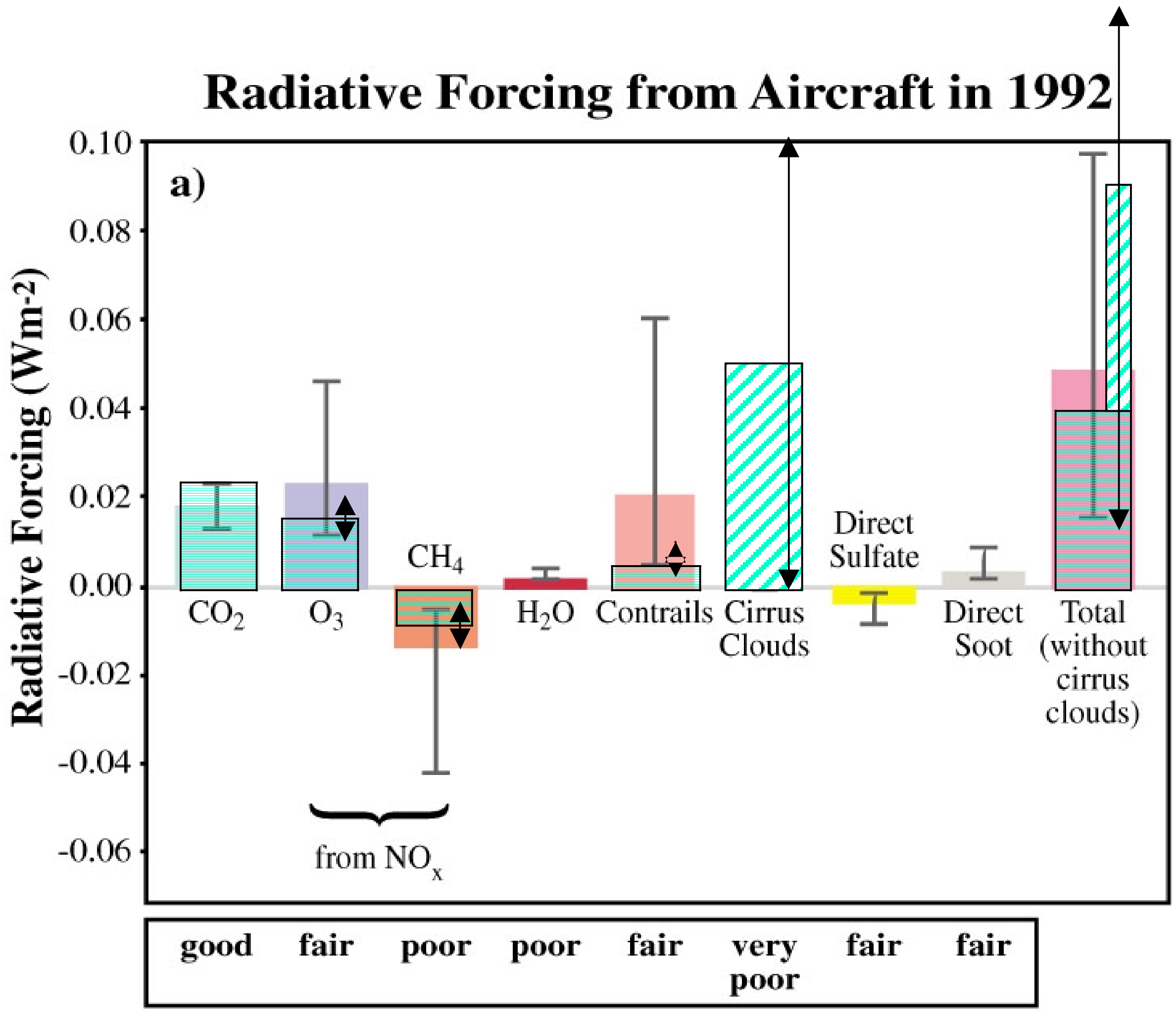
# SCIENTIFIC UNDERSTANDING IN 2003 vs. 1999




Green bars are updated values, with arrows updated uncertainty.

# 1992 CONTRAIL COVERAGE

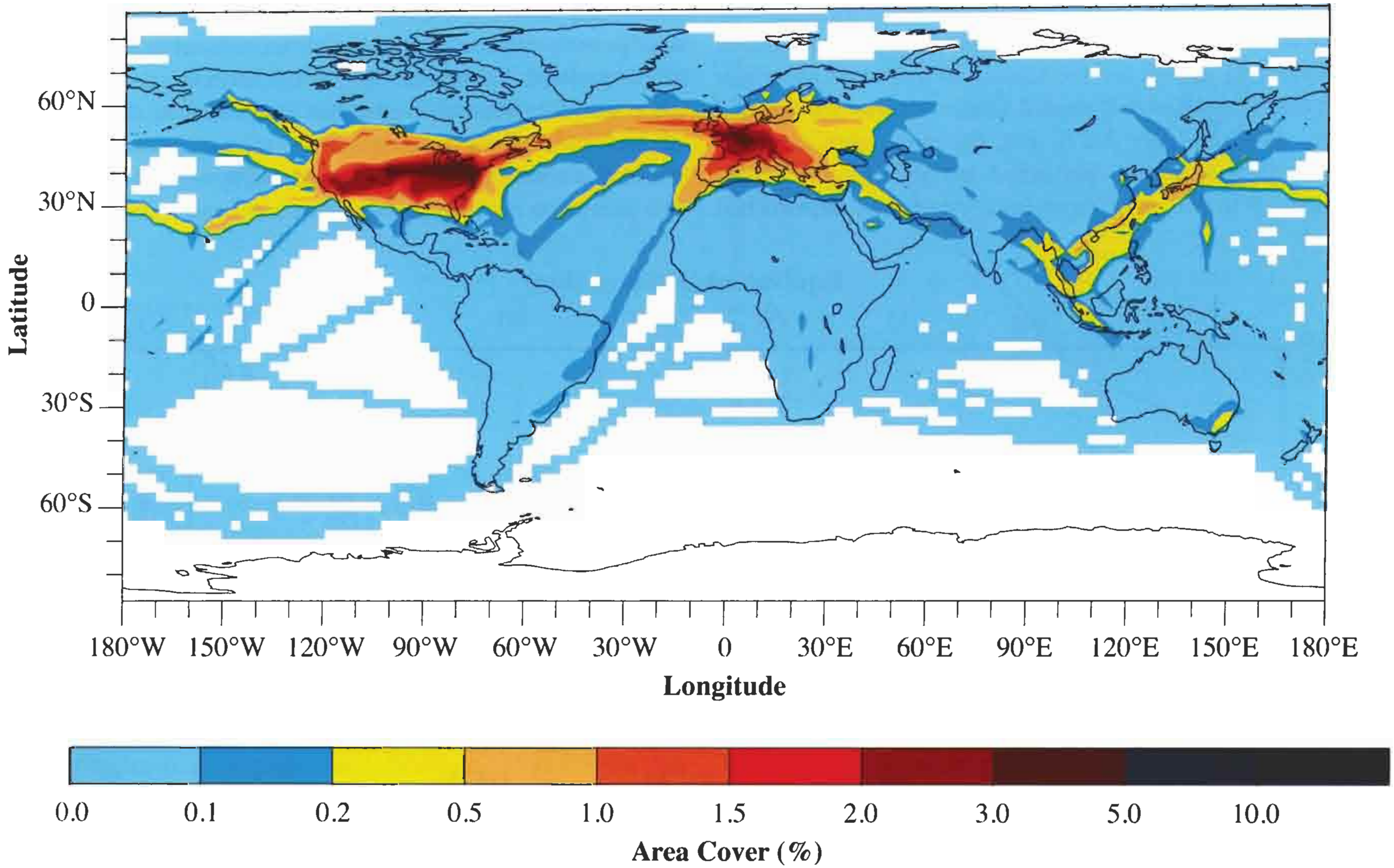
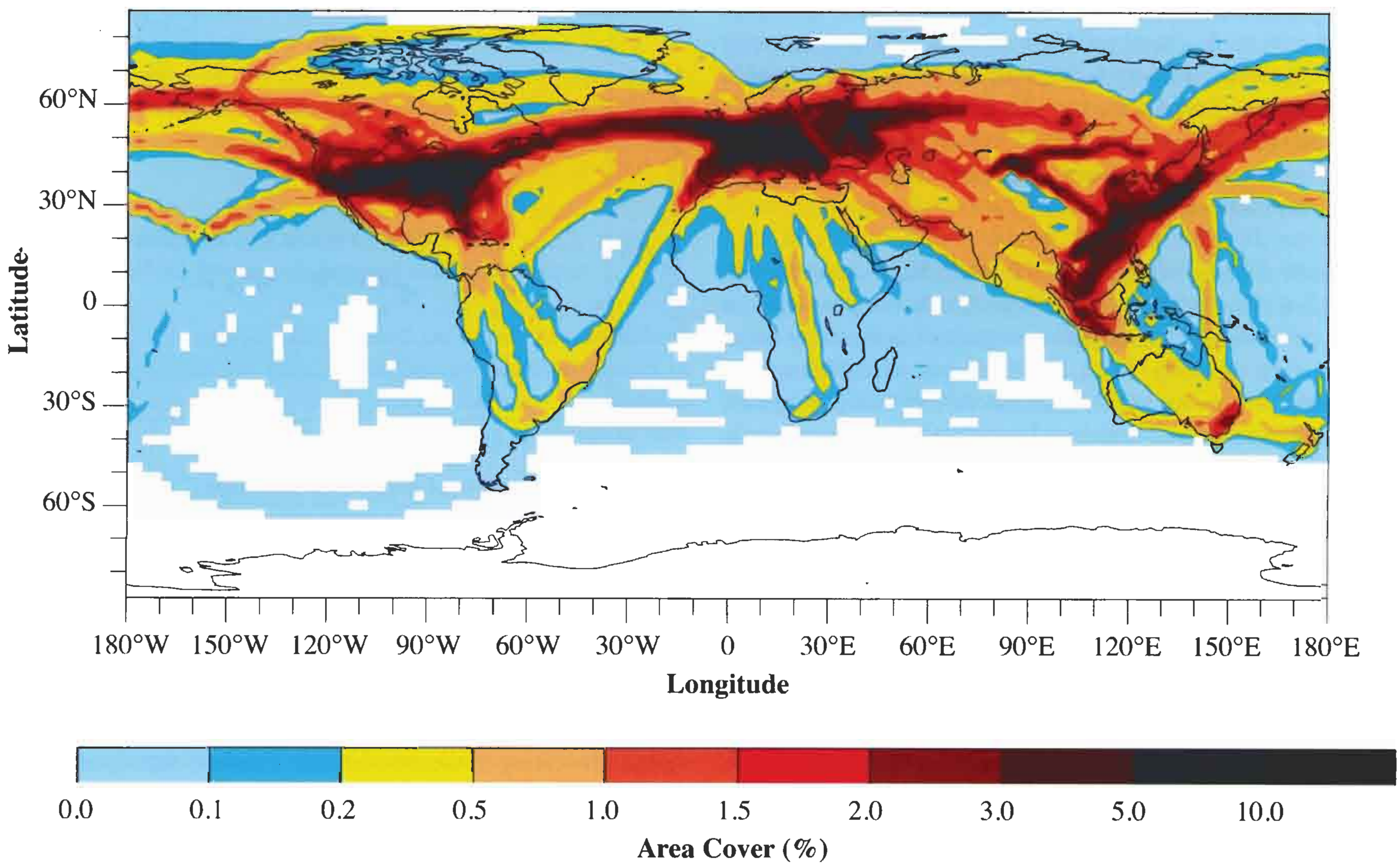



**Figure 3-16:** Persistent contrail coverage (in % area cover) for the 1992 aviation fleet, assuming linear dependence on fuel consumption and overall efficiency of propulsion $\eta$ of 0.3. The global mean cover is 0.1% (from Sausen *et al*., 1998).

