AVIATION & THE ENVIRONMENT

Ian A. Waitz
Professor and Deputy Head
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

© 2003 Waitz
LECTURE OUTLINE

• Overview of environmental effects of aircraft

• Aircraft noise
  – Impacts and regulatory issues
  – Technology trends

• Aircraft pollutant emissions
  – Impacts and regulatory issues
  – Technology and emissions trends

• Summary and references

© 2003 Waitz
AIRPORT RANKING OF ENVIRONMENTAL ISSUES

Current and Future

Noise

Water Quality

Air Quality

Compatibility with Land-use limitations

None Applicable

Wetlands

Number of airports

Most serious problem currently

Most serious problem in future

Source: GAO’s survey of the nation’s 50 busiest commercial service airports.

© 2003 Waitz
CHARACTERISTICS OF NOISE AND EMISSIONS ISSUES

• Noise
  – Local
  – Persistence = minutes
  – Well-established metrics
  – Impacts: annoyance, sleep disturbance, domestic animals?, endangered species?, health impacts?

• Emissions
  – Local, regional, global
  – Effluents: CO$_2$, H$_2$O, NO$_x$, CO, VOC’s, soot, others
  – Persistence = 1 day -1000 years
  – Drastic change in public/scientific perception and regulatory frameworks
  – Impacts: human health, ecosystem health
AVIATION ENVIRONMENTAL IMPACTS

• “EXTERNALITIES”
  - A large fraction of current aviation health and welfare impacts are real costs to society but are not accounted for by the providers or users of the service

“The government’s objectives for aviation are that…the polluter should pay and aviation, like other industries, should meet its external costs, including environmental costs.”

(From UK Department of Transport, Aviation and the Environment, Using Economic Instruments, March 2003)
## EXTERNAL COSTS OF AVIATION

<table>
<thead>
<tr>
<th>VALUATION BASIS</th>
<th>SOCIAL (industry + affected public)</th>
<th>INSTITUTIONAL (regulatory policy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Area (objective)</td>
<td>Total $</td>
<td>$ / capita</td>
</tr>
<tr>
<td>Noise (quiet environs)</td>
<td>$ 26B</td>
<td>$ 2100</td>
</tr>
<tr>
<td>Air Quality (safe air)</td>
<td>$ 11B</td>
<td>$ 140</td>
</tr>
<tr>
<td>Climate Change (stable climate)</td>
<td>~$100B</td>
<td>$ 345</td>
</tr>
<tr>
<td>TOTAL</td>
<td>~$137B</td>
<td></td>
</tr>
</tbody>
</table>

- Regulatory framework currently accommodates ~ 5% potential internalization of external costs

- Noise cost per capita greater than emissions aligns with public opinion and institutional attention
  - Most vociferous opposition to noise, but air quality becoming more of an issue (GAO 2000)

>>PRELIMINARY ESTIMATES ONLY<<

© 2003 Waitz

Lukachko, 2003
GROWTH IN MOBILITY PROVIDED BY U.S. AVIATION INDUSTRY (DOT Form 41 data)

Fastest Growing Mode of Transportation (4-6%/yr)

Revenue Passenger Miles Performed by All Airlines Operating Aircraft with >60 Seats

© 2003 Waitz
AIR TRAVEL PROJECTED TO BE FASTEST GROWING MODE OF TRANSPORTATION (4-6%/yr)

- DRIVEN BY POPULATION AND GDP GROWTH, AND AVAILABLE DAILY TRAVEL TIME -

Automobiles
Buses
Railways
Aircraft

1960
1990
2020
2050

5.5 \times 10^{12} \text{ RPK}
23 \times 10^{12} \text{ RPK}
54 \times 10^{12} \text{ RPK}
105 \times 10^{12} \text{ RPK}

Source: Schafer et al. (1998), GDP/cap growth rates from IPCC IS92a Scenario
MOBILITY AND THE ENVIRONMENT

“Environmental issues are likely to impose the fundamental limitation on air transportation growth in the 21st century.”

U.S. National Science and Technology Council, 1995

Expansion Projects Delayed due to Environmental Issues

- 28% (9 airports) with no impact
- 72% (23 airports) projects delayed

Source: GAO (2000) survey of 50 busiest commercial airports. N=33 for this question, 1 airport did not respond.

