AVIATION & THE ENVIRONMENT

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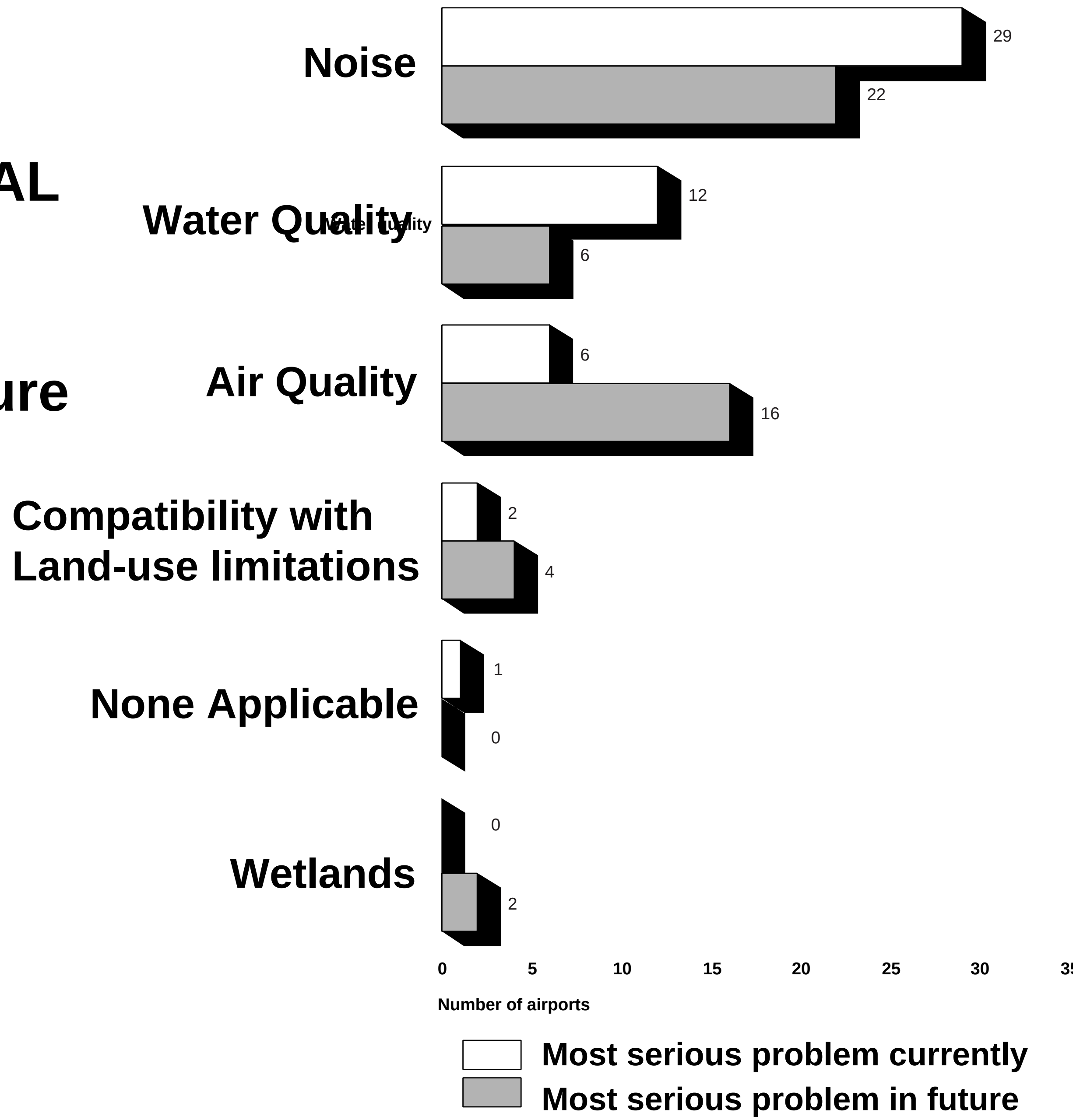
LECTURE OUTLINE

- 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

AIRPORT RANKING OF ENVIRONMENTAL ISSUES

Current and Future



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

(GAO, 2000)

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_2O, 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

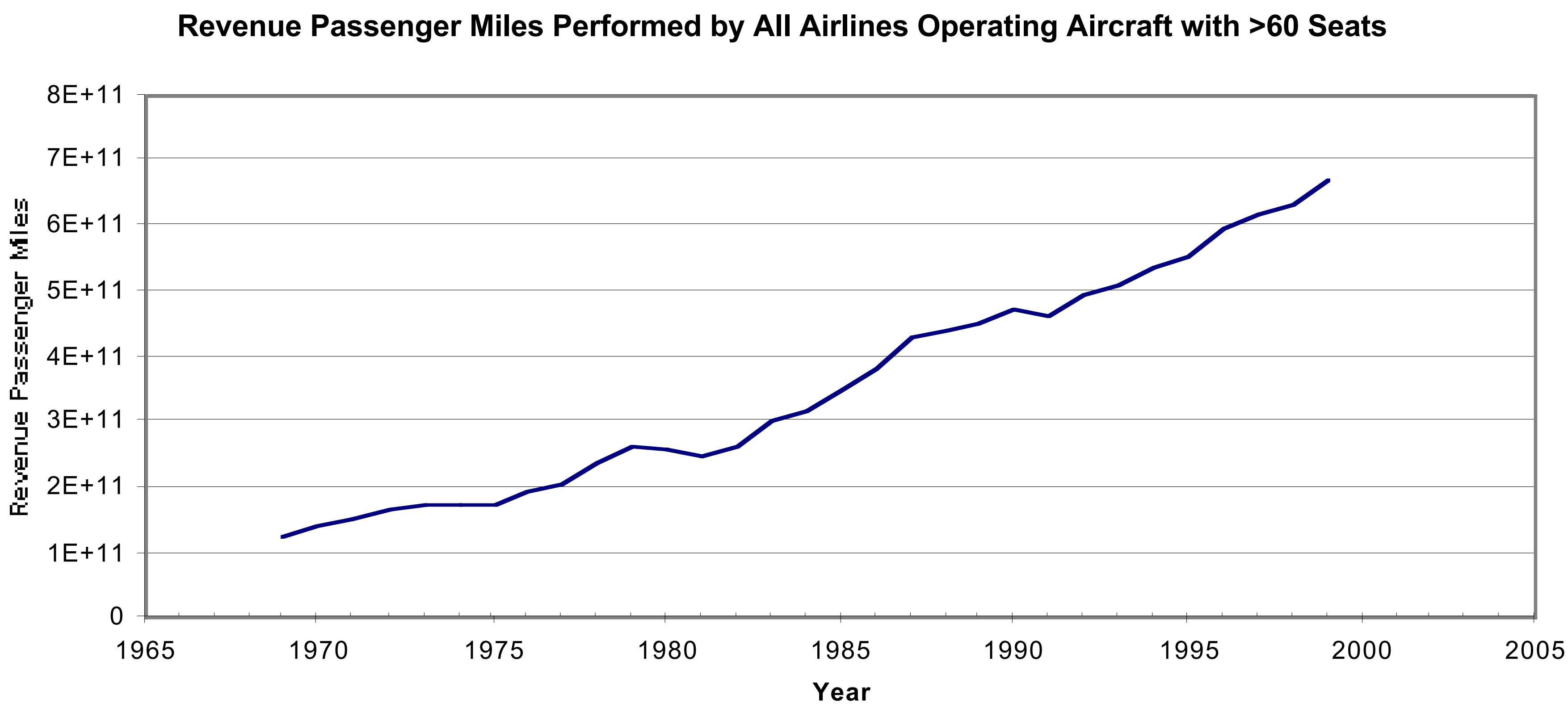
VALUATION BASIS	SOCIAL (industry + affected public)		INSTITUTIONAL (regulatory policy)		
Impact Area (objective)	Total $	$ / capita	Total $	$ / capita	% of Total $ addressed by regulation
Noise (quiet environs)	$ 26B	$ 2100	$ 2.9B	$ 6000	11%
Air Quality (safe air)	$ 11B	$ 140	$ 2.5B	$ 30	22%
Climate Change (stable climate)	~$100B	$ 345	$ 0.0B	$ 0	0%
TOTAL	~$137B		$ 5.4B		5%

- **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<<
Lukachko, 2003

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

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



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

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

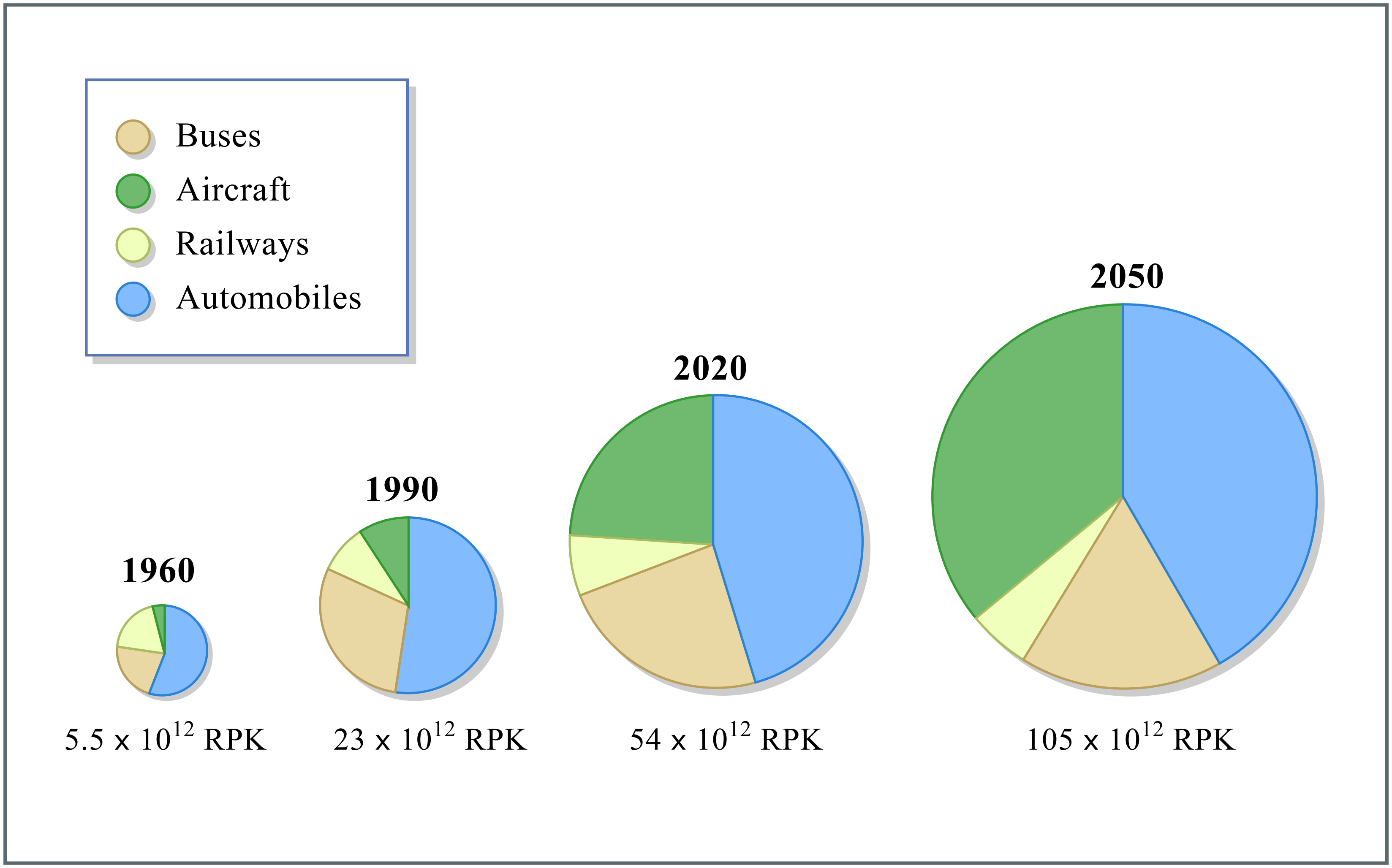


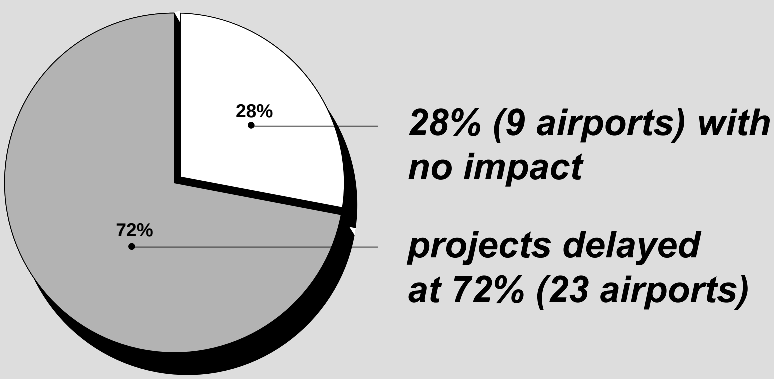
Figure by MIT OCW. Adapted from: Schafer et al. (1998), GDP/cap growth rates from IPCC IS92a Scenario.

