

Energy Source Processing
In-flight refueling avoids burning fuel to carry fuel

Air-to-air refueling:

• Effects on long range fuel consumption with aircraft redesign

• Net effect ~40% on 6,000 - 9,000 nmi flights

• Source: Nangia 2006
Autonomous Aerial Refueling

Air-to-air refueling:

- More feasible with automated system
- Progress on automated aerial refueling for military -- of particular interest for UAV’s
Configuration Concepts: Formation Flight

- Potential for large induced drag reduction
  - Direct effect on emissions
  - Indirect (but large) effect on noise via reduced take-off weight
  - Virtual refueling concept provides additional benefits
Effect of Formation Flight on Aircraft Range

NASA’s Autonomous Formation Flight Program
Aerospace Design for the Environment

20% fuel savings

8% better SFC

Courtesy Boeing
Aerospace Design for the Environment

Courtesy Airbus
Active distributed control using micro-trailing edge flaps:

Aeroelastic control

Maneuver/gust load control
Green Supersonics

- Mach 1.4 - 1.6
- Natural laminar flow
- Good field performance with low sweep, low take-off weight
- Existing engines
- Shielded fans
Summary

New initiative for sustainable aviation provides:

• A framework for integrating research in Aero/Astro
• A vital field of study for future students
• A focus on the most important problem in aviation