Expansion Projects Cancelled or Indefinitely Postponed due to Environmental Issues

- 25% (12 airports) with at least 1 project affected
- 75% (36 airports) no impact

Source: GAO (2000) survey of 50 busiest commercial airports. N=50 for this question, 2 airports with no projects planned.
AIRPORTS ARE REACHING CAPACITY LIMIT

Figure 2: Anticipated Date for Airports to Reach Capacity

Number of airports

<table>
<thead>
<tr>
<th>Estimated time to reach capacity</th>
<th>Number of airports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Already at or above capacity</td>
<td>13</td>
</tr>
<tr>
<td>1-2 years</td>
<td>4</td>
</tr>
<tr>
<td>3-4 years</td>
<td>7</td>
</tr>
<tr>
<td>5-6 years</td>
<td>8</td>
</tr>
<tr>
<td>7-9 years</td>
<td>2</td>
</tr>
<tr>
<td>10 or more years</td>
<td>11</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
</tr>
</tbody>
</table>

Source: GAO's survey of the nation's 50 busiest commercial service airports.
DOD ENCROACHMENT

• External factors such as urbanization, increasing environmental restrictions, and competition with civilian demands on airspace, land, seaspace, and radio frequencies

“The overall trends are adverse because the number of external inputs is increasing, and the readiness impacts are growing. Future testing and training needs will only further exacerbate these issues, as the speed and range of test articles and training scenarios increase…” (DOD Sustainable Ranges Outreach Plan, SROC)

Examples: JSF basing, Oceana operations, Navy in Japan

• Senior Readiness Oversight Council (SROC) action plans:
  – Endangered species, ordnance, frequency encroachment, the maritime sustainability, airspace restrictions, air quality, airborne noise and urban growth

REGULATIONS: BALANCING PUBLIC GOALS

• **Economy and Mobility vs. National Security vs. Environment**
• **State vs. National interests and control**

• **Federal Noise Control Act + local noise restrictions**
  – Commercial **yes**
  – Military **no** (Nat. Sec. Exemption, but NEPA EIS)

• **Federal Clean Air Act + State Implementation Plans**
  – Military **yes** (General Conformity Rule)
  – Commercial “**no**” (Interstate Commerce & Trade exemption)

• **Endangered Species and Marine Mammal Protection Acts**
  – Military “**yes**” (Nat. Sec. Exemption, but never used)
  – Commercial **yes**
GROWTH OF ENVIRONMENTAL REGULATION

Reflects increasing environmental impacts and increasing valuation of the environment

Cumulative Number of Federal Environmental Laws

World-wide Civil Aircraft Noise Restrictions

Materiel Developer’s Guide for Pollution Prevention, Army Acquisition Support Office, 1994

www.boeing.com

© 2003 Waitz
AIRCRAFT REGULATIONS
- Local, National, International -

• Noise
  – Certification standards
  – Phase-outs
  – Curfews
  – Flight control
  – Landing fees
  – Ticket taxes

• Emissions
  – Certification standards
  – Phase-outs
  – Limited local rules in place
LECTURE OUTLINE

• Overview of environmental effects of aircraft
  • Aircraft noise
    – Impacts and regulatory issues
    – Technology trends
  • Aircraft pollutant emissions
    – Impacts and regulatory issues
    – Technology and emissions trends
• Summary and references
AIRCRAFT NOISE GENERATION

AIRFRAME NOISE

ENGINE NOISE

SONIC BOOM?

ATMOSPHERIC PROPAGATION

SPECTRUM, MAGNITUDE, DIRECTIVITY, DURATION FREQUENCY OF OCCURRENCE, TIME OF DAY, LOCATION

HUMAN ANNOYANCE
## NOISE EFFECTS ON PEOPLE

<table>
<thead>
<tr>
<th>Effects Day-Night Average Sound Level in Decibels</th>
<th>Hearing Loss</th>
<th>Annoyance</th>
<th>General Community Attitude Towards Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Qualitative Description</td>
<td>% of Population Highly Annoyed</td>
<td>Average Community Reaction</td>
</tr>
<tr>
<td>75 and above</td>
<td>May begin to occur</td>
<td>37%</td>
<td>Very Severe</td>
</tr>
<tr>
<td>70</td>
<td>Will not likely occur</td>
<td>22%</td>
<td>Severe</td>
</tr>
<tr>
<td>65</td>
<td>Will not occur</td>
<td>12%</td>
<td>Significant</td>
</tr>
<tr>
<td>60</td>
<td>Will not occur</td>
<td>7%</td>
<td>Moderate to slight</td>
</tr>
<tr>
<td>55 and below</td>
<td>Will not occur</td>
<td>3%</td>
<td>Moderate to slight</td>
</tr>
<tr>
<td></td>
<td>Will not occur</td>
<td>7%</td>
<td>Moderate to slight</td>
</tr>
</tbody>
</table>

Noise is likely to be most important of all adverse aspects of the community environment.