MOBILITY AND THE ENVIRONMENT

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

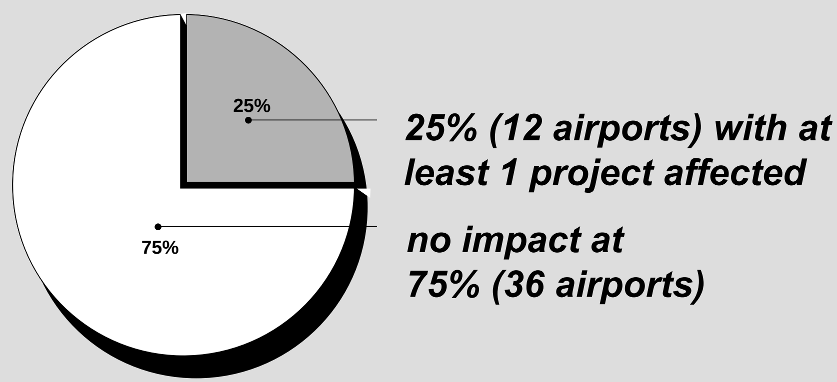
U.S. National Science and Technology Council, 1995

Expansion Projects Delayed due to Environmental Issues



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

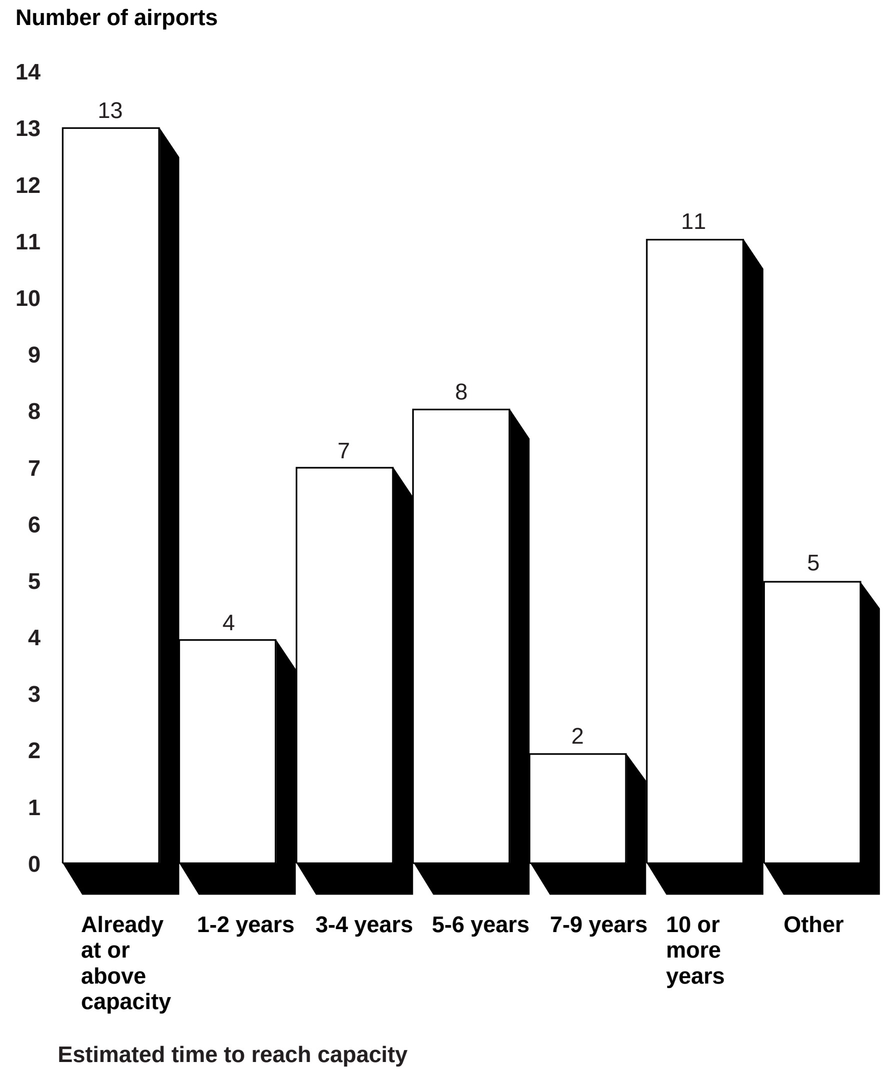
Expansion Projects Cancelled or Indefinitely Postponed due to Environmental Issues



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



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**

- **House of Representatives proposal (2002): <u>National Security Impact Statement</u> with all Environmental Impact Statements**

REGULATIONS: BALANCING PUBLIC GOALS

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

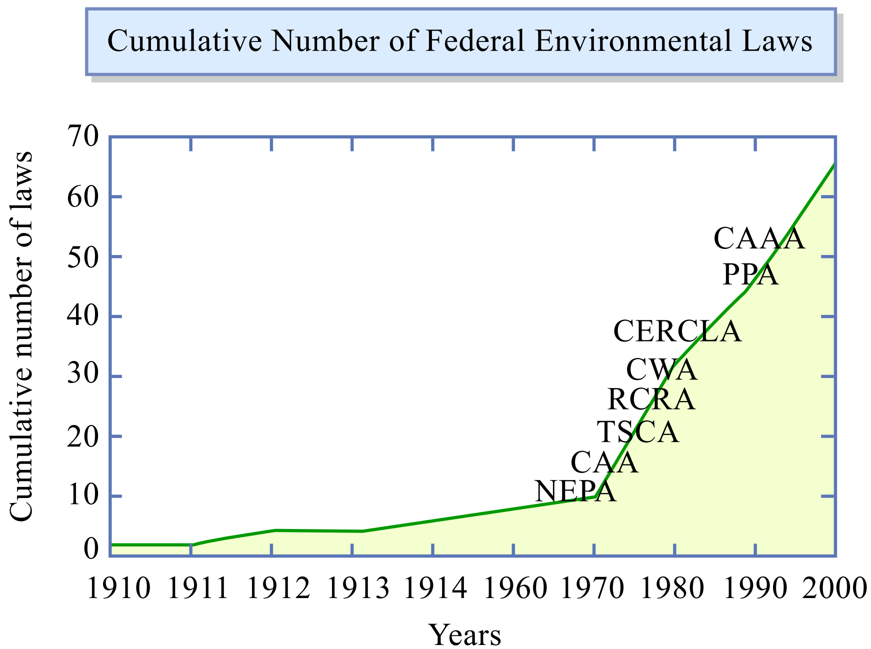
- **Federal Noise Control Act + local noise restrictions**
  - **Commercial yes**
  - **Military no (Nat. Sec. Exemption, but NEPA EIS)**

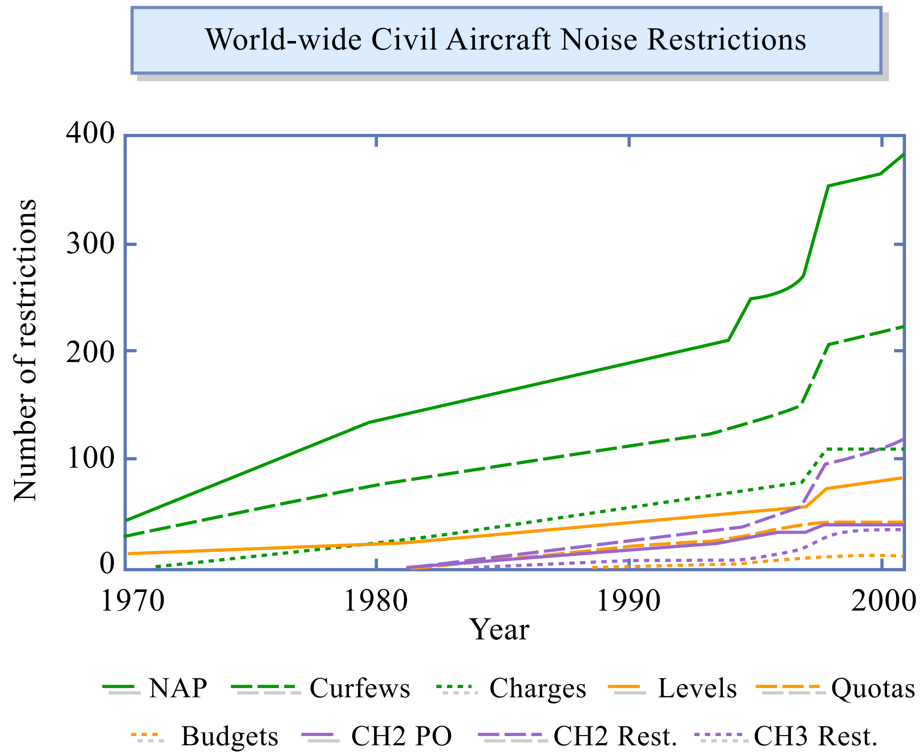
- **Federal Clean Air Act + State Implementation Plans**
  - **Military yes (General Conformity Rule)**
  - **Commercial "no" (Interstate Commerce & Trade exemption)**

- **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





Figures by MIT OCW.

Adapted from: Materiel Developer's Guide for Pollution Prevention, Army Acquisition Support Office, 1994

www.boeing.com

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

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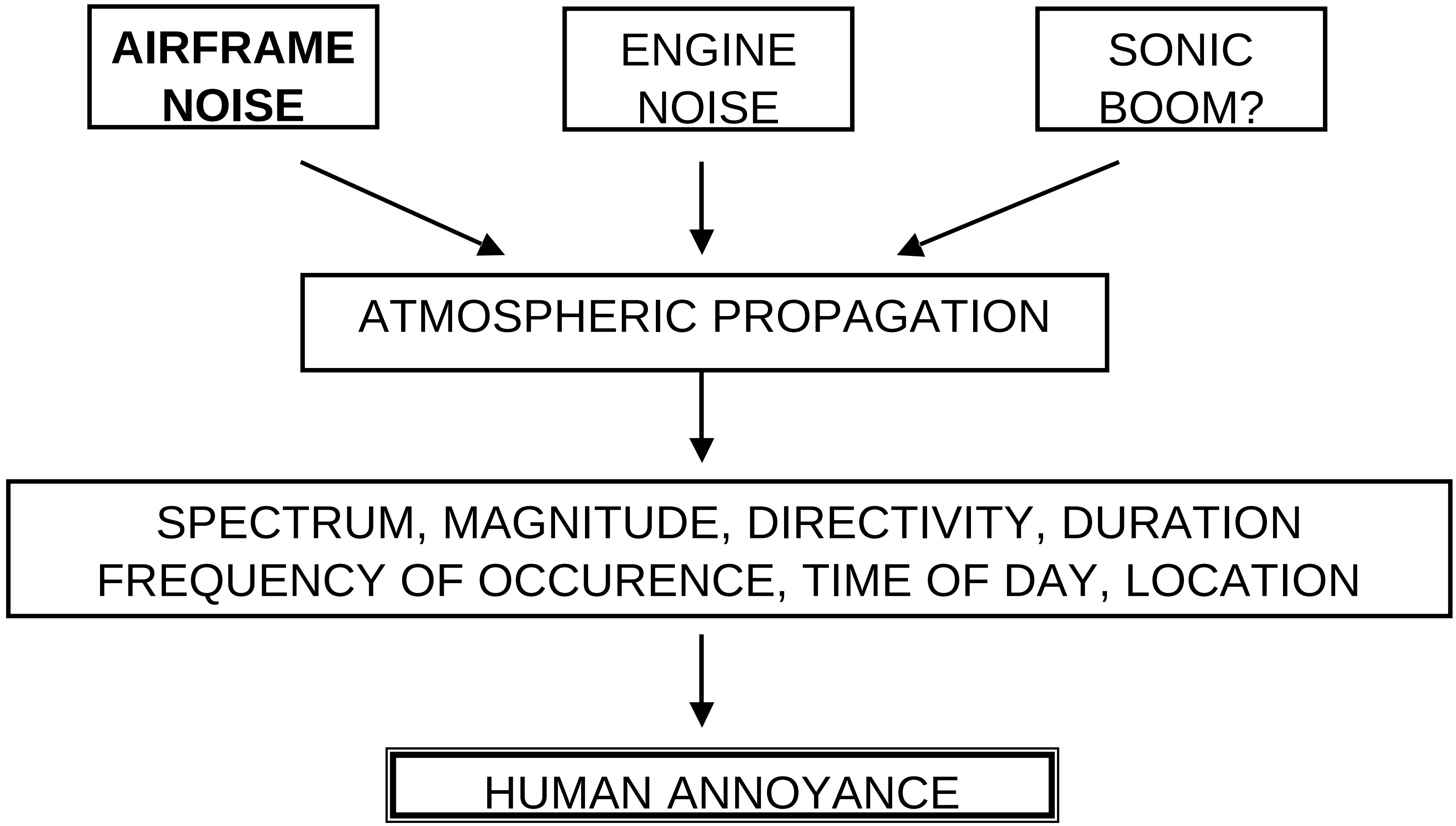
AIRCRAFT NOISE GENERATION