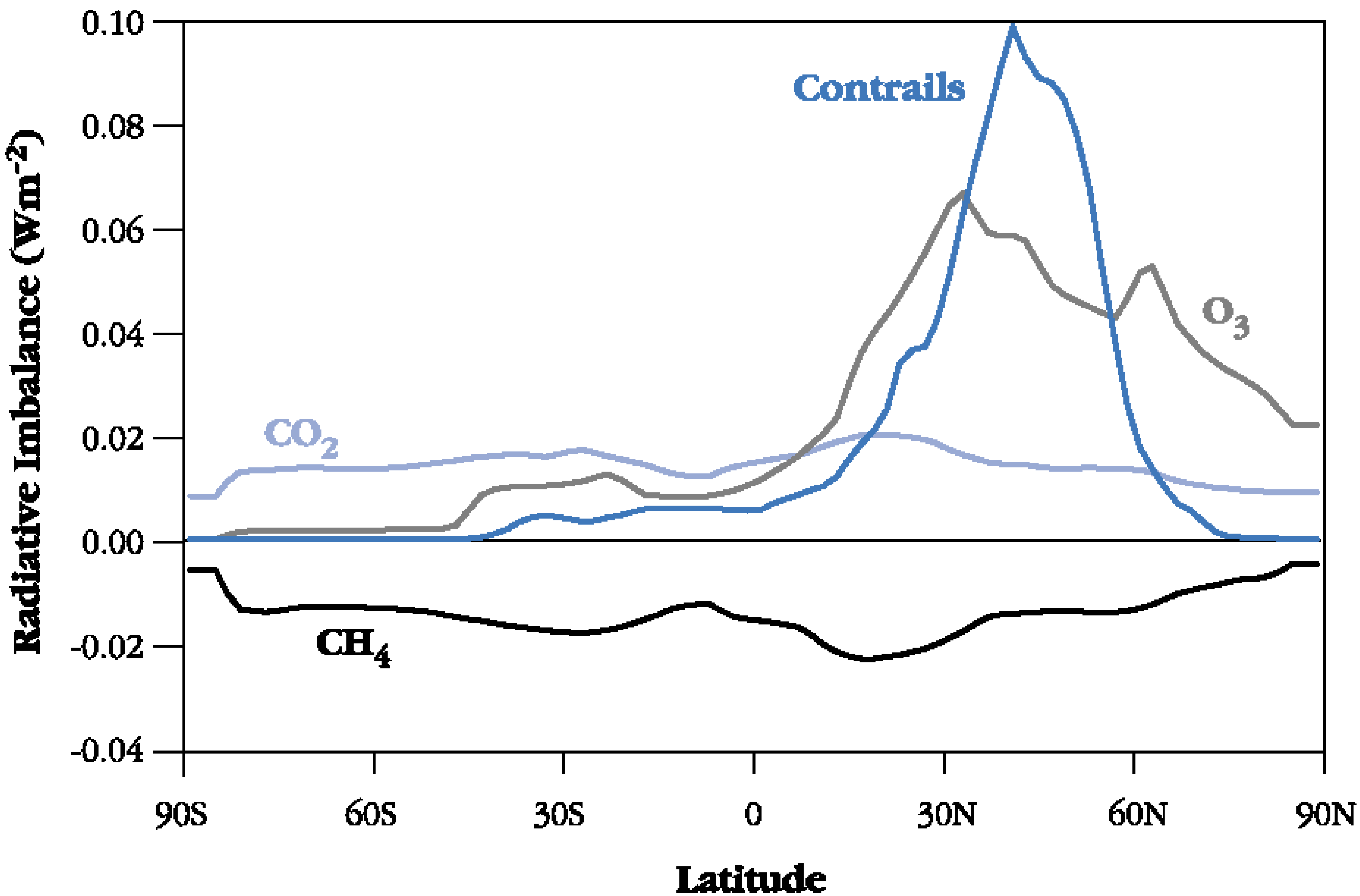
**(IPCC Special Report on Aviation, 1999)**

# 2050 PROJECTED CONTRAIL COVERAGE




(IPCC Special Report on Aviation, 1999)

# RADIATIVE IMBALANCE AT TROPOSPHERE DUE TO AIRCRAFT



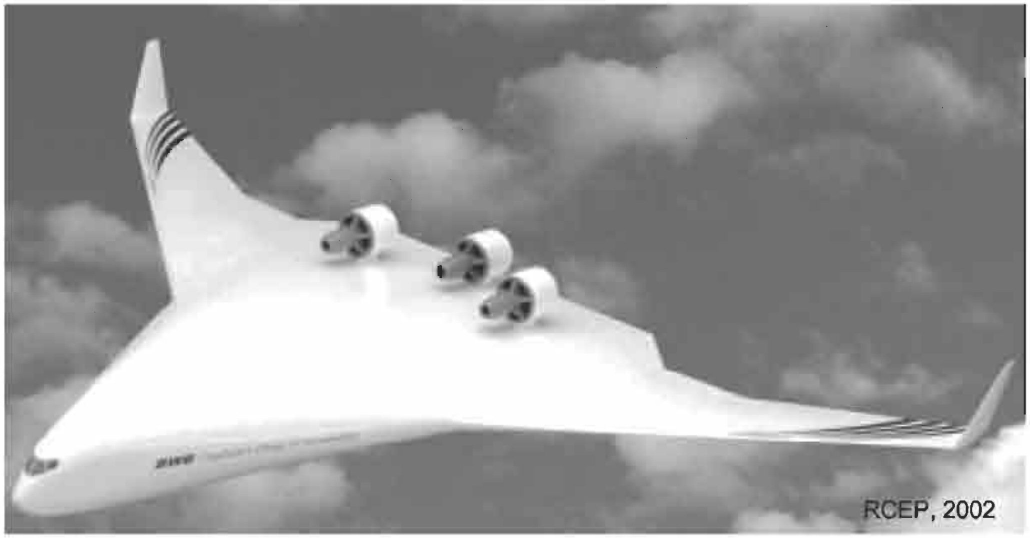

(IPCC Special Report on Aviation, 1999)

# 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**
- **$CO_2$ 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**



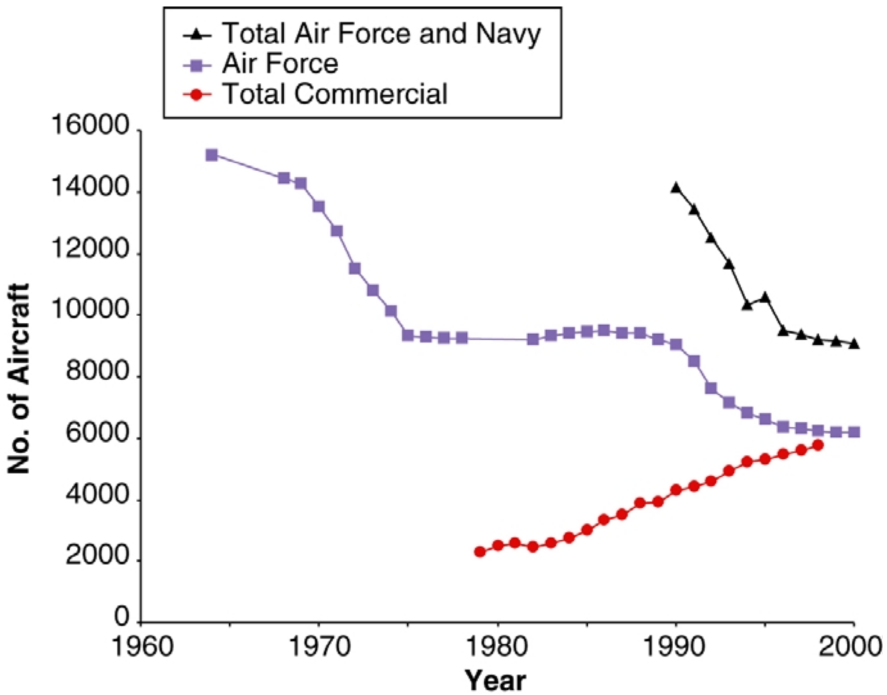

# TECHNOLOGY CHOICES: BOEING


"**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)