Noise is one of the most adverse aspects of the community environment.

Noise is one of the adverse aspects of the community environment.

Noise may be considered an adverse aspect of the community environment.

Noise considered no more important than various other environmental factors.
• Phase-out
  – 55% of U.S. fleet
  – 94% reduction in impact
  – During 6X mobility growth
  – $10B US cost
  – $43/person/DNLdB
  – TECHNOLOGY foundation
• $1B/yr in US for sound abatement
  – $960/person/DNLdB
  – Low cost effectiveness
COMMERCIAL AND MILITARY NOISE IMPACTS

- **Norfolk Intl. Airport**
  - 210 TO/day

- **Oceana**
  - 121 TO/day
  - 7 FCLP/day

- **Fentress**
  - 20 TO/day
  - 354 FCLP/day

AIRCRAFT NOISE SUMMARY

• Difficult connection between human annoyance and physics
  – Public becoming more sensitive to aviation noise
  – Relatively mature regulatory history

• Step changes in fleet unlikely

• Increased commercial certification stringency likely but probably within current technological capabilities

• Growing problem for the military

• Local restrictions make noise a product differentiator
  – For GE-90 powered B-777 (-6EPNdB cumulative relative to other engines) twice as many t/o and landings allowed at Heathrow
  – Manufacturers willing to trade 2% fuel burn for 2 dB (A380)
LECTURE OUTLINE

• Overview of environmental effects of aircraft

• Aircraft noise
  – Impacts and regulatory issues
  – Technology trends

• Aircraft pollutant emissions
  – Impacts and regulatory issues
  – Technology and emissions trends

• Summary and references
EMISSIONS IMPACTS

- **Local air quality** \((\text{NO}_x, \text{CO}, \text{UHC}, \text{PM})\)
  - Focus of current regulations

- **Regional/global atmospheric effects**
  
  1) **Stratospheric ozone depletion** (time-scale=10 years)
    - Largely a concern for supersonic aircraft (NOx)
  
  2) **Climate change** (time-scale = 100-1000 years)
    - Subsonic and supersonic aircraft
      - \(\text{CO}_2\) and \(\text{H}_2\text{O}\)
      - \(\text{NO}_x\) through ozone production
    - Particulates \((\text{SO}_x\text{ and soot})\) through heterogeneous chemistry and cloud nucleation
AIRCRAFT ENGINE EXHAUST

• Composition
  – Reservoir and primary combustion products
    \[ \text{CO}_2, \text{H}_2\text{O}, \text{N}_2, \text{O}_2: \text{O}(10000-100000) \text{ ppmv} \]
  – Secondary products and pollutant emissions
    \[ \text{CO}, \text{NO}_x, \text{HC}, \text{soot}: \text{O}(1-100) \text{ ppmv} \]
  – Trace species constituents
    \[ \text{NO}_y, \text{SO}_x, \text{HO}_x: \text{O}(0.0001-0.1) \text{ ppmv} \]

• Most constituents play some role in atmospheric processes
  – \textit{e.g.} If 100\% of SO\textsubscript{2} in engine oxidizes to SO\textsubscript{3} it may double stratospheric ozone depletion
  – Primary and secondary species relatively well-understood
  – Relative magnitudes and engine/operations effects on trace species poorly characterized
LOCAL AIR QUALITY

• Approx. 1% of US mobile source NO$_x$ emissions are from aircraft
• NO$_x$, particulate matter, VOCs, CO -- ozone
  – Lung function, cardiovascular disease, respiratory infection
LOCATION OF “NON-ATTAINMENT” AREAS FOR CRITERIA POLLUTANTS AS OF SEPTEMBER, 1998

Notes: Incomplete data, not classified, and Section 185(a) areas are not shown. Ozone nonattainment areas on map based on pre-existing ozone standard. Nonattainment designations based on revised 8-hour ozone standard will not be designated until 2000. PM-10 nonattainment areas on map are based on pre-existing PM-10 standards. Nonattainment designations based on revised PM-10 standards have not yet been made. Source: U.S. EPA, *National Air Quality and Emissions Trends Report*, 1997.