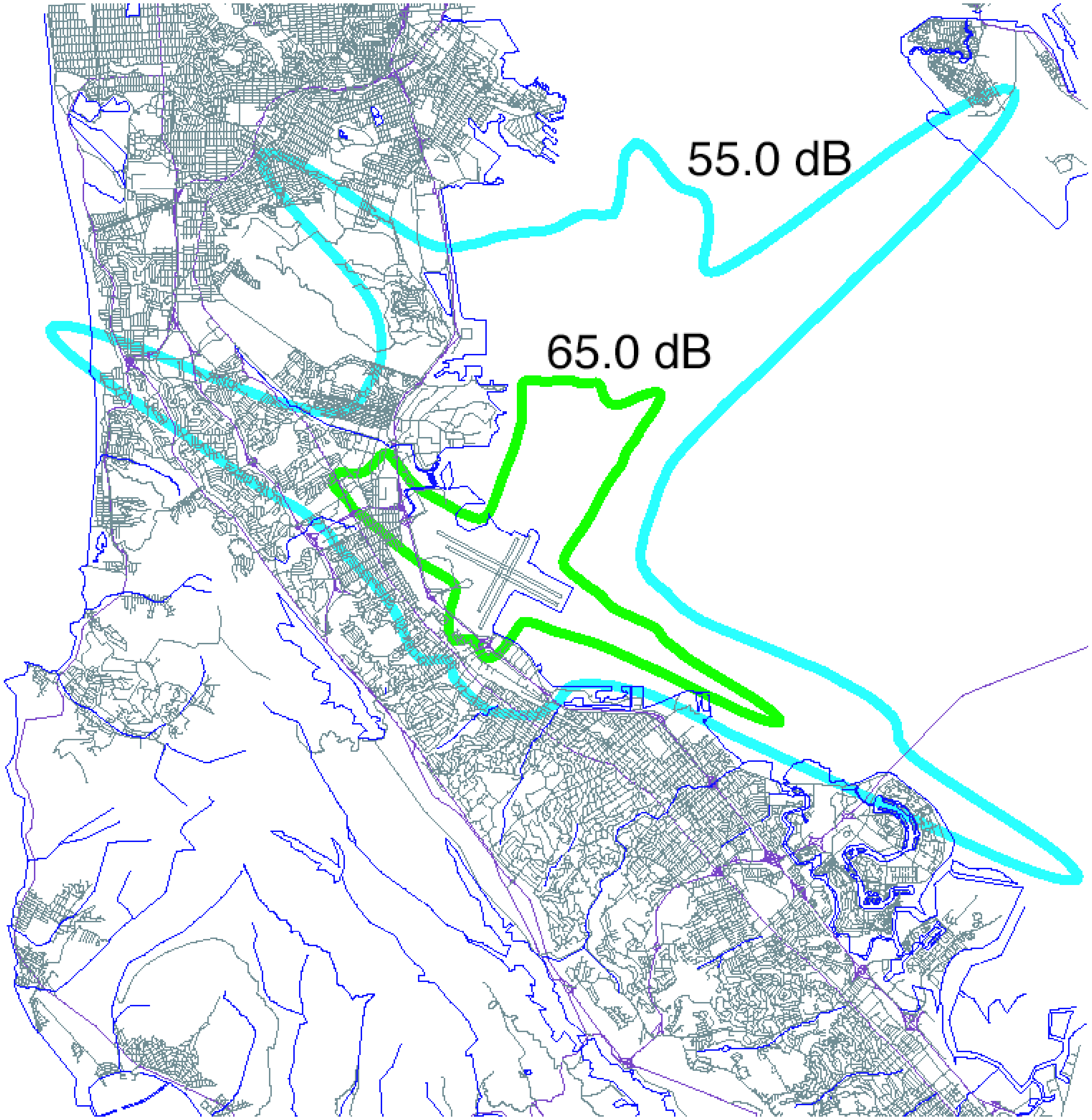


NOISE EFFECTS ON PEOPLE

Effects	Hearing Loss	Annoyance		
Day-Night Average Sound Level in Decibels	Qualitative Description	% of Population Highly Annoyed	Average Community Reaction	General Community Attitude Towards Area
75 and above	May begin to occur	37%	Very Severe	Noise is likely to be most important of all adverse aspects of the community environment
70	Will not likely occur	22%	Severe	Noise is one of the most adverse aspects of the community environment
65	Will not occur	12%	Significant	Noise is one of the adverse aspects of the community environment
60	Will not occur	7%	Moderate to slight	Noise may be considered an adverse aspects of the community environment
55 and below	Will not occur	3%	Moderate to slight	Noise considered no more important than various other environmental factors

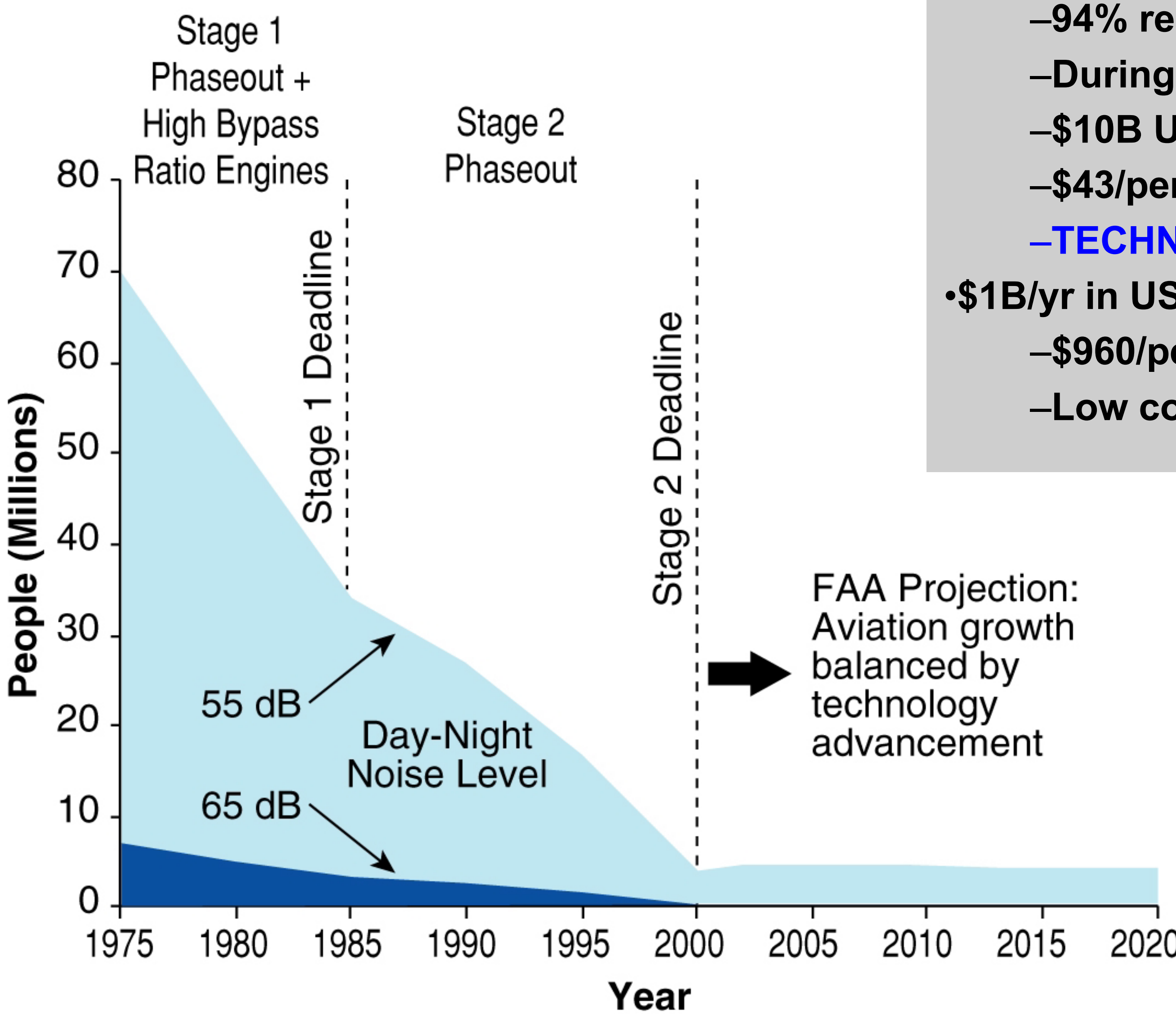
(FICON, 1992)

COMMERICAL AIRPORT NOISE EXPOSURE MAP
(DNL levels)



(INM, 1999)

NOISE IMPACT TRENDS



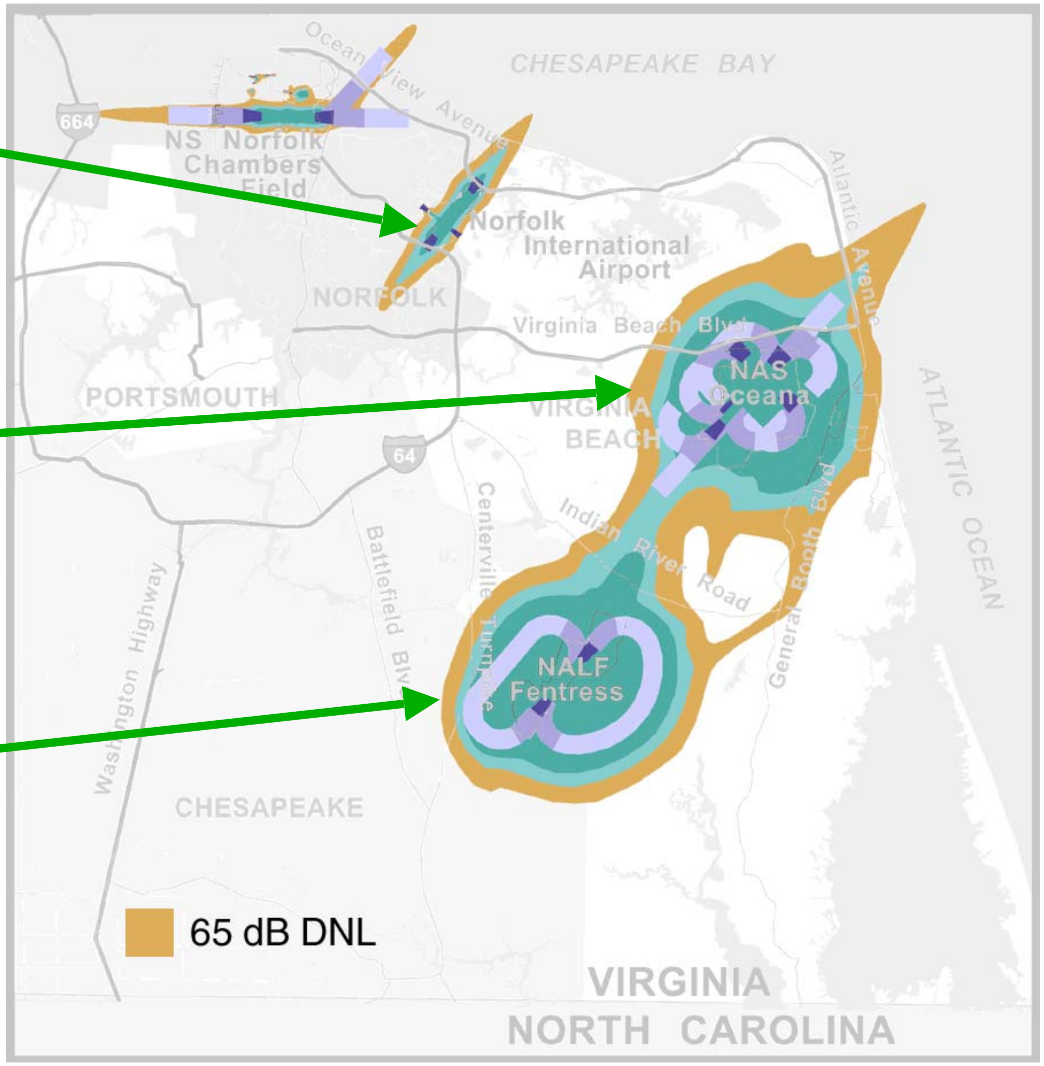
- Phase-out
  - 55% of U.S. fleet
  - 94% reduction in impact
  - During 6X mobility growth
  - $10B US cost
  - $43/person/DNLdB
  - TECHNOLOGY foundation
- $1B/yr in US for sound abatement
  - $960/person/DNLdB
  - Low cost effectiveness

COMMERCIAL AND MILITARY NOISE IMPACTS

Norfolk Intl. Airport
210 TO/day

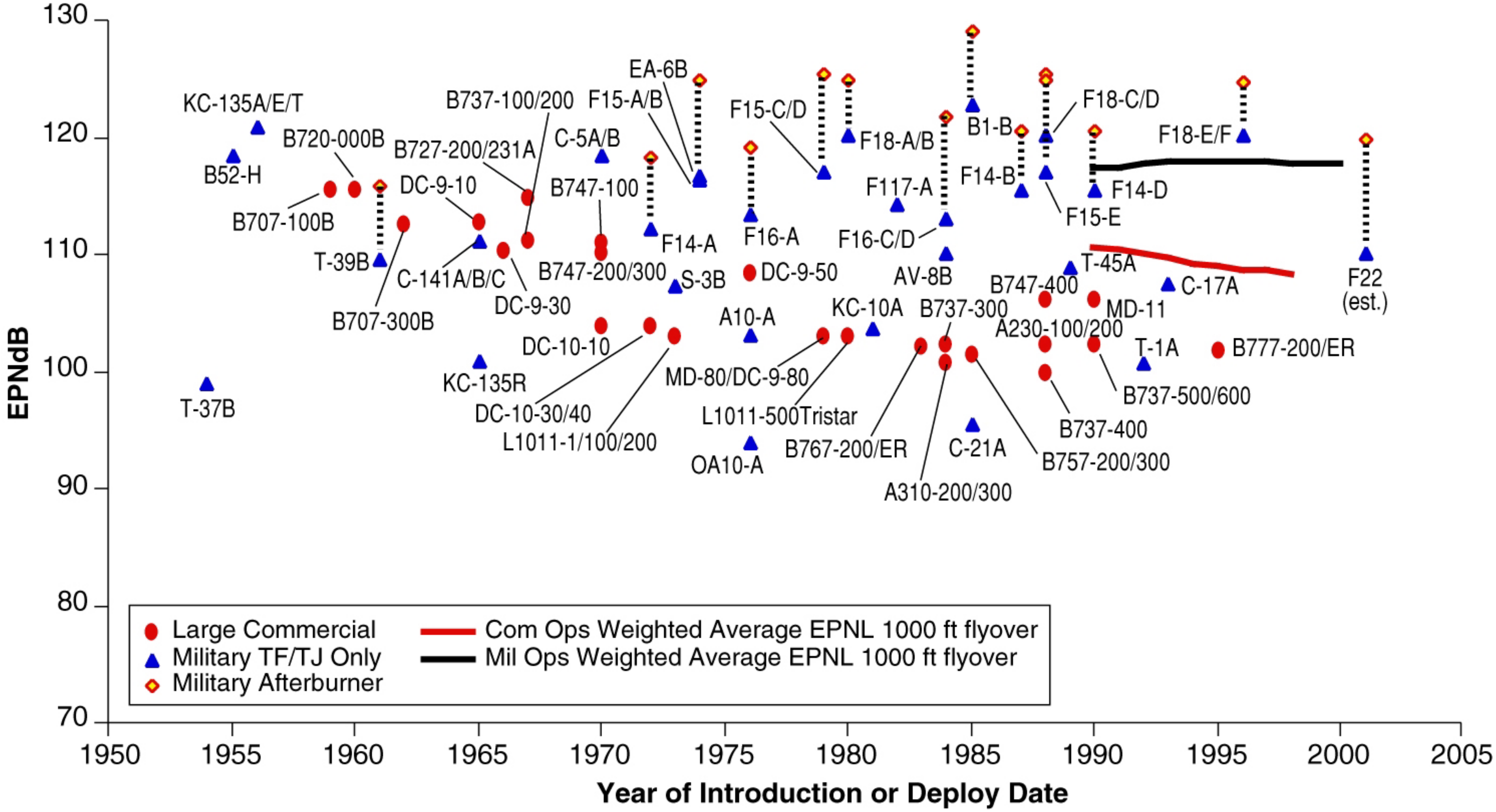
Oceana
121 TO/day
7 FCLP/day

Fentress
20 TO/day
354 FCLP/day



http://www.norfolkairport.com, http://www.nasoceana.navy.mil/AICUZ_files/frame.htm