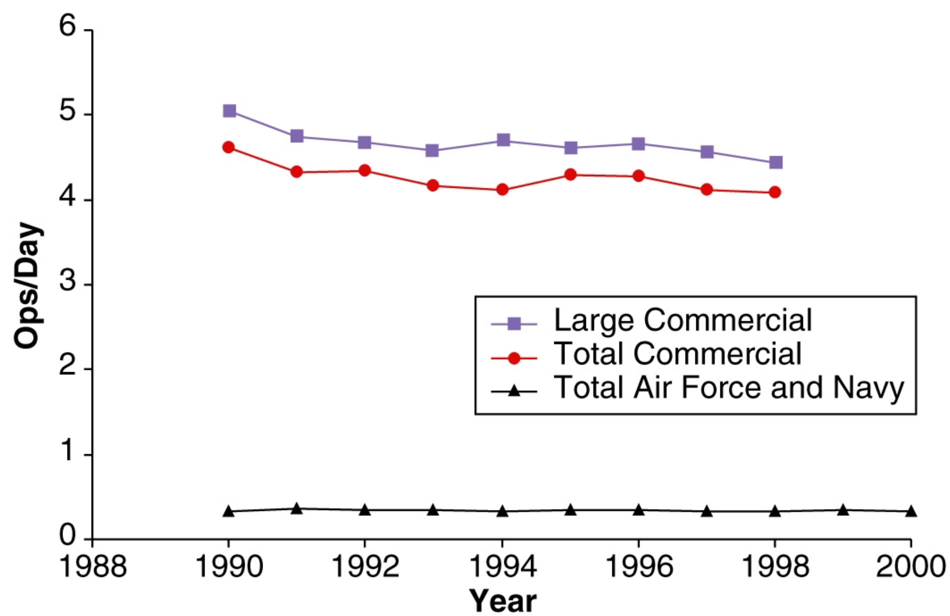
# COMMERCIAL vs. MILITARY FLEET TRENDS

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

**Number of Aircraft**

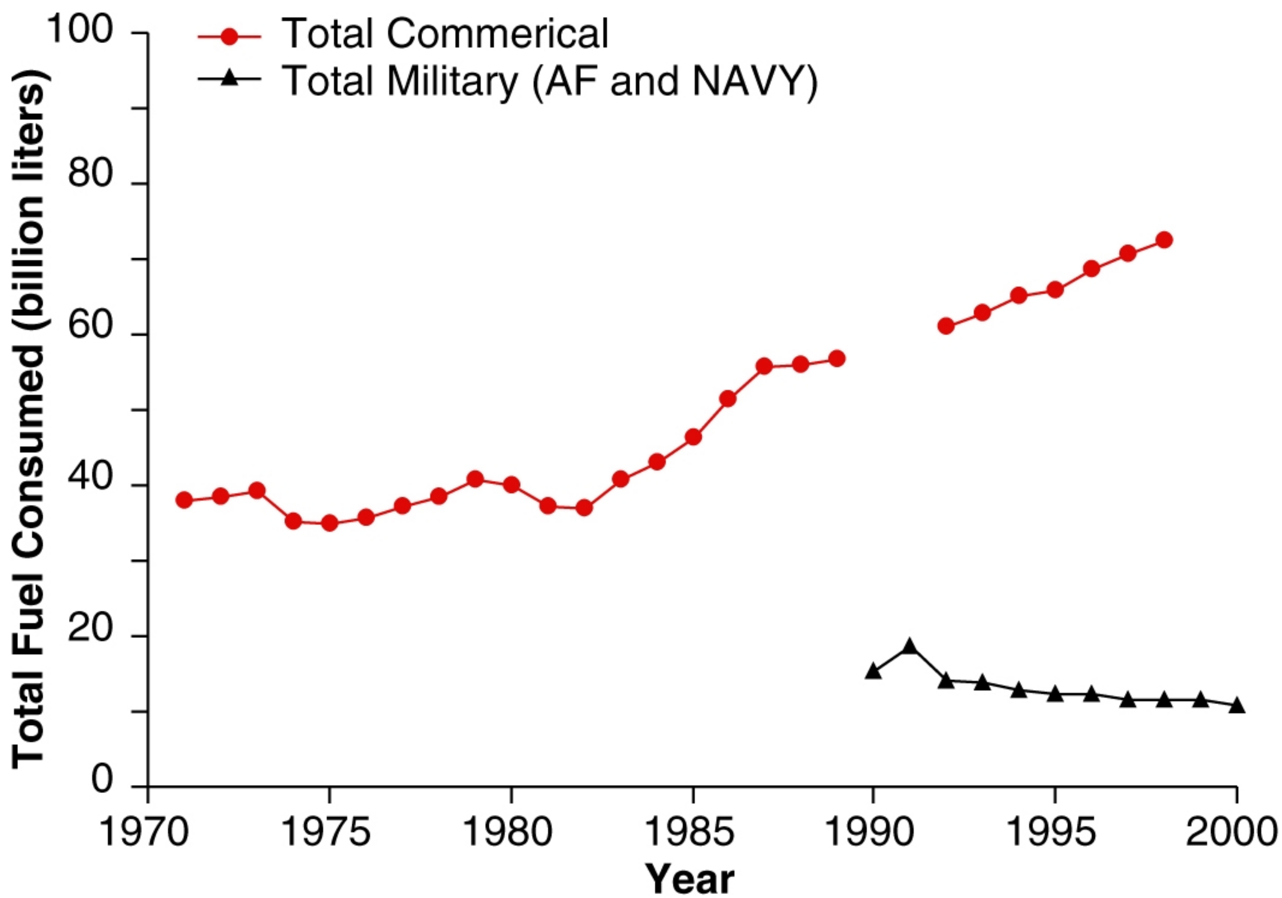



**Flights/day**

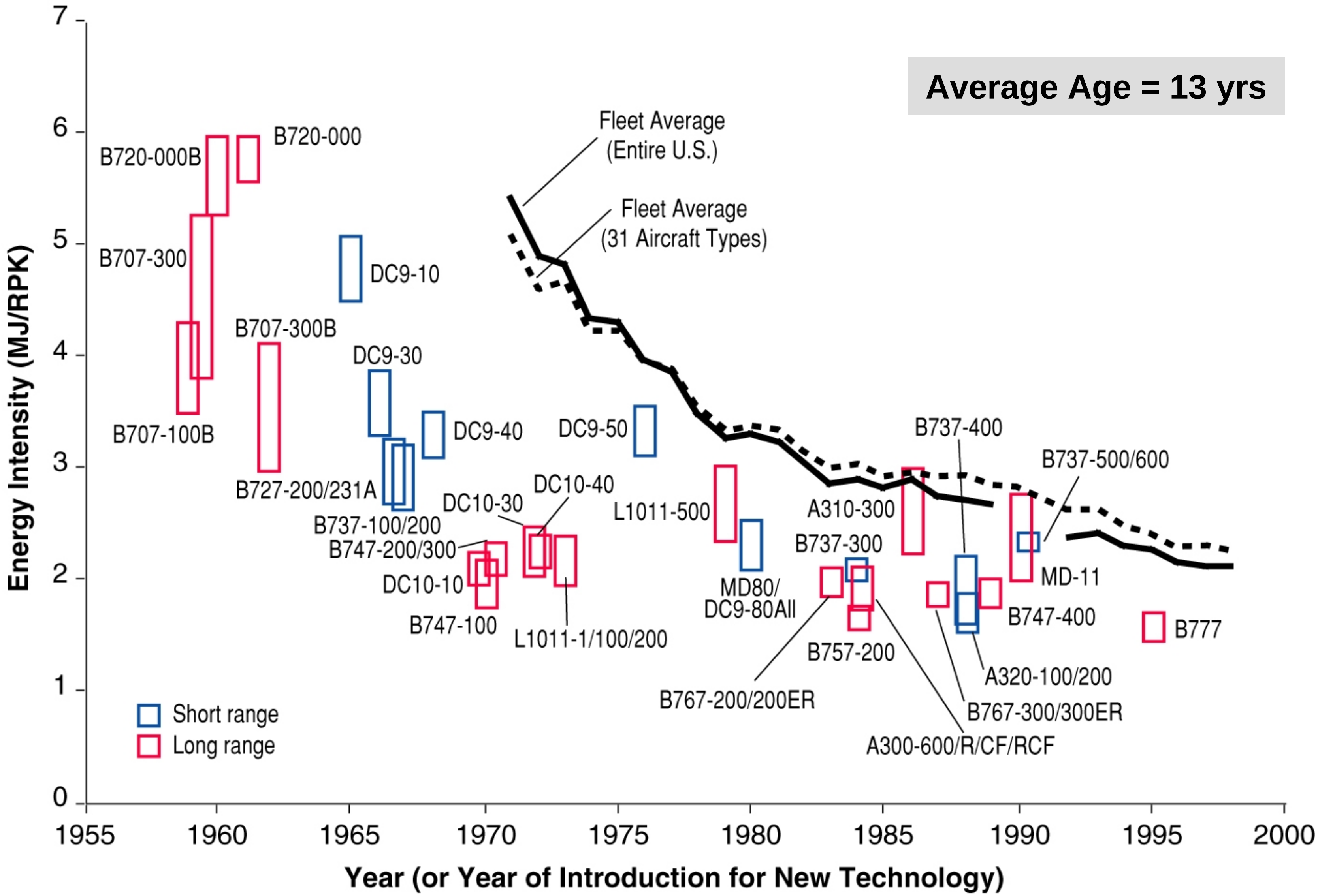


# FUEL CONSUMPTION TRENDS

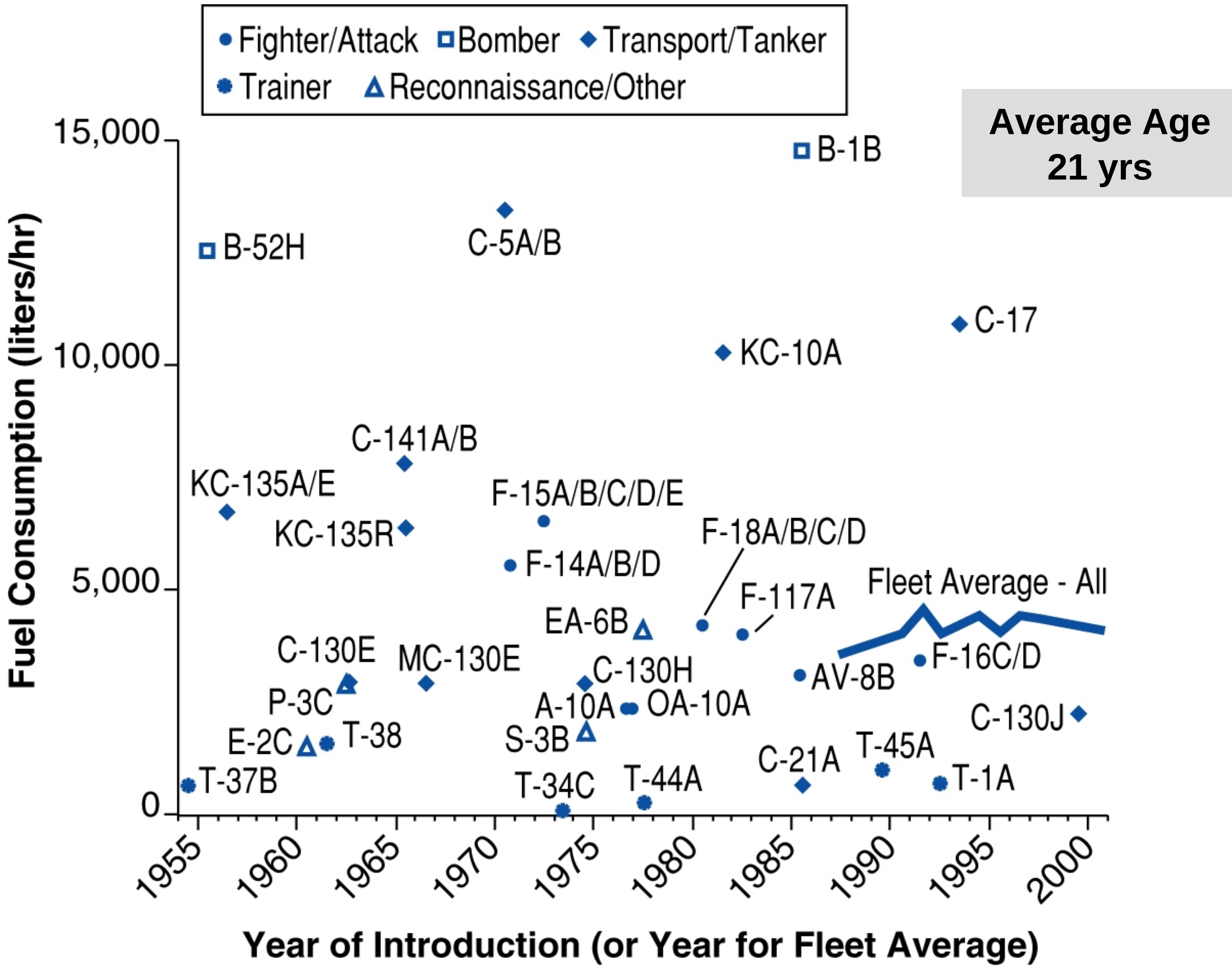
**Aircraft responsible for 2%-3% of U.S fossil fuel use**