(Chang, 1999)
AIRCRAFT CONTRIBUTION TO REGIONAL MOBILE SOURCE NOX EMISSIONS AT SELECTED US CITIES IS ESTIMATED TO INCREASE

Estimated commercial aircraft contribution to regional mobile source emissions of NOx

Source: Table 4-2, EPA 420-R-99-013, "Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft," April, 1999

(Chang, 1999)
AIRCRAFT AND OZONE

• Aircraft: NEGATIVE EFFECT AT ALL ALTITUDES
  – Subsonics: +0.9% total column ozone (global warming)
  – Supersonics (1000, < 5% of fleet): -1.3% total column ozone
  – Combined fleet: -0.4% total column ozone

SCIENTIFIC UNDERSTANDING IN 2003 vs. 1999

Radiative Forcing from Aircraft in 1992

Green bars are updated values, with arrows updated uncertainty.
NOTES ON CLIMATE CHANGE IMPACTS

- Burning a gallon of fuel at 11km has about **double the radiative impact** of burning a gallon of fuel at sea-level.
- Burning a gallon of fuel at 19km has about 5 times the impact at sea-level.
- **CO₂ is not the biggest global concern** (potential impacts from contrails and cirrus clouds are greater).
- **Large imbalance** between northern and southern hemisphere.
- Improving engine efficiency tends to make NOx and contrails worse.
- High uncertainty.
THE ROLE OF TECHNOLOGY:
CHARACTERISTICS OF AVIATION SYSTEMS

• Safety critical
• Weight and volume limited
• Complex
• 10-20 year development times
• $30M to $1B per unit capital costs
• 25 to 100 year usage in fleet
• Slow technology development and uptake
“Boeing is focusing its product development efforts on a super efficient airplane. This is the airplane that airline customers around the globe agree will bring the best value to an industry in need of improved performance. The advanced technologies that allowed the Sonic Cruiser configuration to provide 15 to 20 percent faster flight at today’s efficiencies now will be used to bring 15 to 20 percent lower fuel usage at the top end of today’s commercial jet speeds. Boeing believes that in the future airlines will again be interested in faster flight and we will be ready with a concept and technologies to meet this need.” (www.boeing.com, March, 2003)
COMMERCIAL vs. MILITARY FLEET TRENDS

- Demand growth for civil aviation (3.8%/year in US)
- Military fleet contraction
- Ops tempo (4.3/day commercial, 0.35/day military)

© 2003 Waitz
Aircraft responsible for 2%-3% of U.S fossil fuel use
COMMERCIAL AIRCRAFT EFFICIENCY

Average Age = 13 yrs

© 2003 Waitz
MILITARY AIRCRAFT FUEL BURN

- Fighter/Attack
- Bomber
- Transport/Tanker
- Trainer
- Reconnaissance/Other

Average Age: 21 yrs

Year of Introduction (or Year for Fleet Average)

Fuel Consumption (liters/hr)
ENERGY EFFICIENCY

• Function of performance of entire system
  – Aircraft technology (structures, aerodynamics, engines)
  – Aircraft operations (stage length, fuel load, taxi/take-off/landing time, flight altitude, delays, etc.)
  – Airline operations (load factor)

• Each component of system can be examined independently for reduced fuel burn and impacts on local air quality and regional/global atmospheric effects
RANGE EQUATION

Technology and Operations

Stage Length = \frac{V(L/D)}{g \cdot SFC} \ln \left( 1 + \frac{W_{\text{fuel}}}{W_{\text{payload}} + W_{\text{structure}} + W_{\text{reserve}}} \right)

\text{= Technology}
\text{= Operations}

Efficiency \propto \frac{W_{\text{payload}} \cdot \text{StageLength}}{W_{\text{fuel}}},

\text{ASK} = \frac{\text{StageLength} \cdot \# \text{seats}}{\text{kg}_{\text{fuel}}} = \frac{W_f}{g}

Use data to separate effects and understand influences of technology

© 2003 Waitz
TRENDS IN LOAD FACTOR


© 2003 Waitz
FLIGHT AND GROUND DELAYS

© 2003 Waitz
HISTORICAL TRENDS

Aerodynamic Efficiency

Babikian et al. (2002)

- Turboprops
- Regional Jets
- Large Aircraft

Data Unavailable For:
- EMB-145
- CV-880
- BAE RJ85
- Beech 1900
- CV-580
- CV-600

- FH-227
- Nihon YS-11
- SA-226
- DHC-8-100
- L-188
- DHC-7
HISTORICAL TRENDS

Structural Efficiency

© 2003 Waitz
EFFICIENCY
Regional Jets Versus Turboprops

Energy Usage (MJ/ASK)