AIRCRAFT NOISE TECHNOLOGY TRENDS



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)

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EMISSIONS IMPACTS

- **Local air quality** (NO_x, CO, UHC, 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
     - CO_2 and H_2O
     - NO_x through ozone production
     - Particulates (SO_x and soot) through heterogeneous chemistry and cloud nucleation

AIRCRAFT ENGINE EXHAUST

- **Composition**
  - **Reservoir and primary combustion products**

    CO_2, H_2O, N_2, O_2: O(10000-100000) ppmv
  - **Secondary products and pollutant emissions**

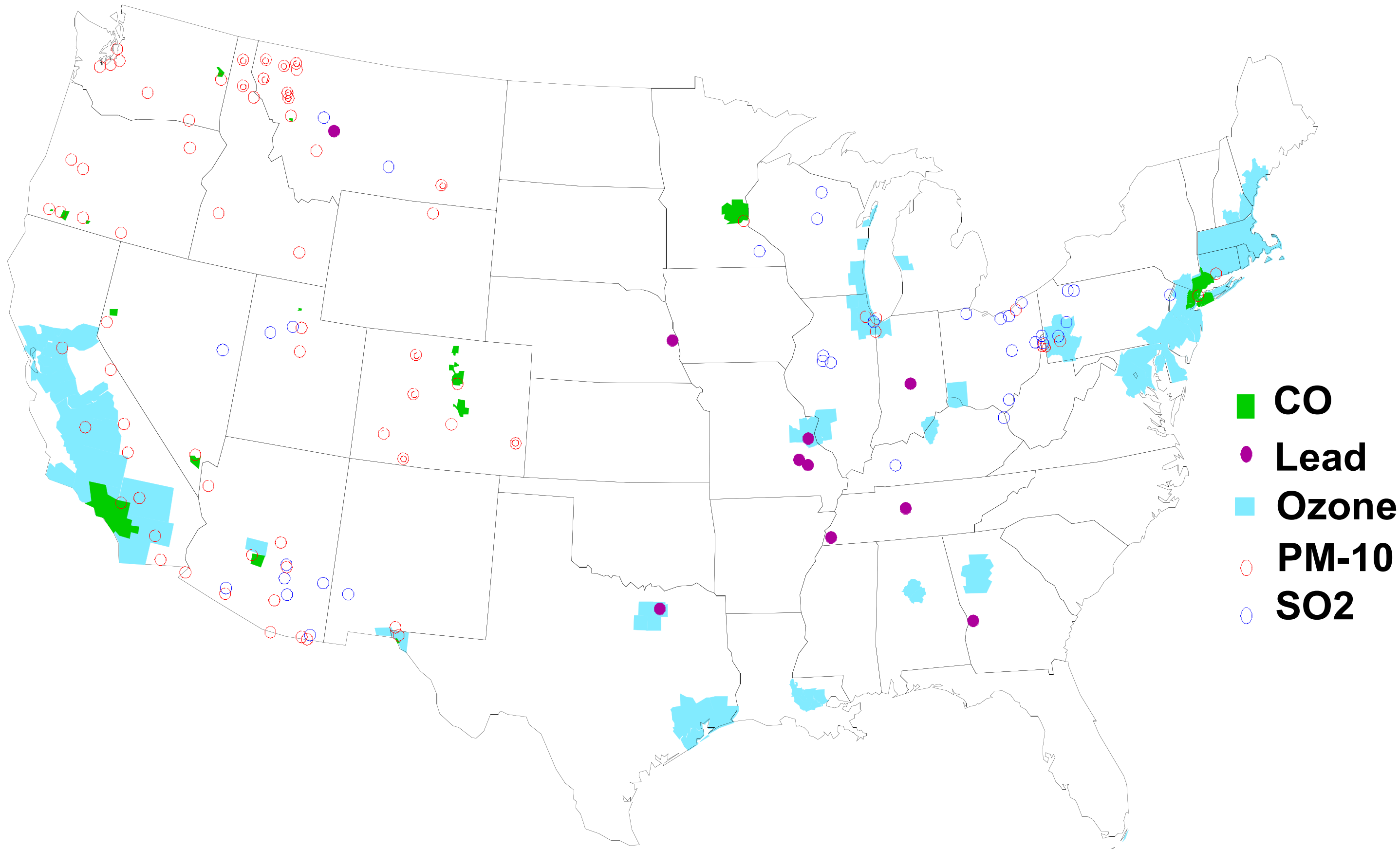
    CO, NO_x, HC, soot: O(1-100) ppmv
  - **Trace species constituents**

    NO_y, SO_x, HO_x: O(0.0001-0.1) ppmv
- **Most constituents play some role in atmospheric processes**
  - ***e.g*. If 100% of SO_2 in engine oxidizes to SO_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**

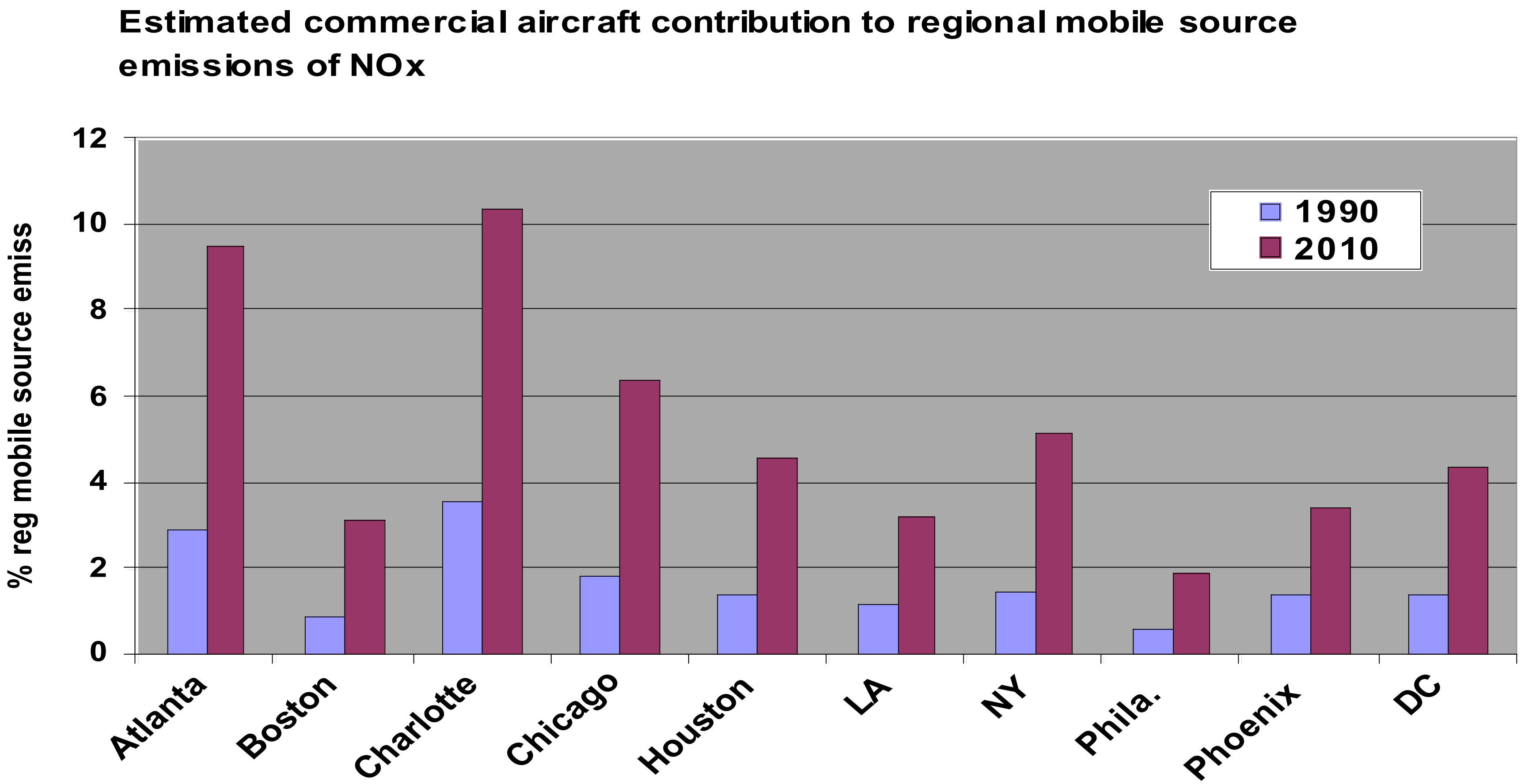
LOCATION OF “NON-ATTAINMENT” AREAS FOR CRITERIA POLLUTANTS AS OF SEPTEMBER, 1998



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)

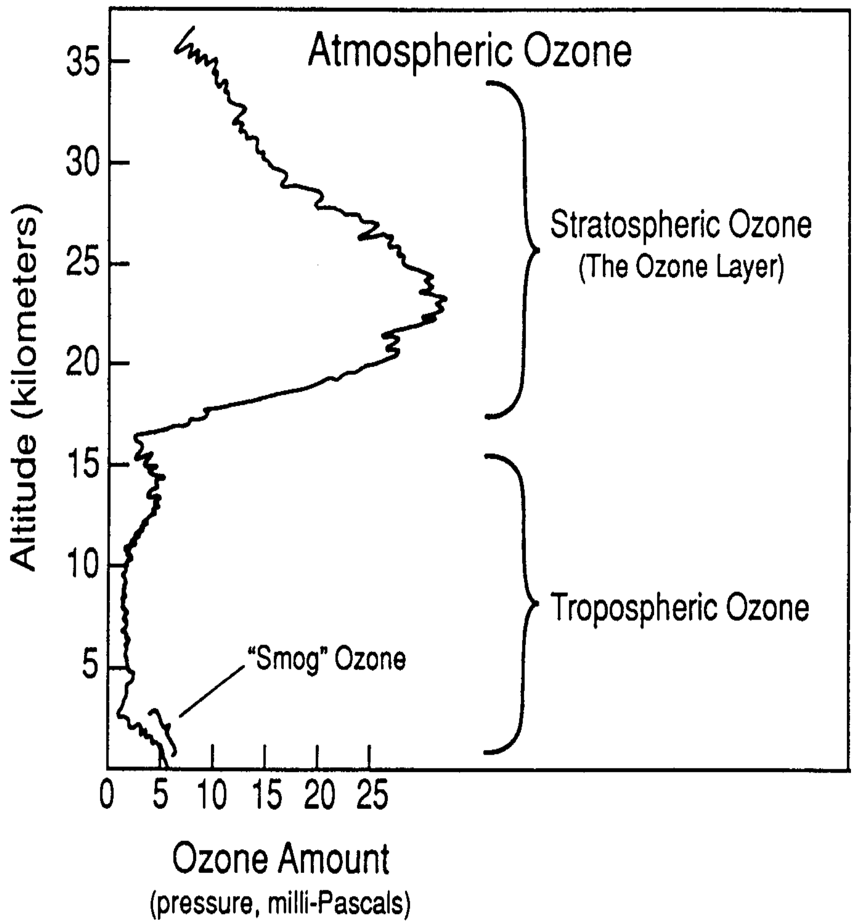
AIRCRAFT CONTRIBUTION TO REGIONAL MOBILE SOURCE NO_X EMISSIONS AT SELECTED US CITIES IS ESTIMATED TO INCREASE



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

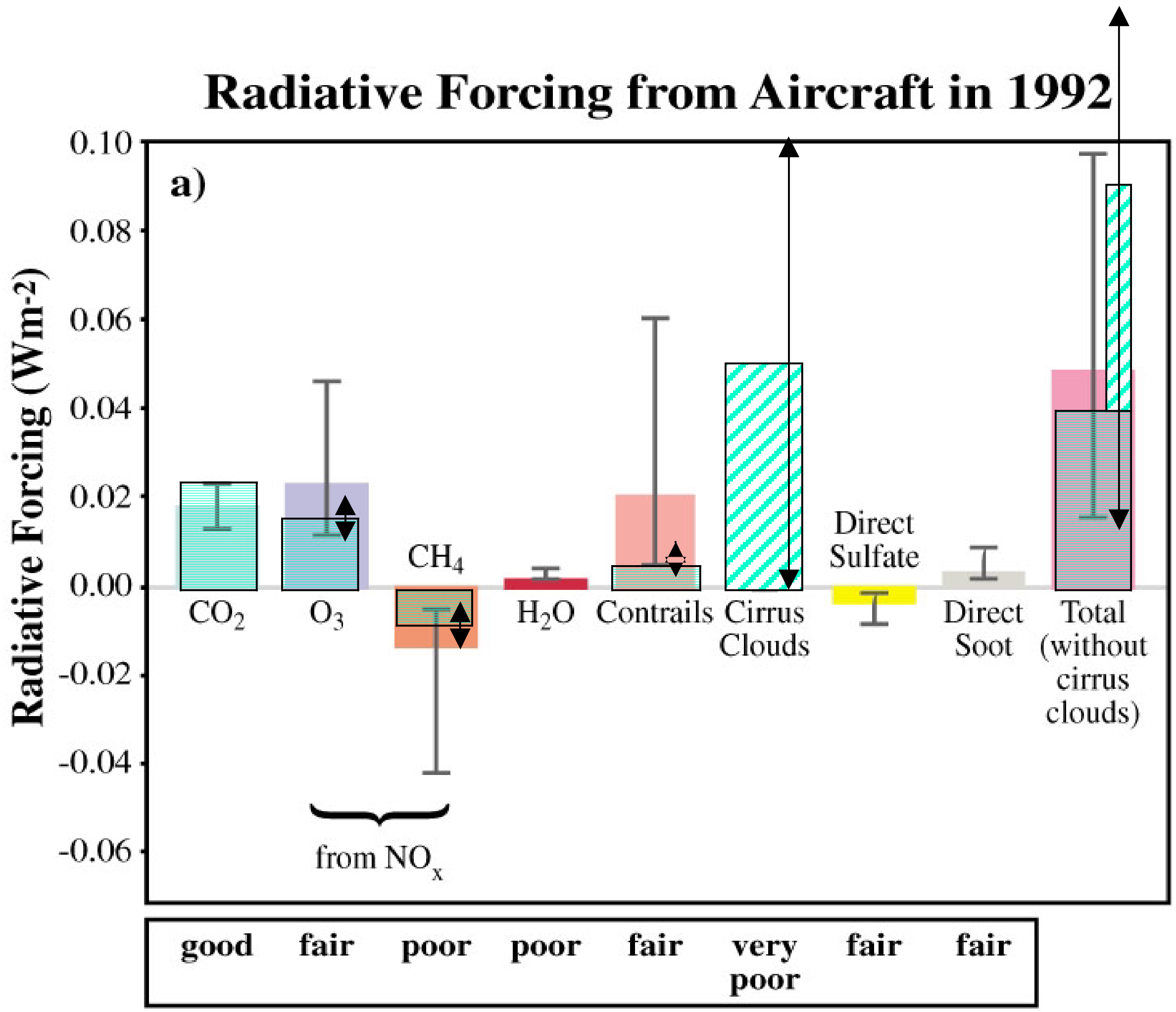


(NOAA, NASA, UNEP, WMO, "Scientific Assessment of Ozone Depletion: 1994")