# COMMERCIAL AIRCRAFT EFFICIENCY



# MILITARY AIRCRAFT FUEL BURN



# 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*

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

= Technology

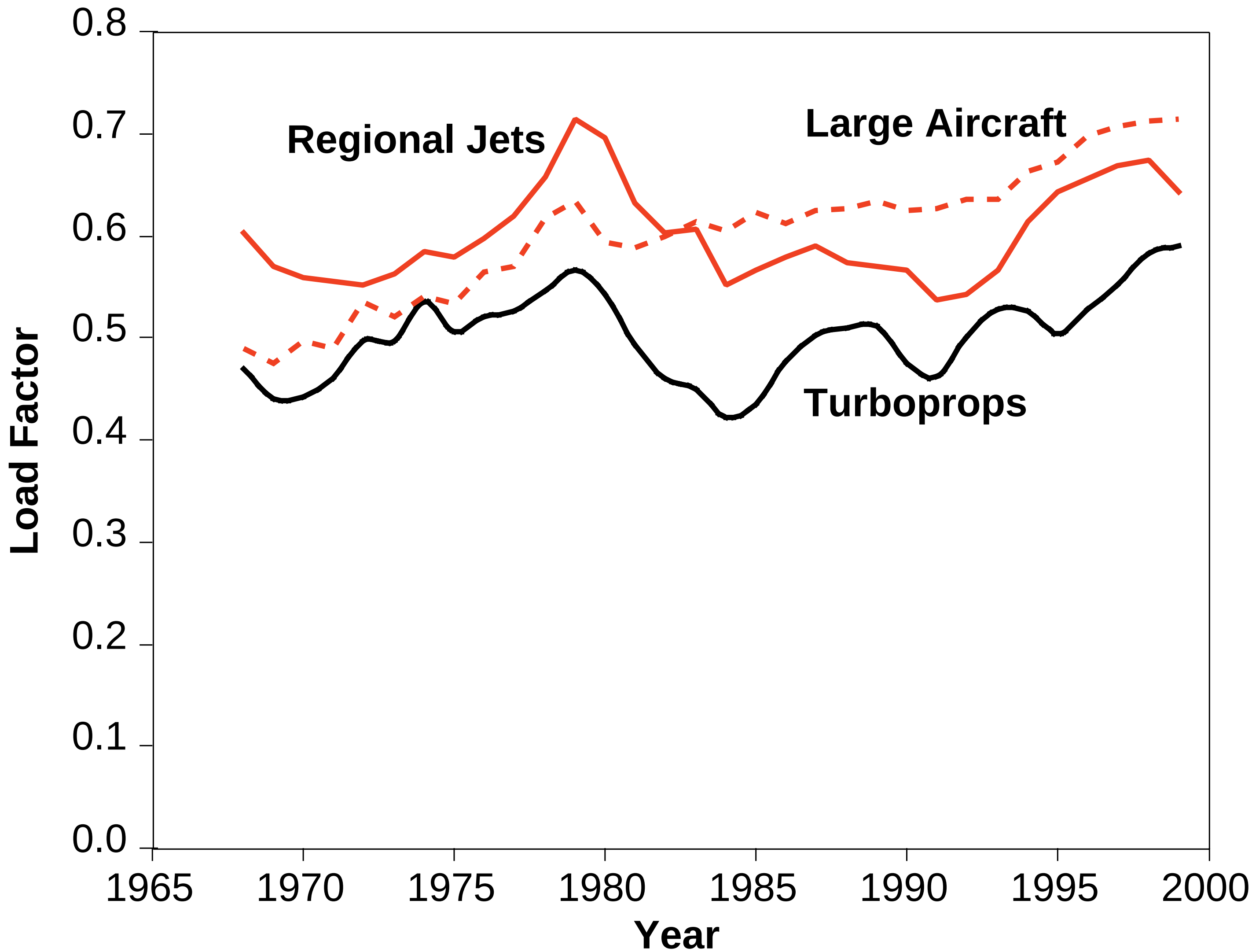
= Operations

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

$$\frac{ASK}{kg_{fuel}} = \frac{\text{Stagelength}\ \#\ \text{seats}}{W_f/g}$$

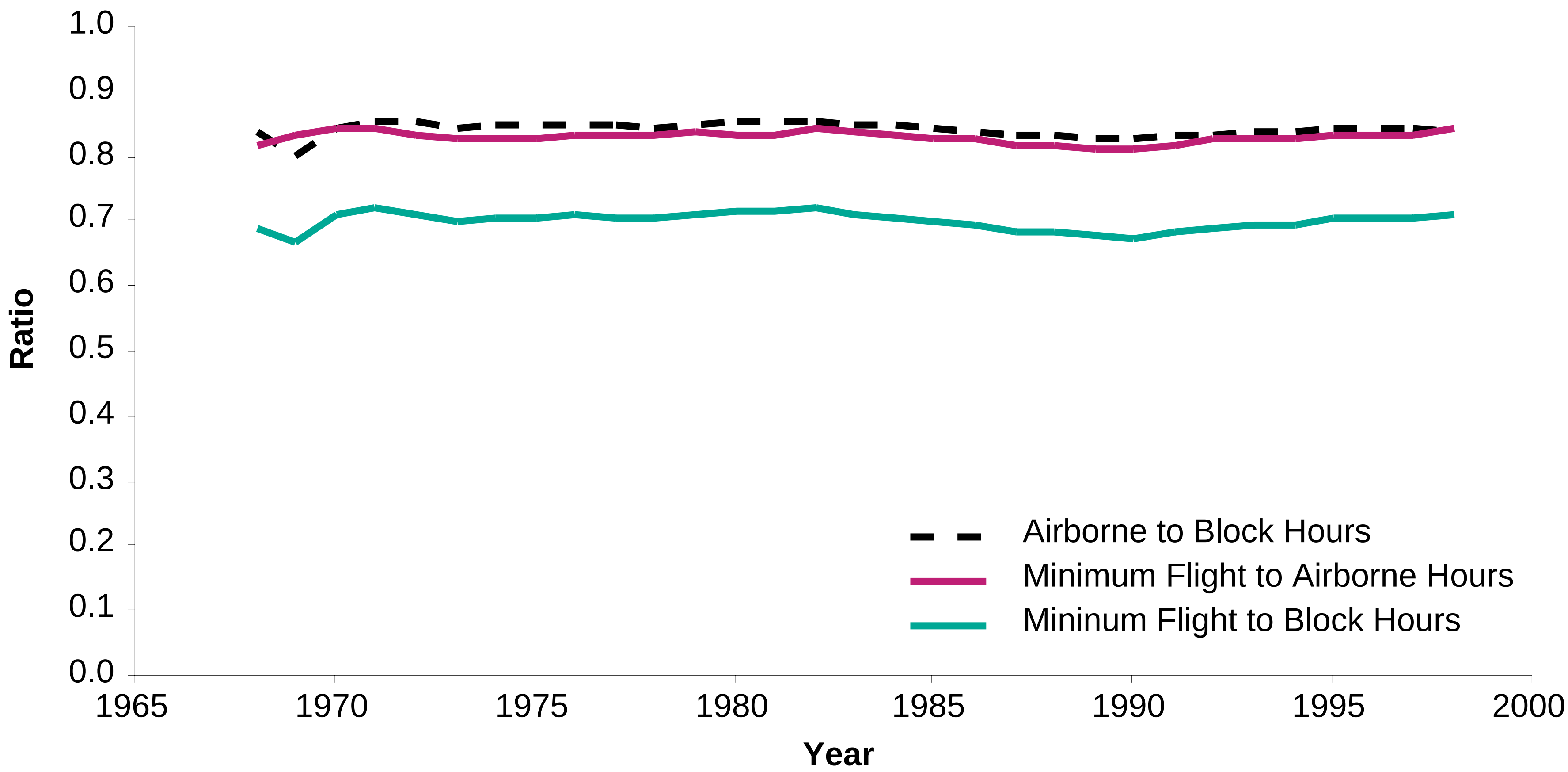
***Use data to separate effects and understand influences of technology***