Babikian et al. (2002)

Turboprop Fleet
Regional Jet Fleet
Regional Aircraft Fleet

© 2003 Waitz
ENERGY USAGE

Total Versus Cruise

Babikian (2001)

© 2003 Waitz
COMMERCIAL AIRCRAFT ENERGY INTENSITY TRENDS

- New technology energy intensity has been reduced 60% over last 40 years (jet age)
  - 57% due to increases in engine efficiency
  - 22% due to increases aerodynamic performance
  - 17% due to load factor
  - 4% due to other (structures, flight time efficiency, etc.)
  - Structural efficiency constant (but traded for aero, passenger comfort, noise and SFC)
  - Flight time efficiency constant (balance of capacity constraints and improved ATM)
- Fleet average energy intensity has been reduced 60% since 1968
  - Lags new technology by 10-15 years
SHORT HAUL AIRCRAFT

Facing Increasing Scrutiny

Royal Commission on the Environment (2002)

“...deeply concerned at the prospect of continuing rapid increases in air transport, particularly an increase in short haul flights...”

“It is essential that the government should divert resources...encouraging and facilitating a modal shift from air to high-speed rail.”
IMPACT OF NASA TECHNOLOGY SCENARIOS

Effect of Proposed Environmental CO₂ Goals

- - - No Improvement Beyond 1997 Technology
- - - - 25% Reduction Introduced in 2007
- - - - - 50% Reduction Introduced in 2022
- - - - - - Zero CO₂ Emission A/C Introduced in 2027
- - - - - - - Zero CO₂ Emission A/C Introduced in 2037

( - GA and Military Emissions based on Boeing forecast
- IPCC IS92a based ICAO demand model
- No retrofit of technologies)

Change Relative to 1990: +340%
+230%
+140%
+40%
-20%

U.S. DOE reported fuel use

1990-5% Level

Emission inventories

Kyoto Protocol Timing For Reductions

Global CO₂ Emitted per Year

Year

© 2003 Waitz
J. E. Rohde, NASA 1999
IMPACTS OF MISSION REQUIREMENTS (NOx & Noise)

- **Range/payload ~ fuel efficiency (commercial and military)**
  - Thermal efficiency
    - High pressures and temperatures
    - High NOx
  - Propulsive efficiency
    - Large mass flow with small velocity change
    - Low Noise

- **Maneuverability (military)**
  - High thrust-per-weight, small compact engine
    - High energy conversion per unit volume (high temperatures and pressures)
    - High NOx

- **Supersonic flight (military)**
  - Low drag, small compact engine
    - Small mass flow with large velocity change
    - High Noise
NO$_x$ EMISSIONS TECHNOLOGY TRENDS

© 2003 Waitz
NO\textsubscript{x} EMISSIONS TRENDS

Total Commercial

Total Military (AF and NAVY)

Year

© 2003 Waitz
HISTORICAL FLEET CRUISE EMISSIONS PER PASSENGER PER KILOMETER

Relative Emission / Pass-km

NO\textsubscript{x}, CO\textsubscript{2}, H\textsubscript{2}O, CO, HC

Year (DuBois, Boeing)

© 2003 Waitz
TECHNOLOGY AND EMISSIONS

• Improvements will not keep up with growth

• Aircraft typically have greater impact per unit of fuel burned

• “Solutions” for global climate will require unprecedented action (demand management/regulations, electric vehicles, contrail avoidance, etc.)

• Current understanding is that hydrogen makes problem worse

• High uncertainty relative to global impacts

• Engine efficiency improvements exacerbate \( \text{NO}_x \) and contrails

• Significant improvements in structural efficiency, aero and operations are possible
  
  – Improvements in these areas do not exacerbate other problems
SUMMARY

• Broad range of environmental impacts from aircraft
  – Social costs of same order as industry profits
  – Currently not internalized
  – Current technology path and regulations not aligned with social costs

• Strong growth in demand

• Increasing public concern/regulatory stringency

• High uncertainty

• Many competing trades
  – Environmental impacts
  – Design, operations
SELECTED REFERENCES


• Penner et al., United Nations Environment Programme, Intergovernmental Panel on Climate Change (IPCC), Special Report on Aviation and the Global Atmosphere, 1999. (Summary for Policy Makers available on Waitz web page)

• RCEP, “The Environmental Effects of Civil Aircraft In Flight,” Royal Commission on Environmental Pollution (RCEP), England, December, 2003