- **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**

(IPCC, 1999)

SCIENTIFIC UNDERSTANDING IN 2003 vs. 1999



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
- 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**

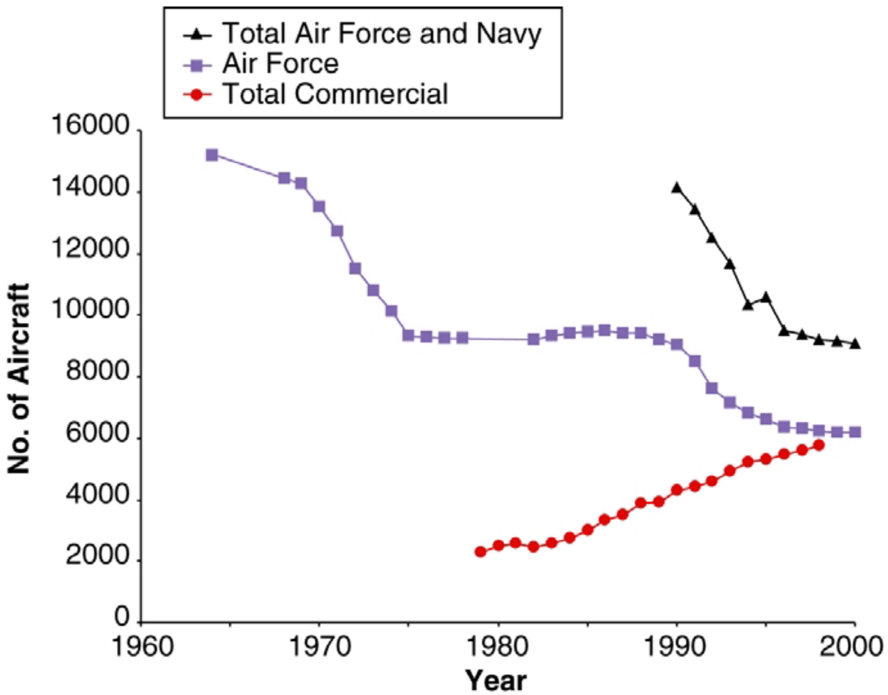
TECHNOLOGY CHOICES: BOEING

"**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)