# TRENDS IN LOAD FACTOR



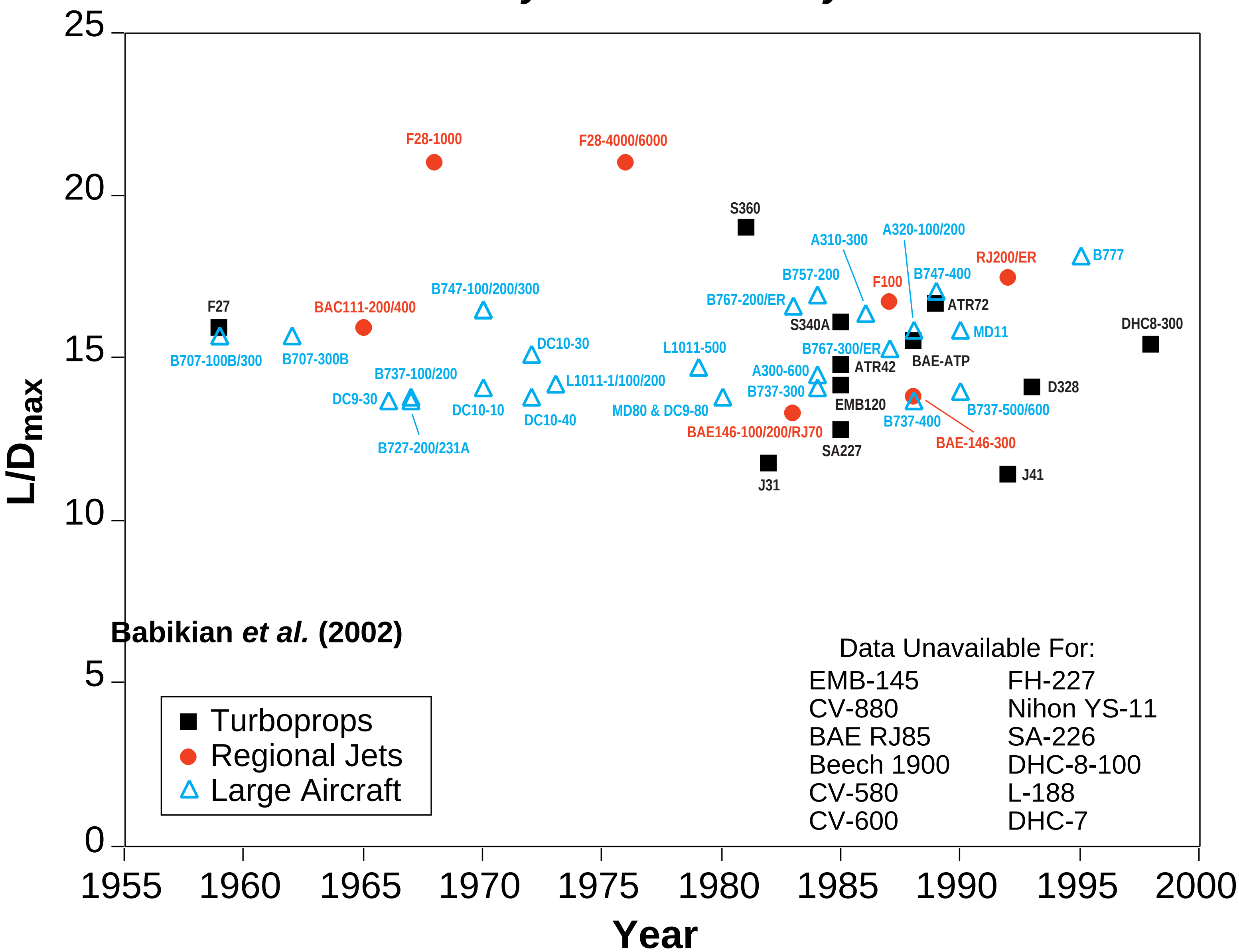

Babikian, Raffi, *The Historical Fuel Efficiency Characteristics of Regional Aircraft From Technological, Operational, and Cost Perspectives*, SM Thesis, Massachusetts Institute of Technology, June 2001