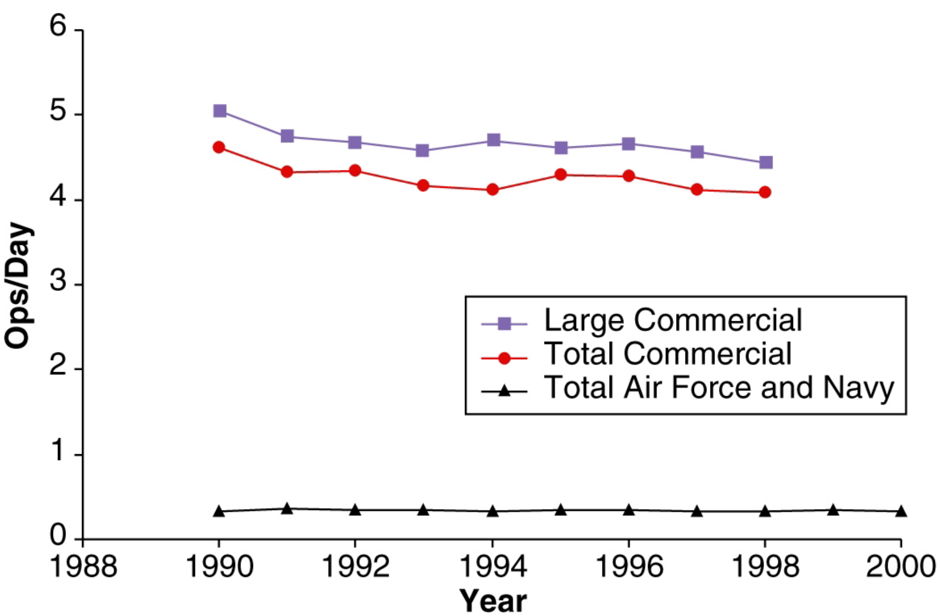
COMMERCIAL vs. MILITARY FLEET TRENDS

- **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

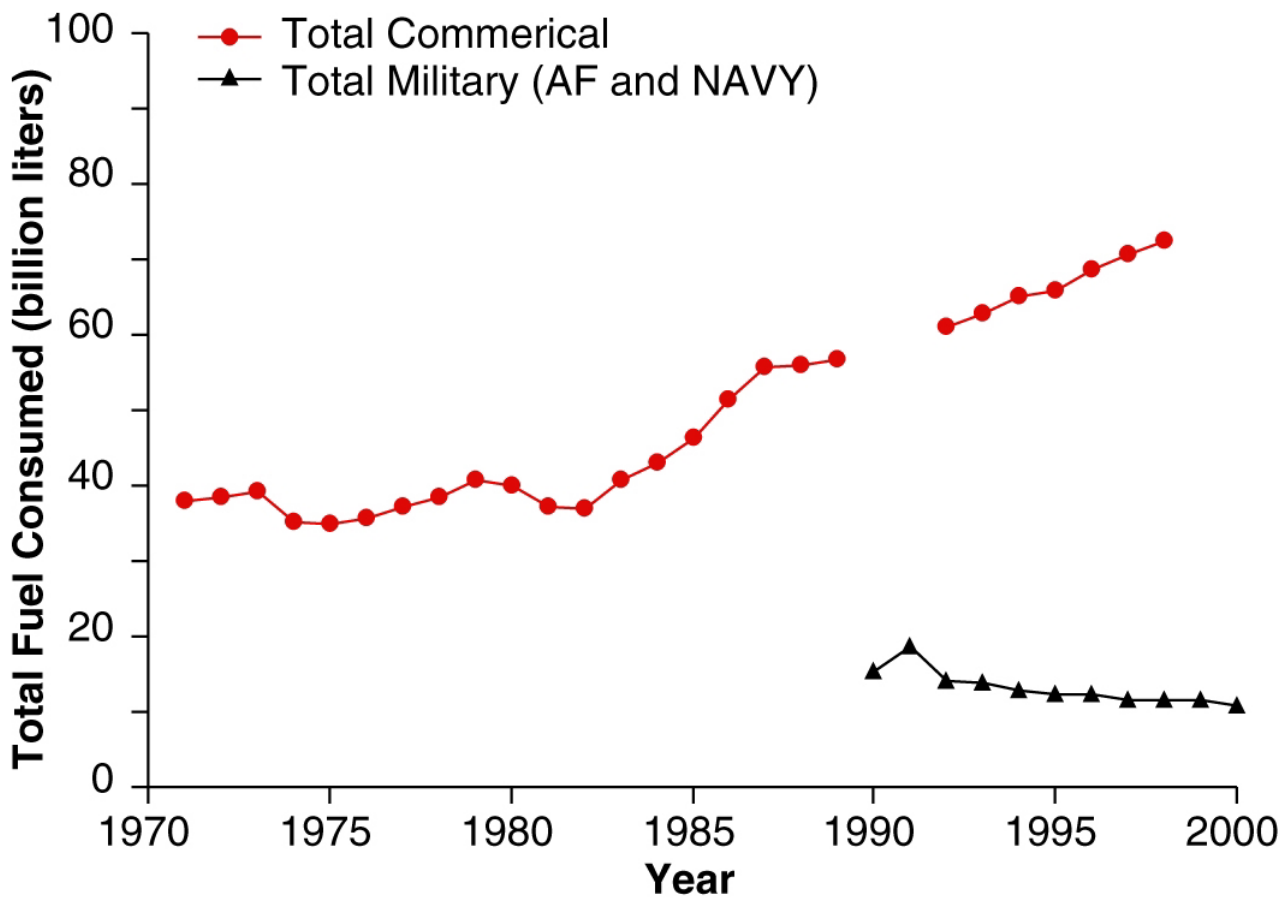


Flights/day

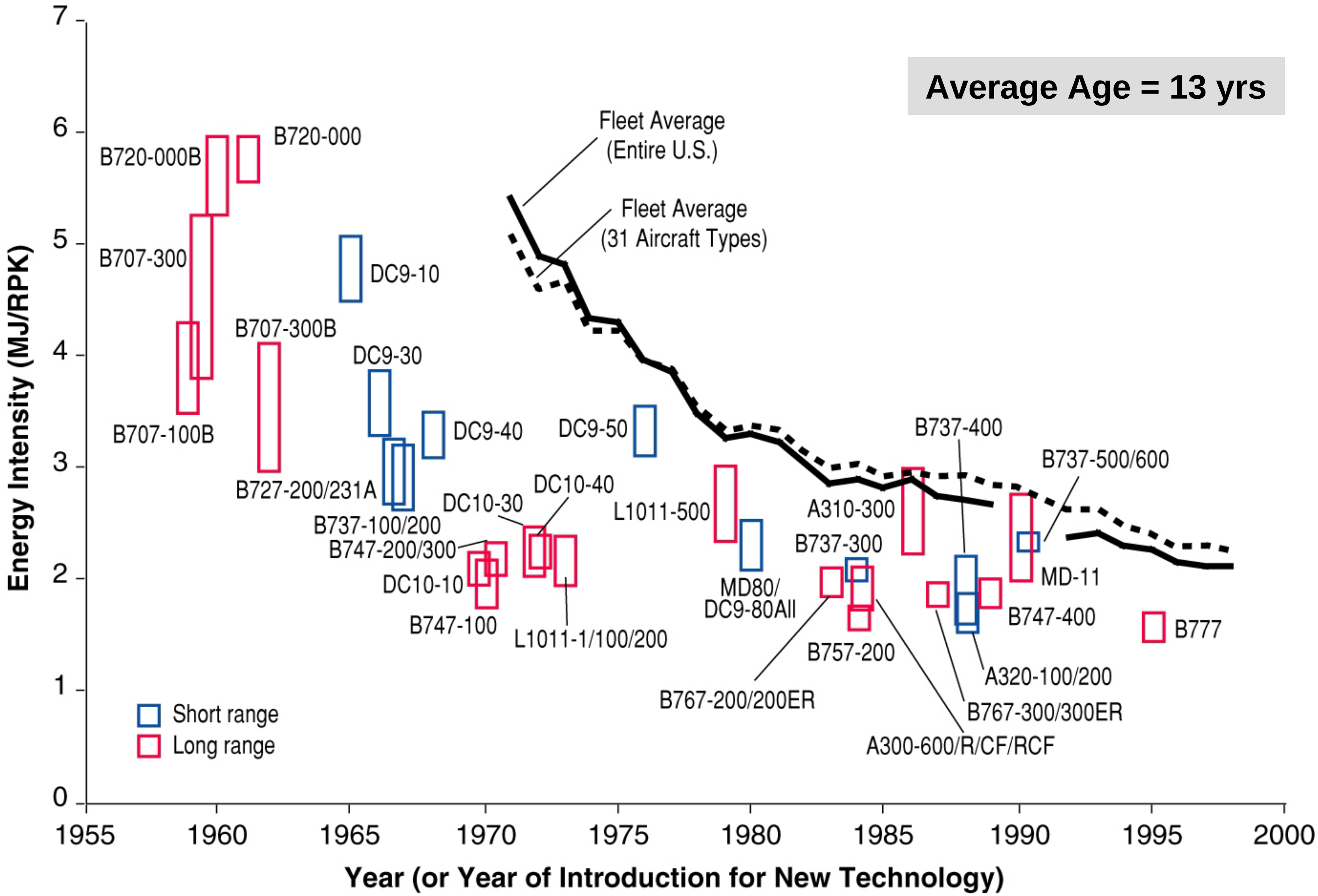


FUEL CONSUMPTION TRENDS

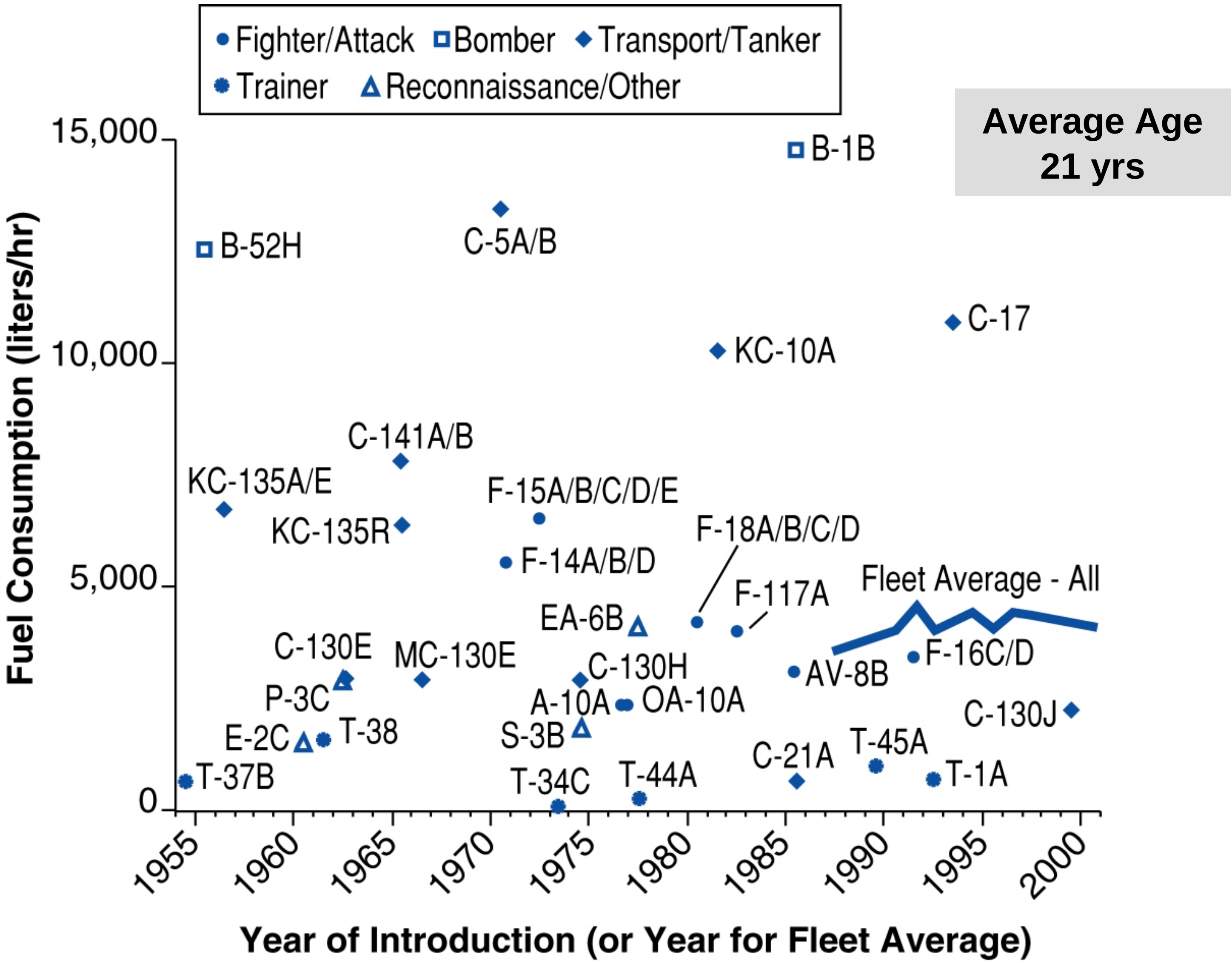
Aircraft responsible for 2%-3% of U.S fossil fuel use



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

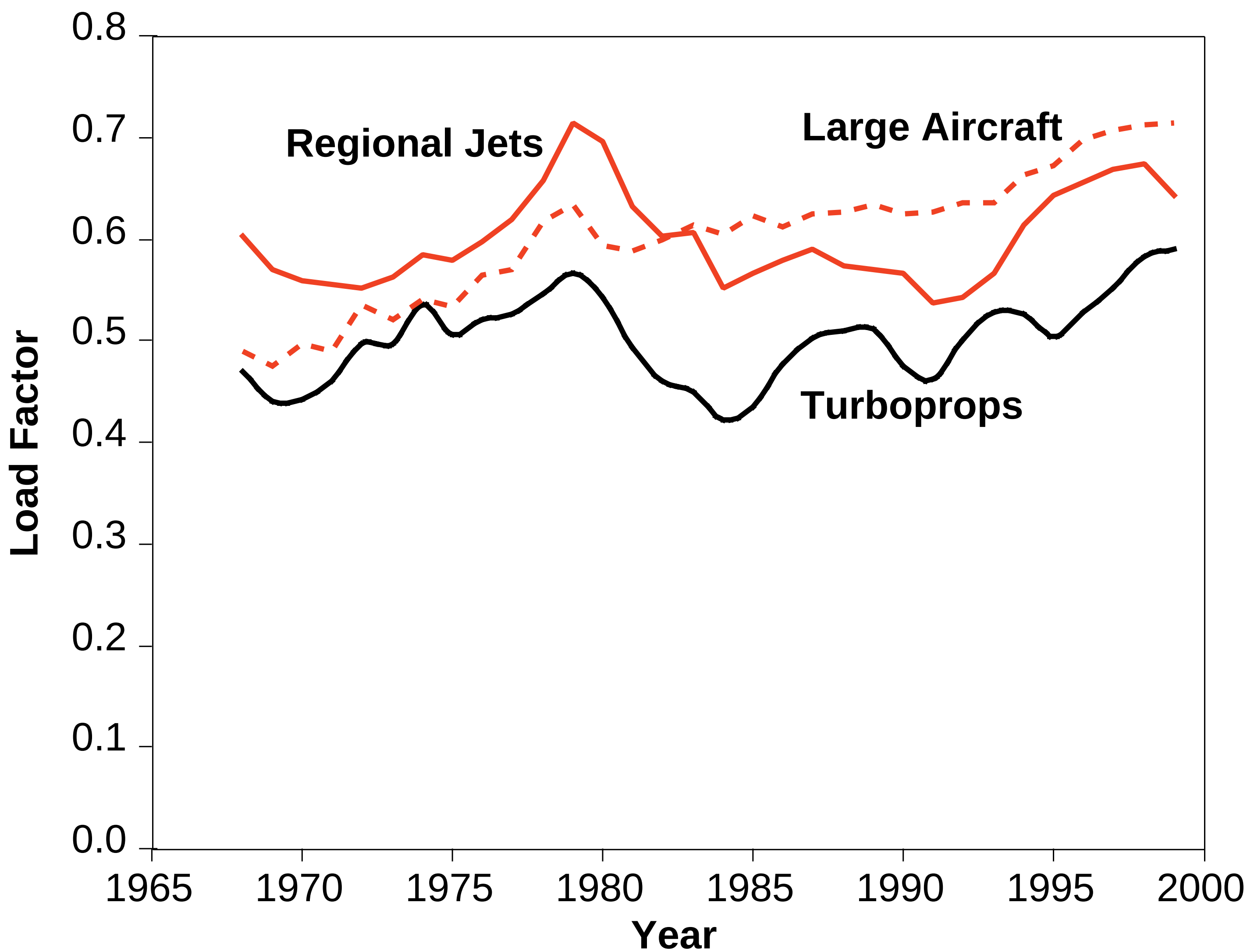
= Operations

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

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

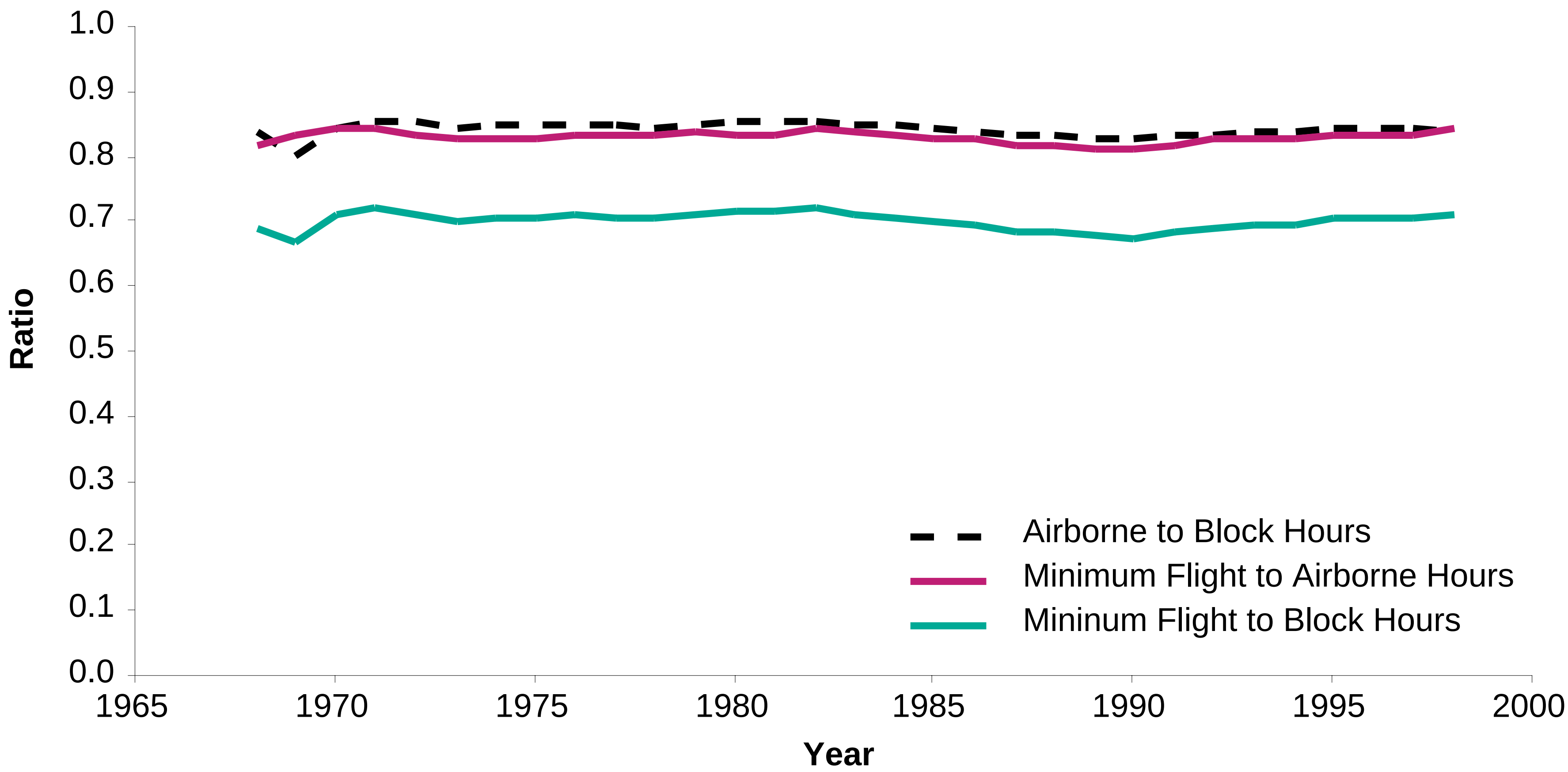
Use data to separate effects and understand influences of technology

TRENDS IN LOAD FACTOR



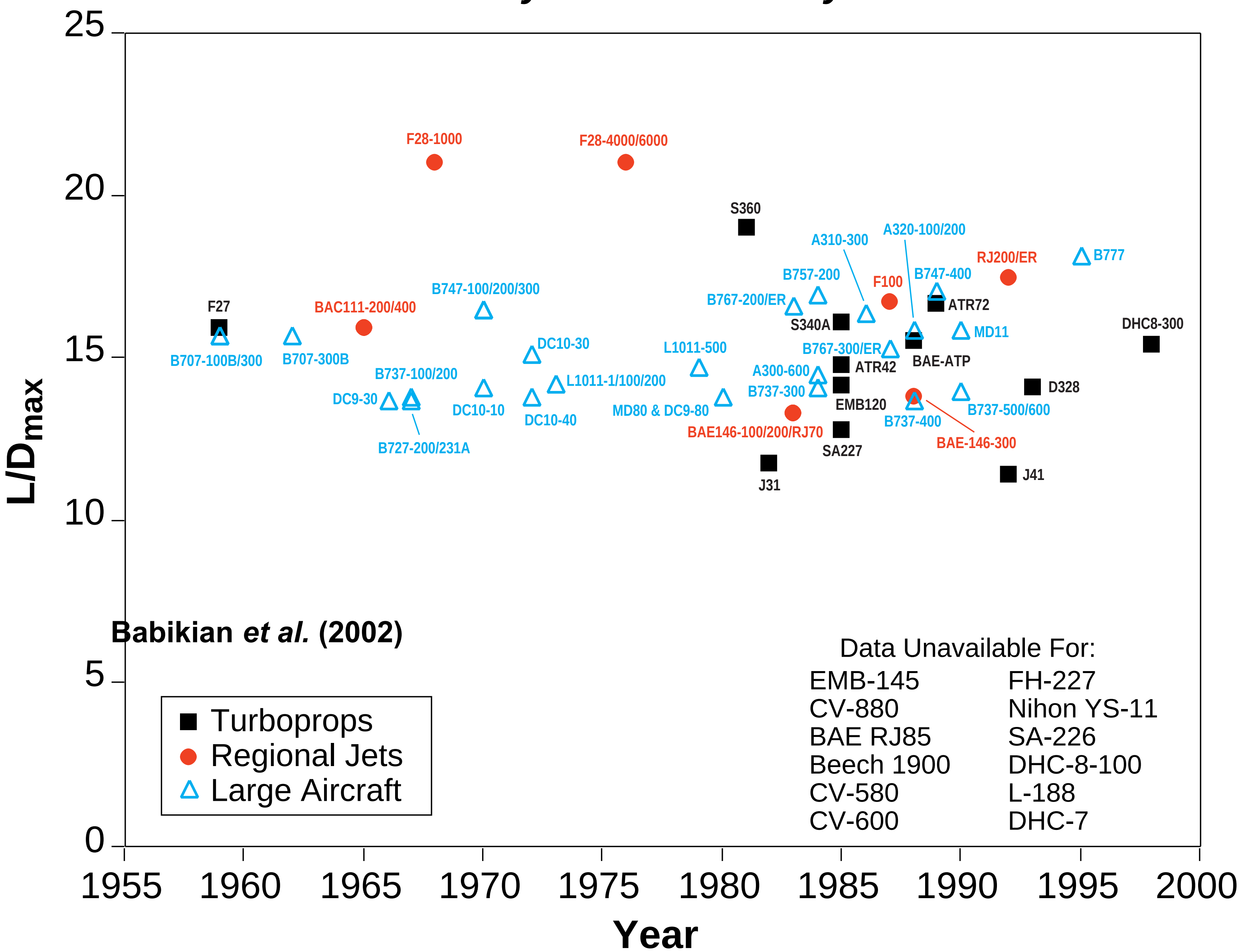
Babikian, Raffi, *The Historical Fuel Efficiency Characteristics of Regional Aircraft From Technological, Operational, and Cost Perspectives*, SM Thesis, Massachusetts Institute of Technology, June 2001