# FLIGHT AND GROUND DELAYS



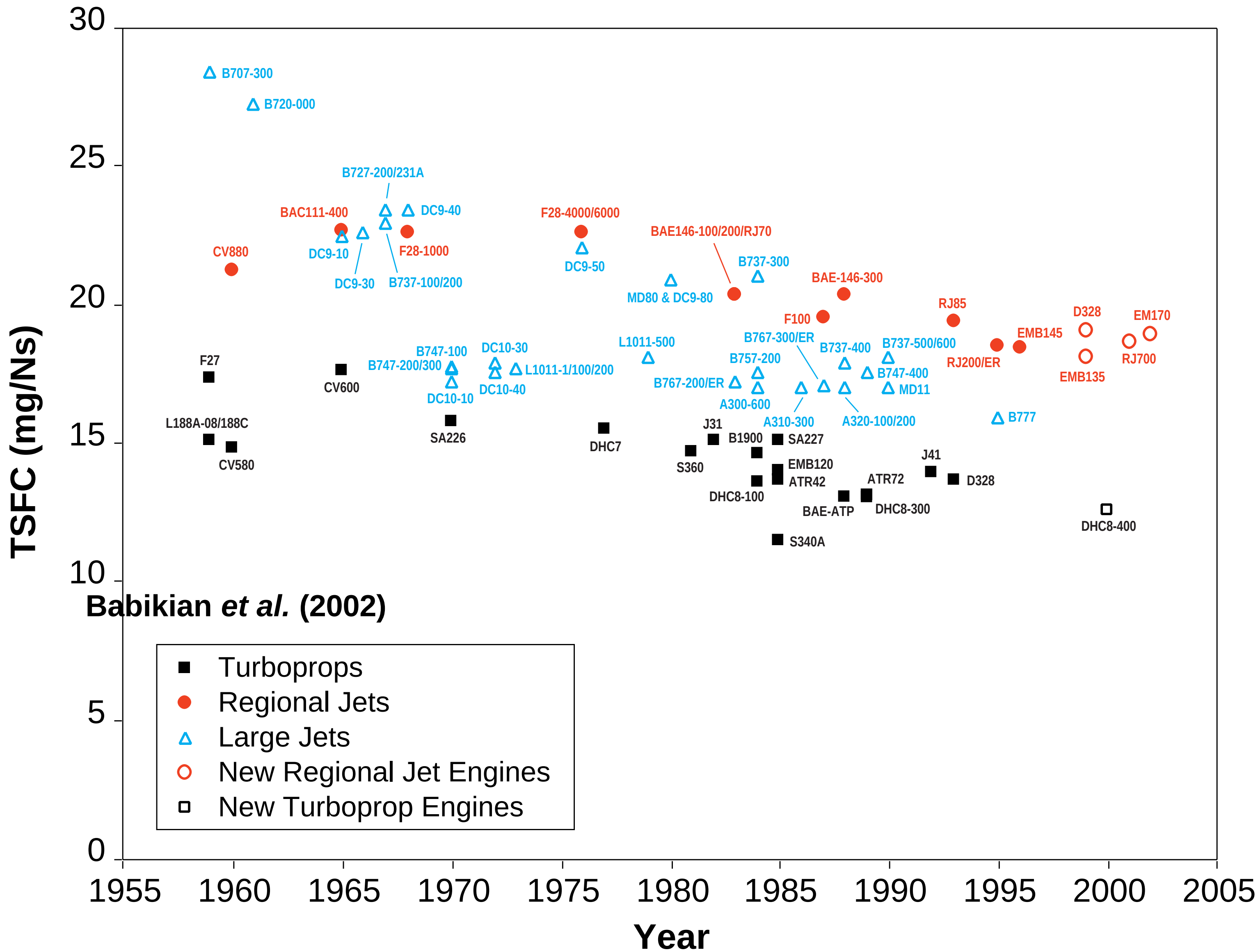
# HISTORICAL TRENDS

## *Aerodynamic Efficiency*



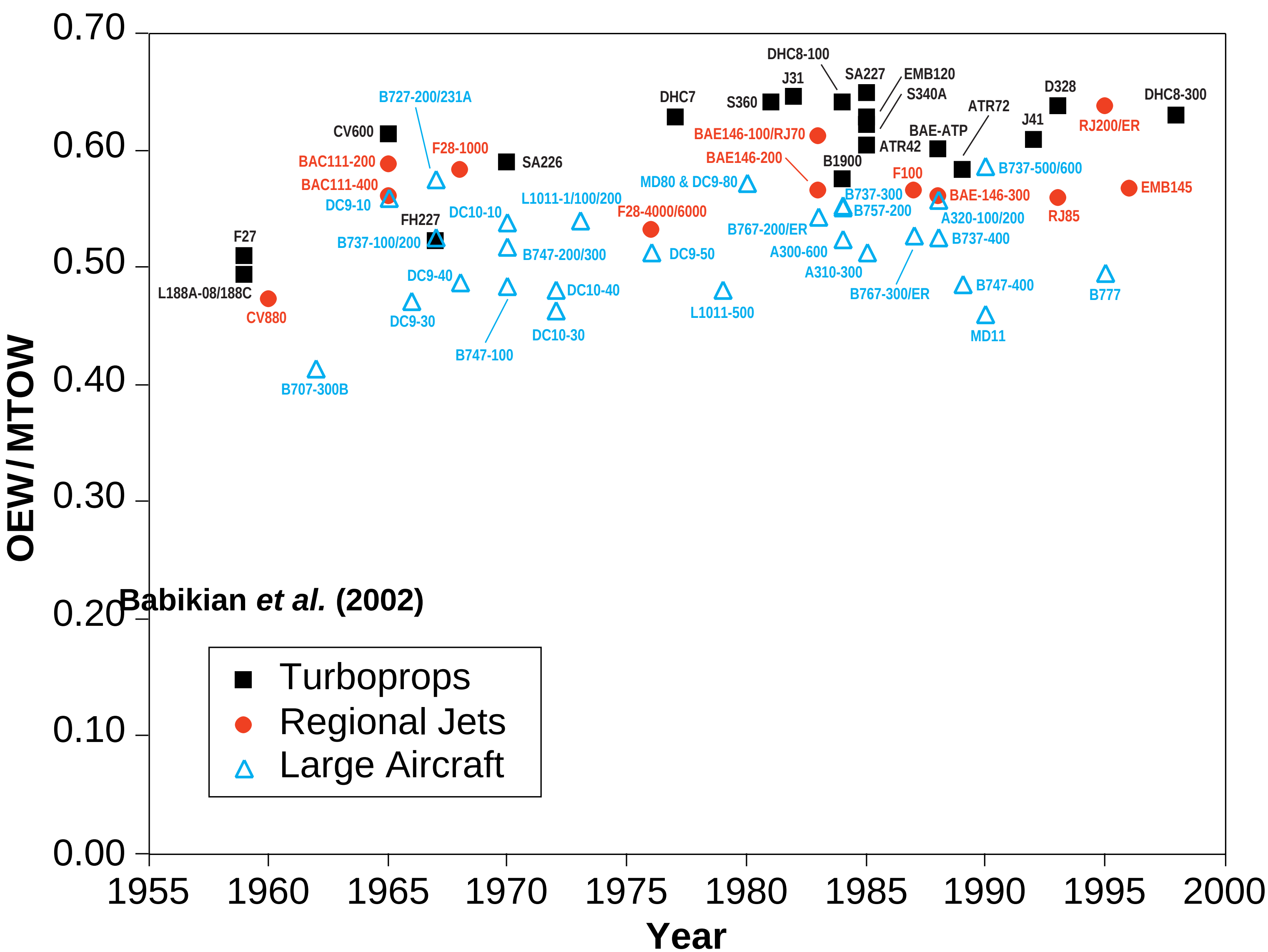
# HISTORICAL TRENDS

***Engine Efficiency***



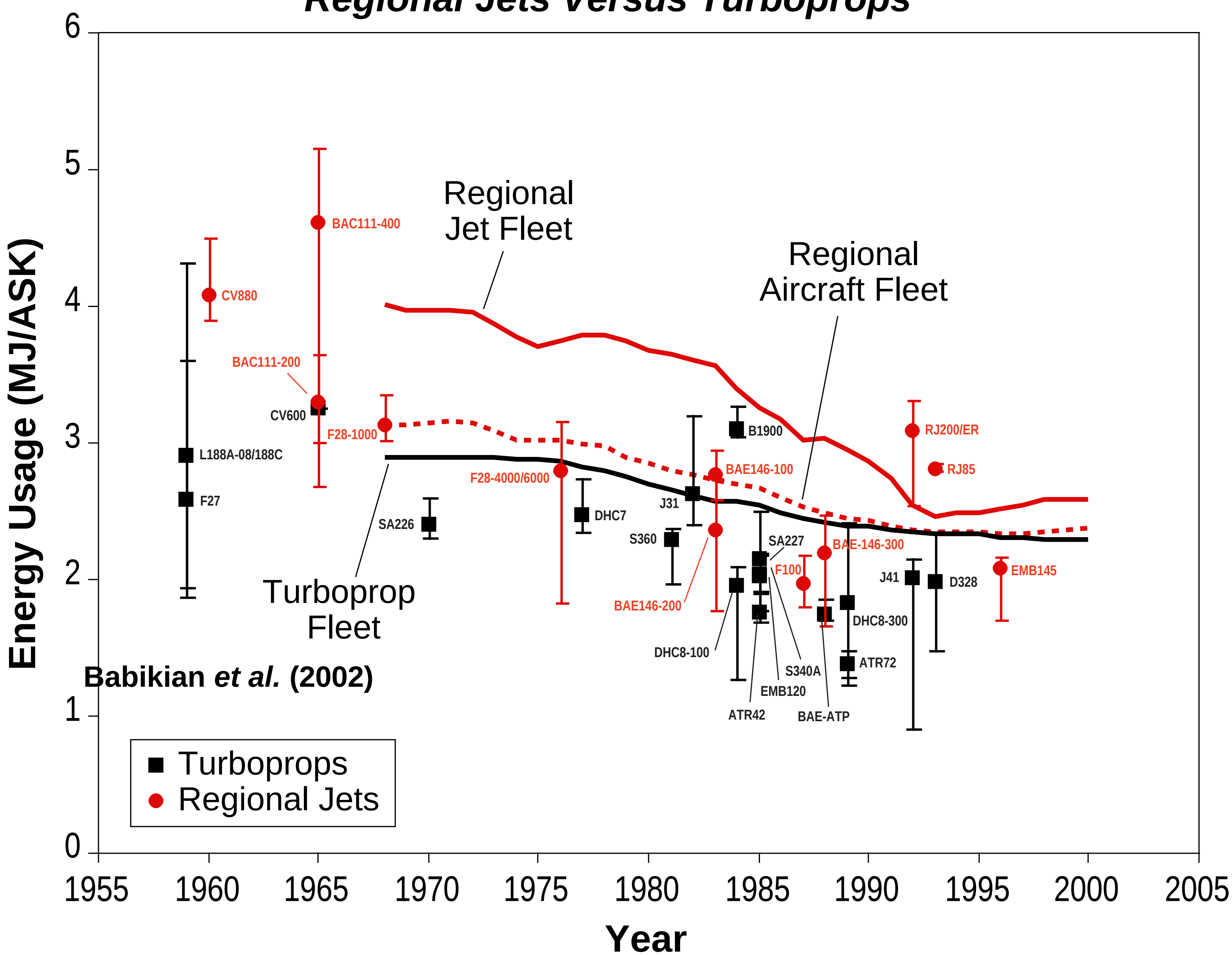
# HISTORICAL TRENDS

***Structural Efficiency***



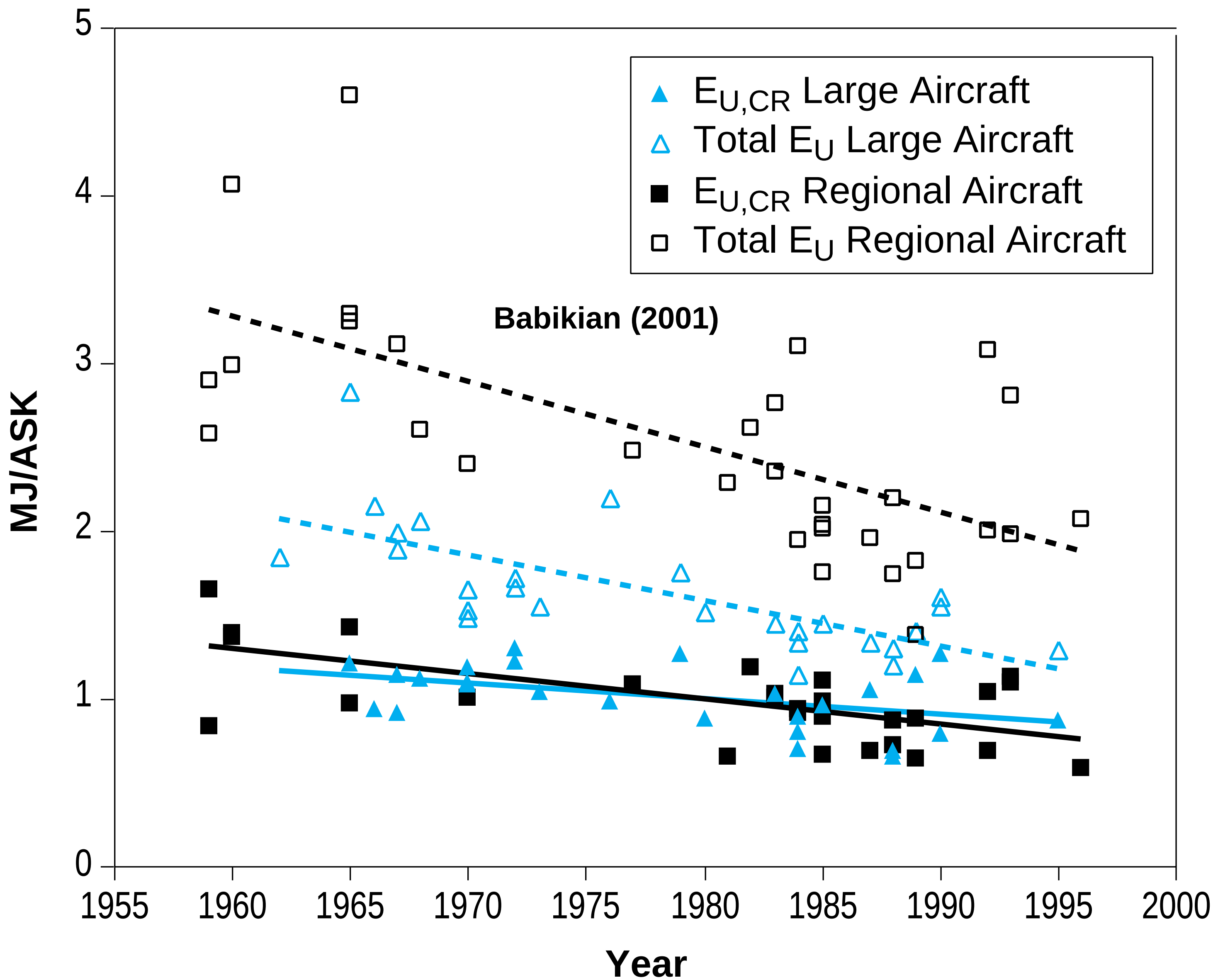
# EFFICIENCY

***Regional Jets Versus Turboprops***



# ENERGY USAGE

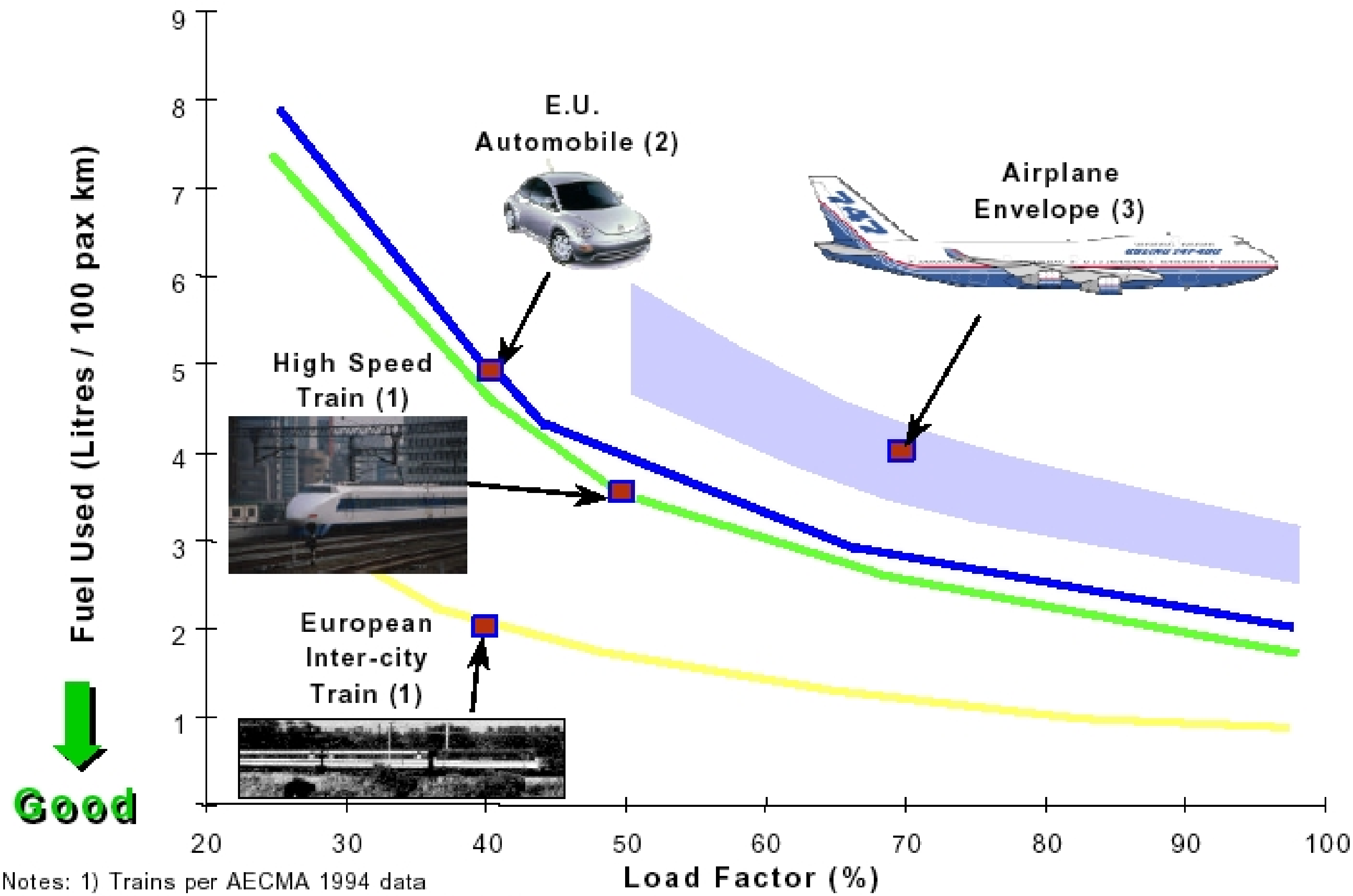
***Total Versus Cruise***



# 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**

# COMPARISON TO OTHER TRANSPORT MODES



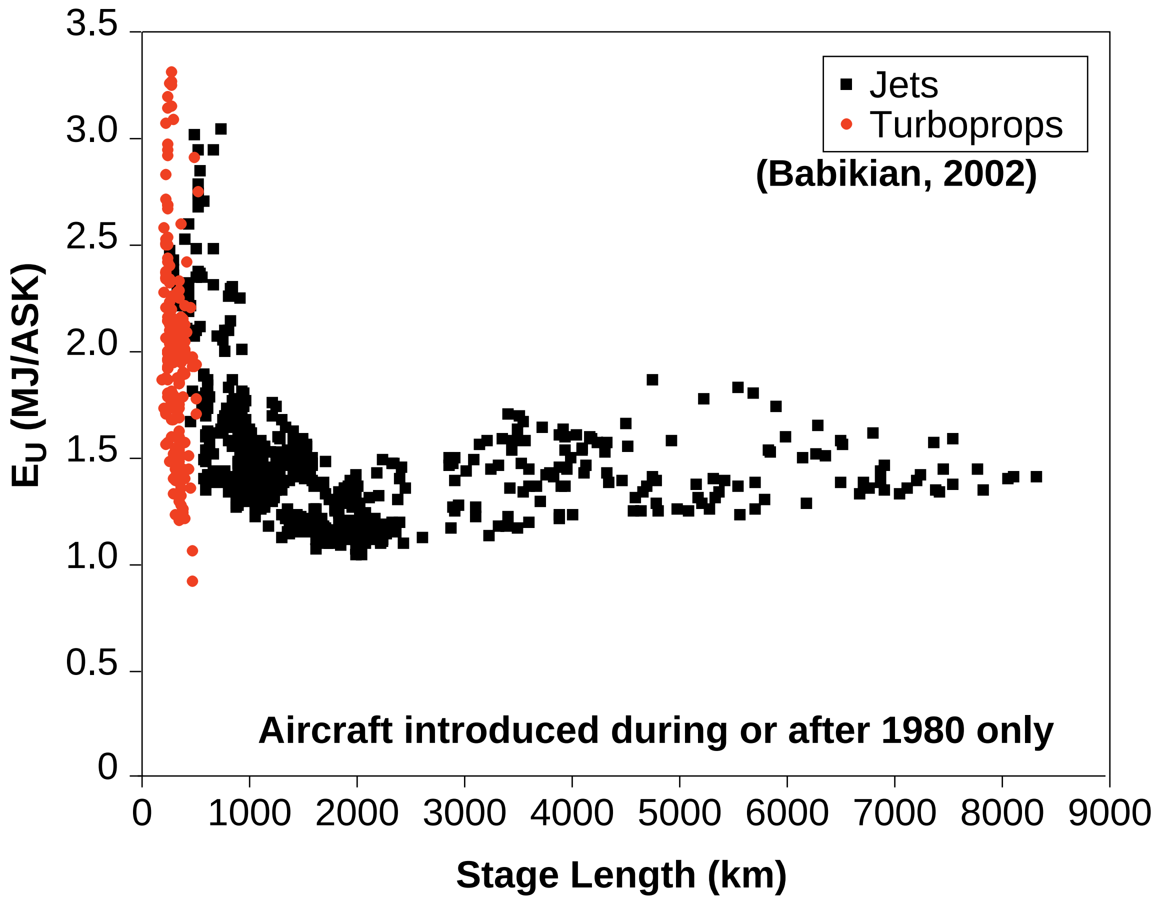