FLIGHT AND GROUND DELAYS



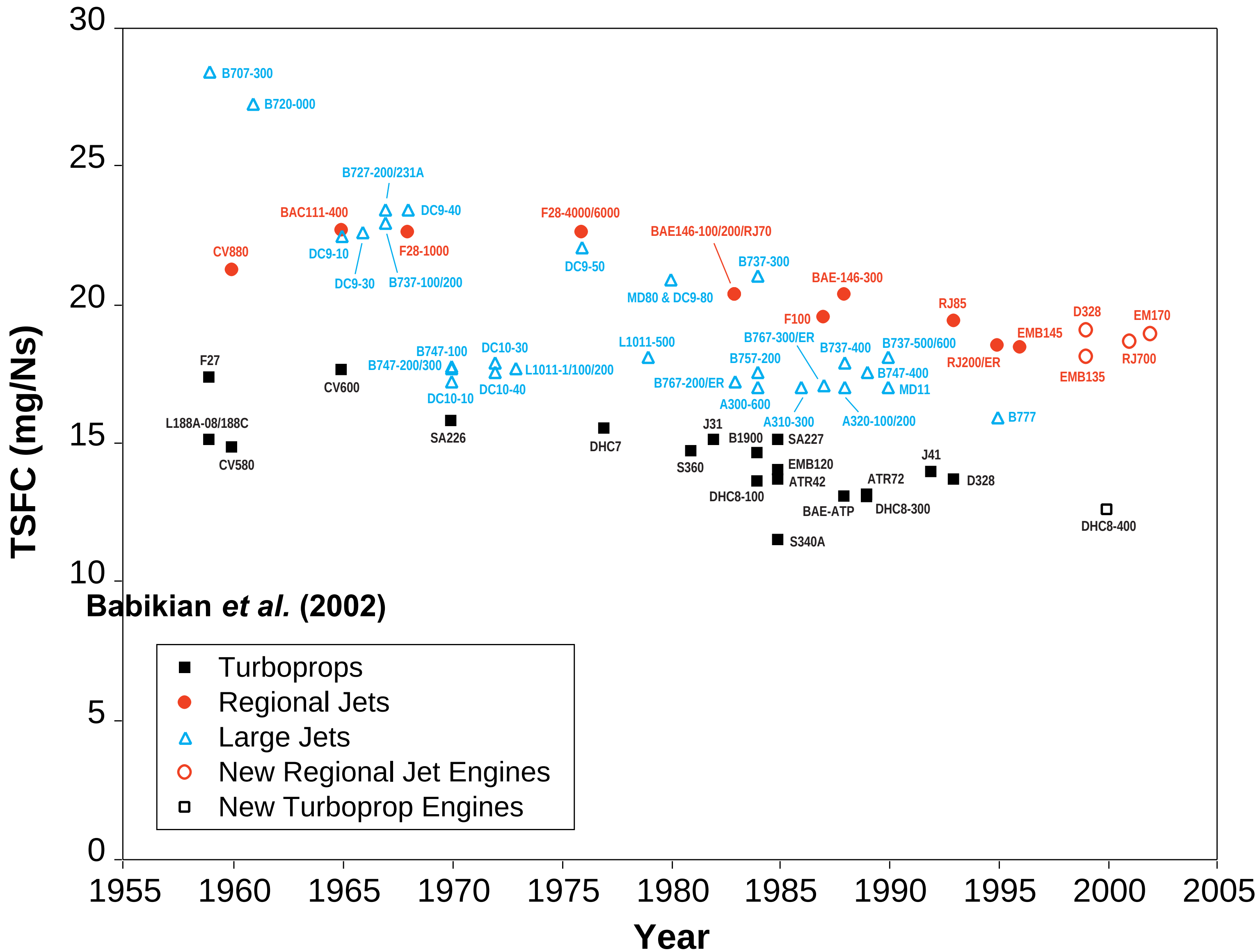
HISTORICAL TRENDS

Aerodynamic Efficiency



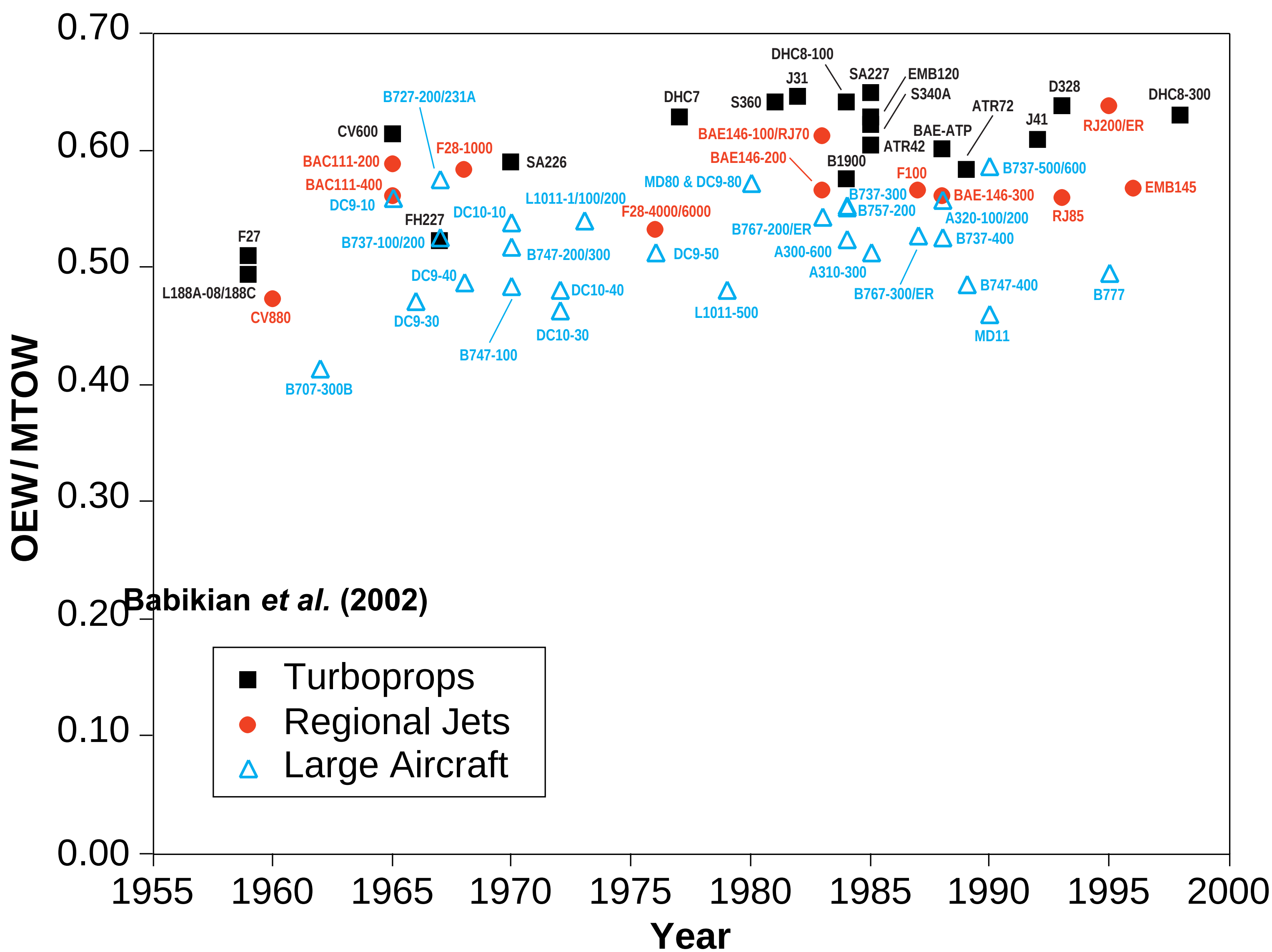
HISTORICAL TRENDS

Engine Efficiency



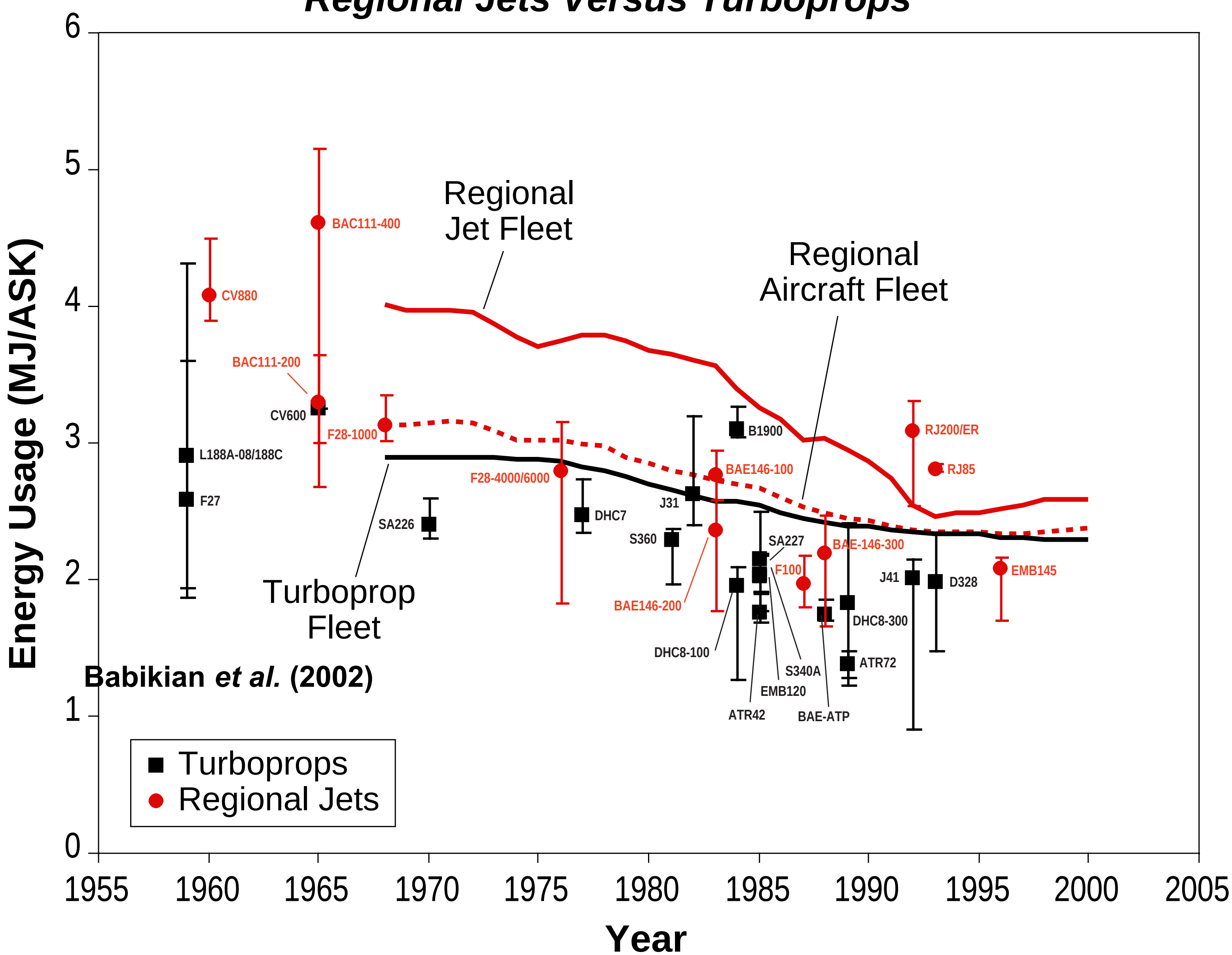
HISTORICAL TRENDS

Structural Efficiency



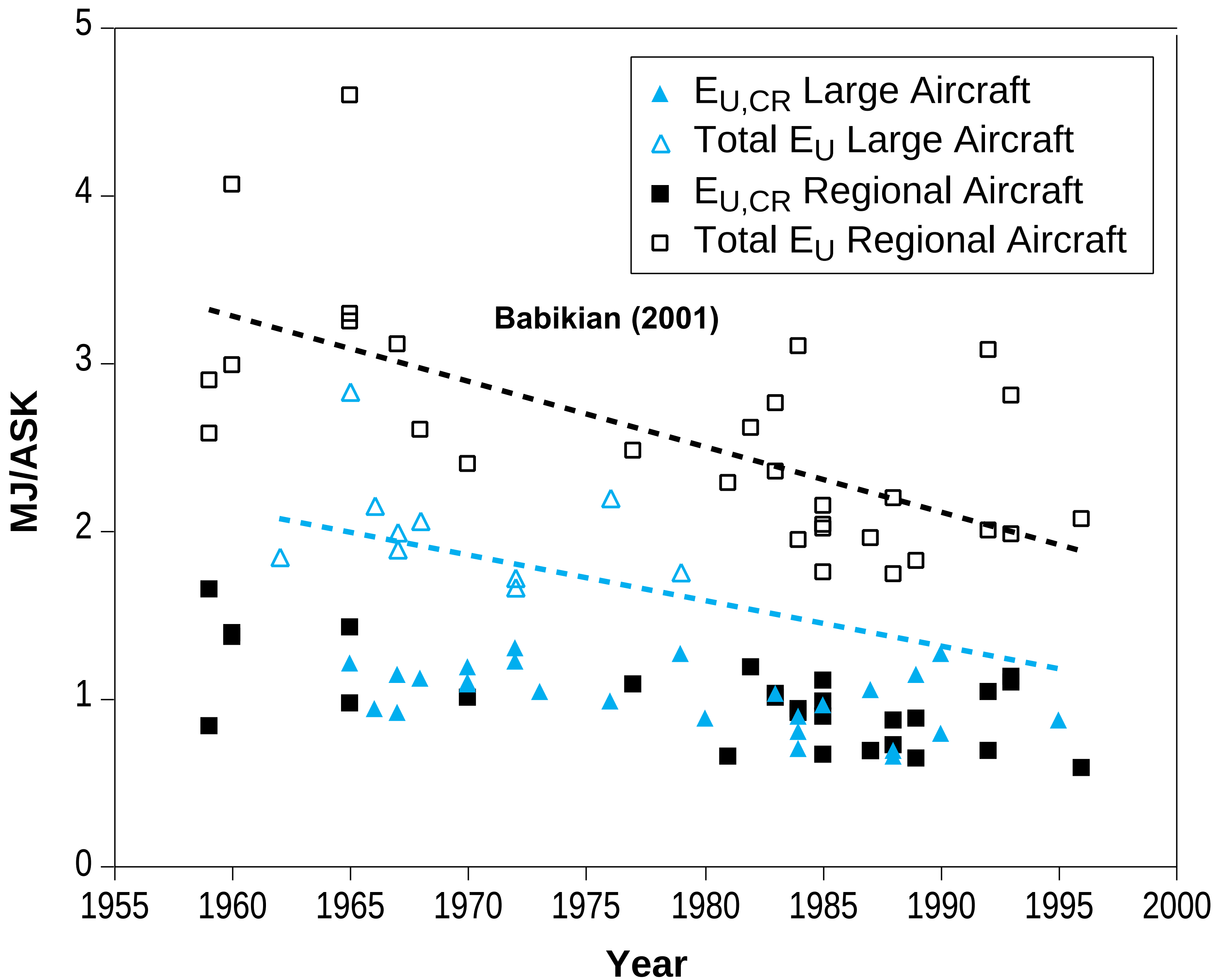
EFFICIENCY

Regional Jets Versus Turboprops



ENERGY USAGE

Total Versus Cruise

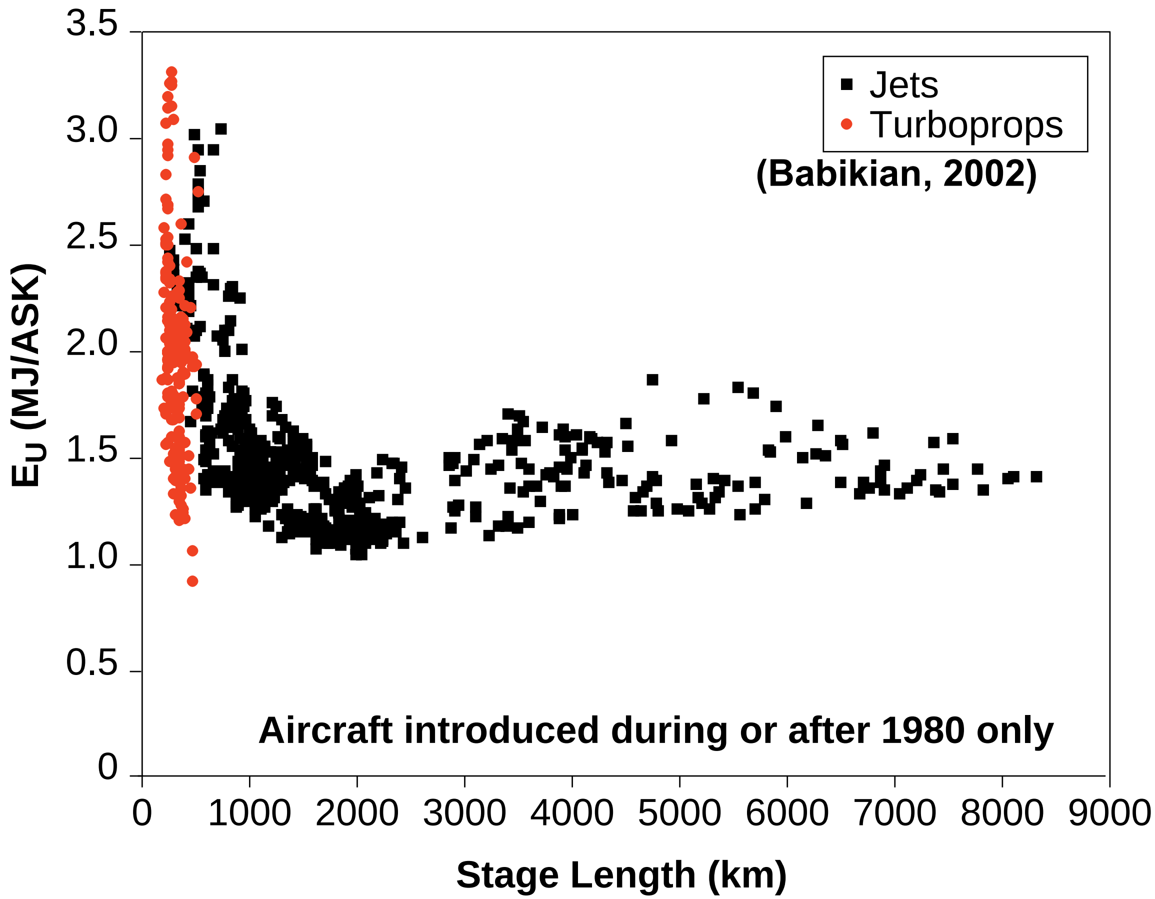


COMMERCIAL AIRCRAFT ENERGY INTENSITY TRENDS

- 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

SHORT HAUL AIRCRAFT

Facing Increasing Scrutiny