Notes: 1) Trains per AECMA 1994 data
2) Typical EU Car per Eurostat (12.6 km/ltr, 1.7 passengers)
3) Planes on 1500nmi mission, 70% LF, most popular seating config., best operating conditions

■ = Typical Load Factors

**(Mark Janes, Boeing, in ICAO CAEP/5, 2002)**

# SHORT HAUL AIRCRAFT

## *Facing Increasing Scrutiny*

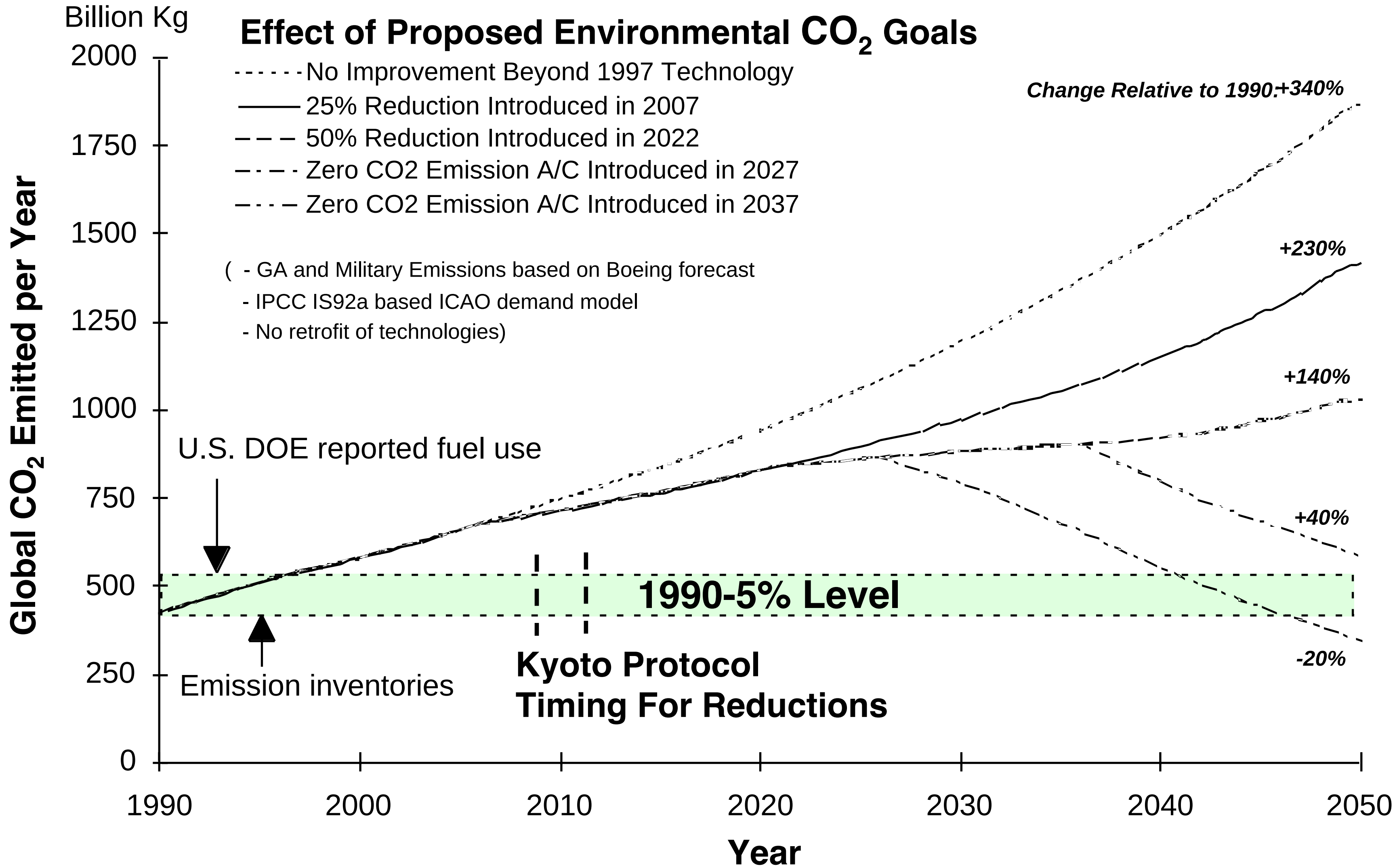



***Royal Commission on the Environment (2002)***

**"…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




J. E. Rohde, NASA 1999

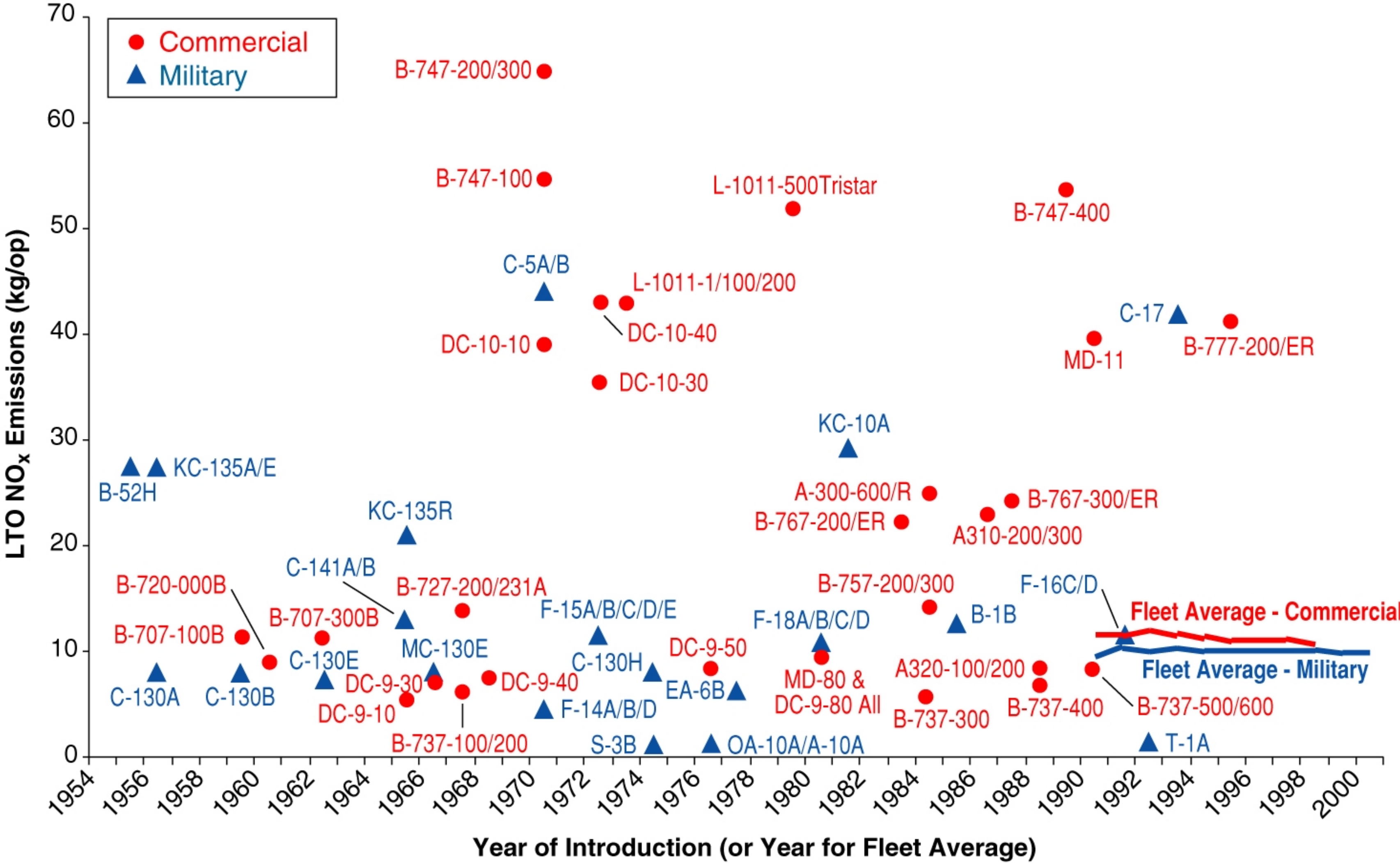
# IMPACTS OF MISSION REQUIREMENTS (NOx & Noise)

- **Range/payload ~ fuel efficiency (commercial and military)**
  - **Thermal efficiency** — **High pressures and temperatures** — **High $NO_x$**
  - **Propulsive efficiency** — **Large mass flow with small velocity change** — **Low Noise**
- **Maneuverability (military)**
  - **High thrust-per-weight, small compact engine**
- **Supersonic flight (military)**
  - **Low drag, small compact engine**

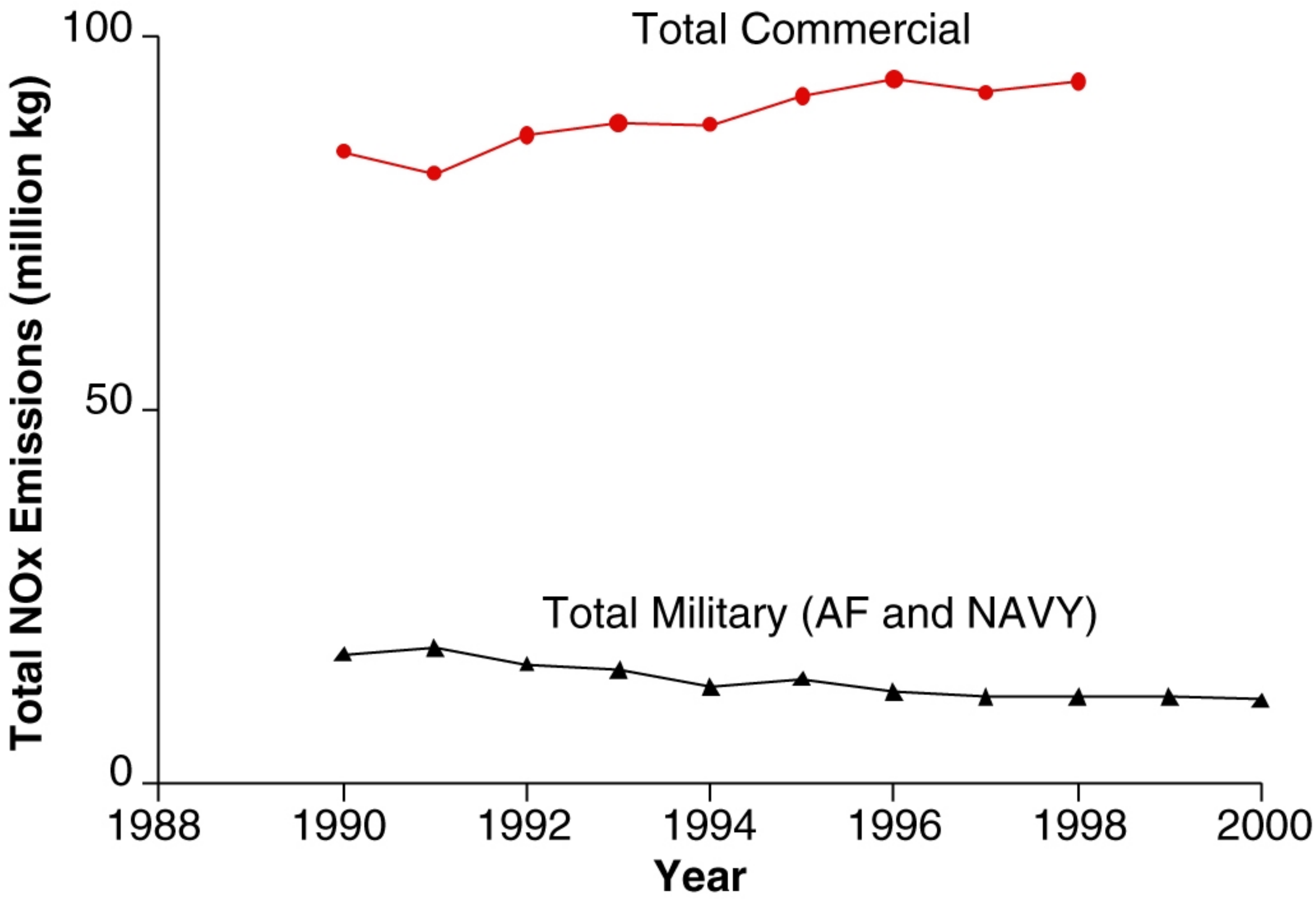
**High energy conversion per unit volume (high temperatures and pressures)** — **High $NO_x$**

**Small mass flow with large velocity change** — **High Noise**

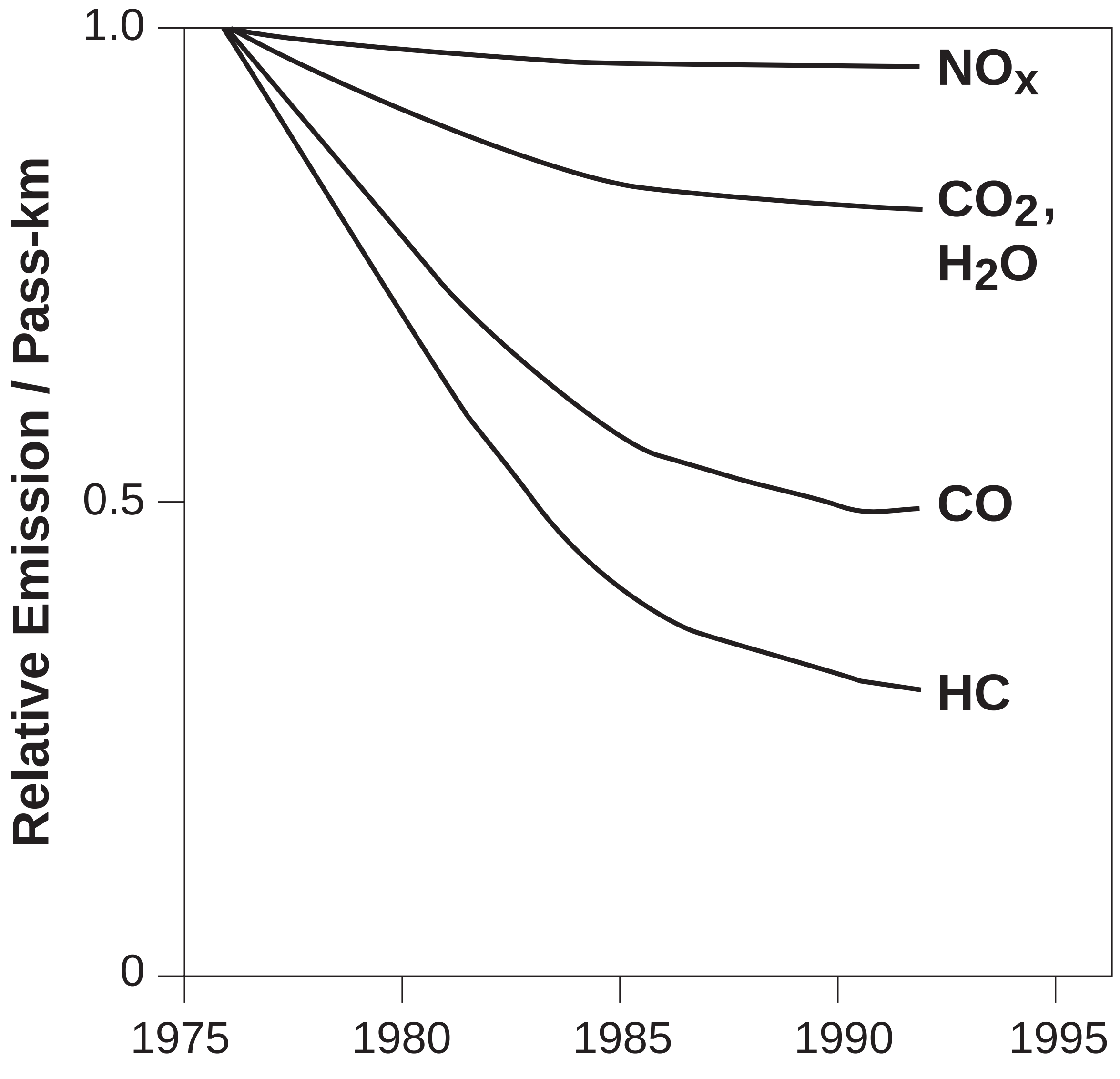
# $NO_x$ EMISSIONS TECHNOLOGY TRENDS



# $NO_x$ EMISSIONS TRENDS



# HISTORICAL FLEET CRUISE EMISSIONS PER PASSENGER PER KILOMETER




(DuBois, Boeing)

# 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 $NO_x$ 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

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- **Lee, J. J., Lukachko, S. P., Waitz, I. A., and Schafer, A., "Historical and Future Trends in Aircraft Performance, Cost and Emissions,"** ***Annual Review of Energy and the Environment,*** **Volume 26, 2001.**
- **Waitz, I. A., Lukachko, S. P., and J. J. Lee, "Military Aviation and the Environment: Historical Trends and Comparison to Civil Aviation," AIAA-2003-2620, invited contribution to AIAA/ICAS International Air and Space Symposium and Exposition, Dayton, Ohio, July 14-17, 2003.**
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