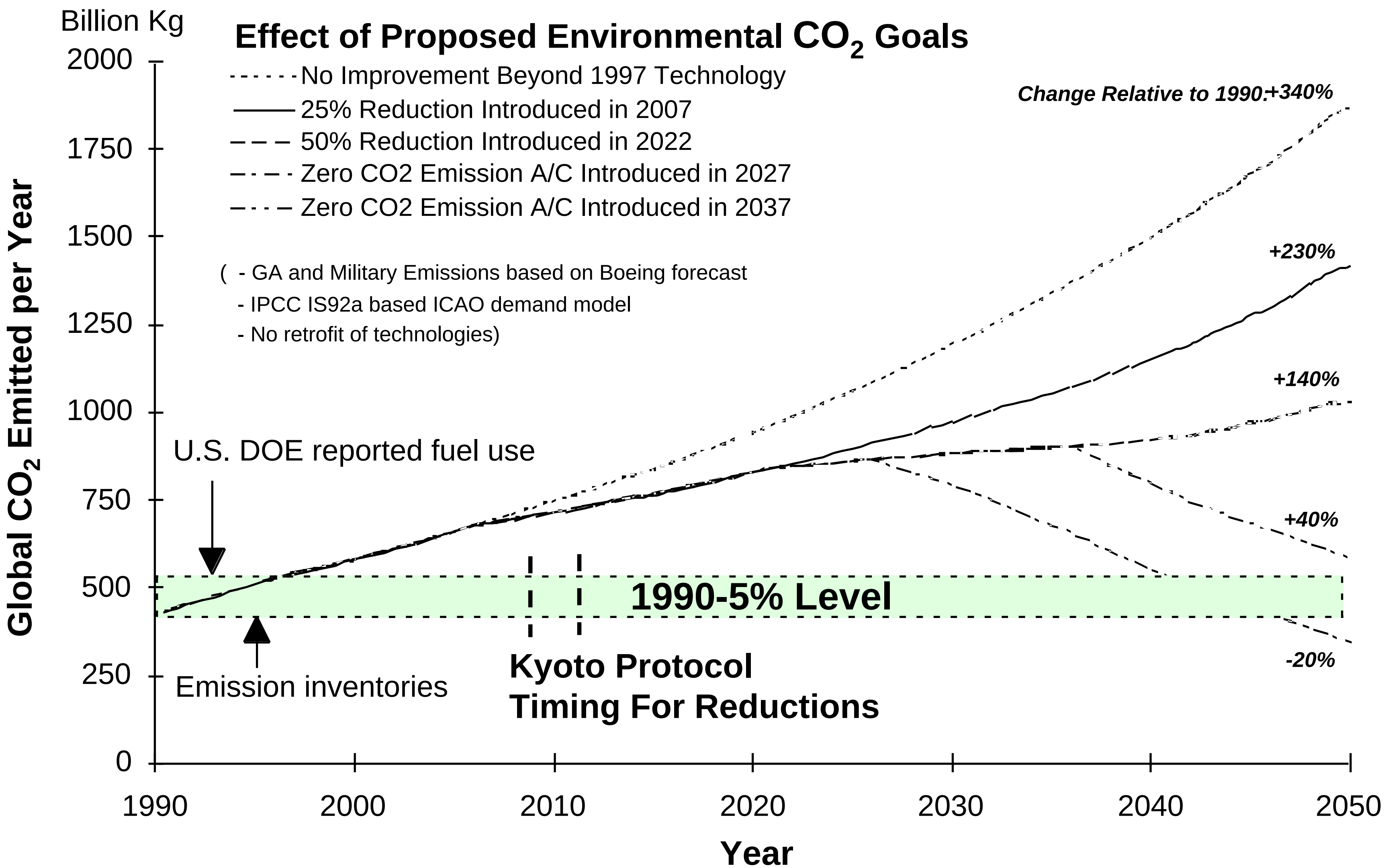


Royal Commission on the Environment (2002)

"…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)

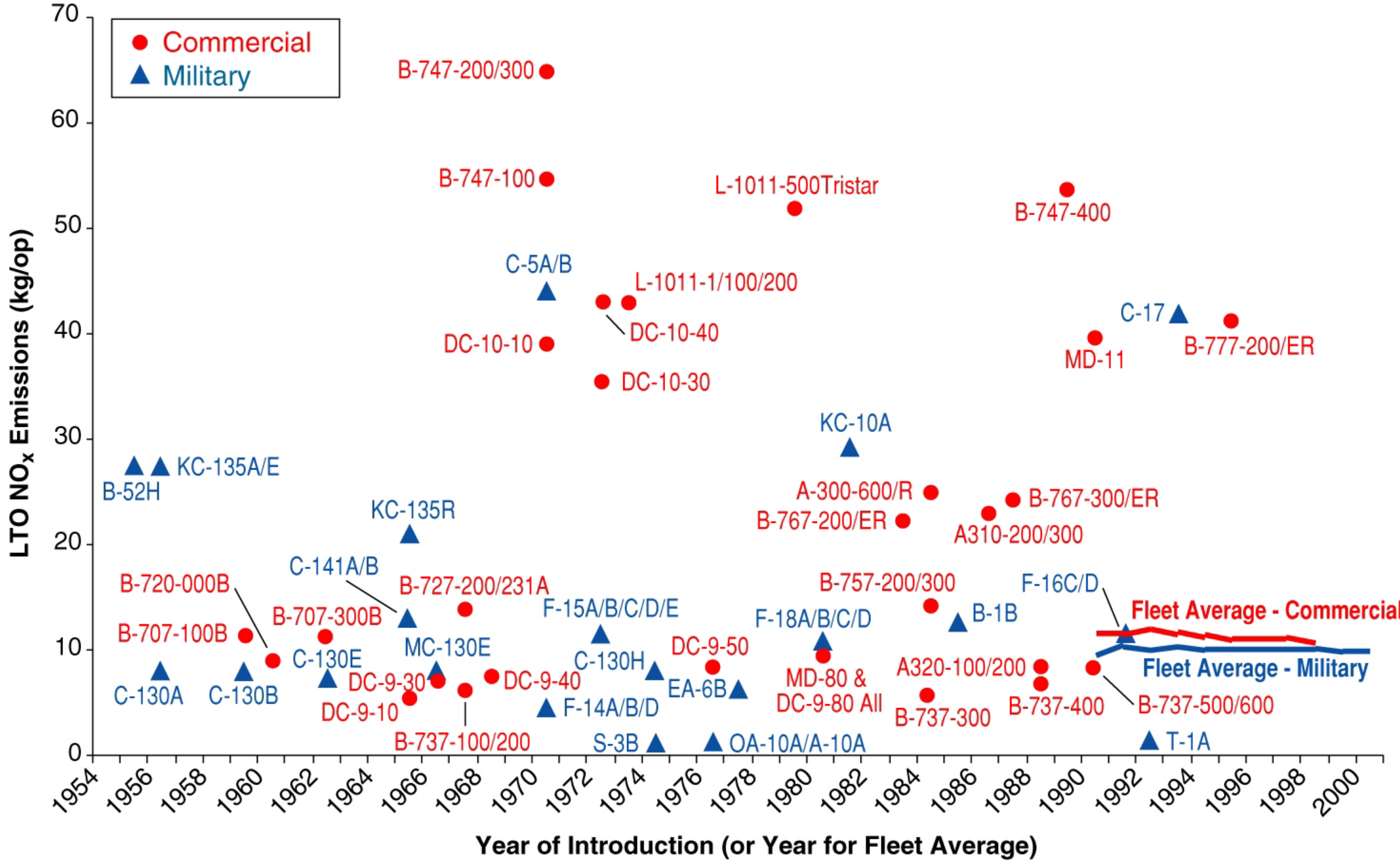
- Range/payload ~ fuel efficiency (commercial and military)
  - Thermal efficiency — High pressures and temperatures → **High NO_x**
  - Propulsive efficiency — Large mass flow with small velocity change → **Low Noise**
- Maneuverability (military)
  - High thrust-per-weight, small compact engine
- Supersonic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

(Maneuverability and supersonic flight:)

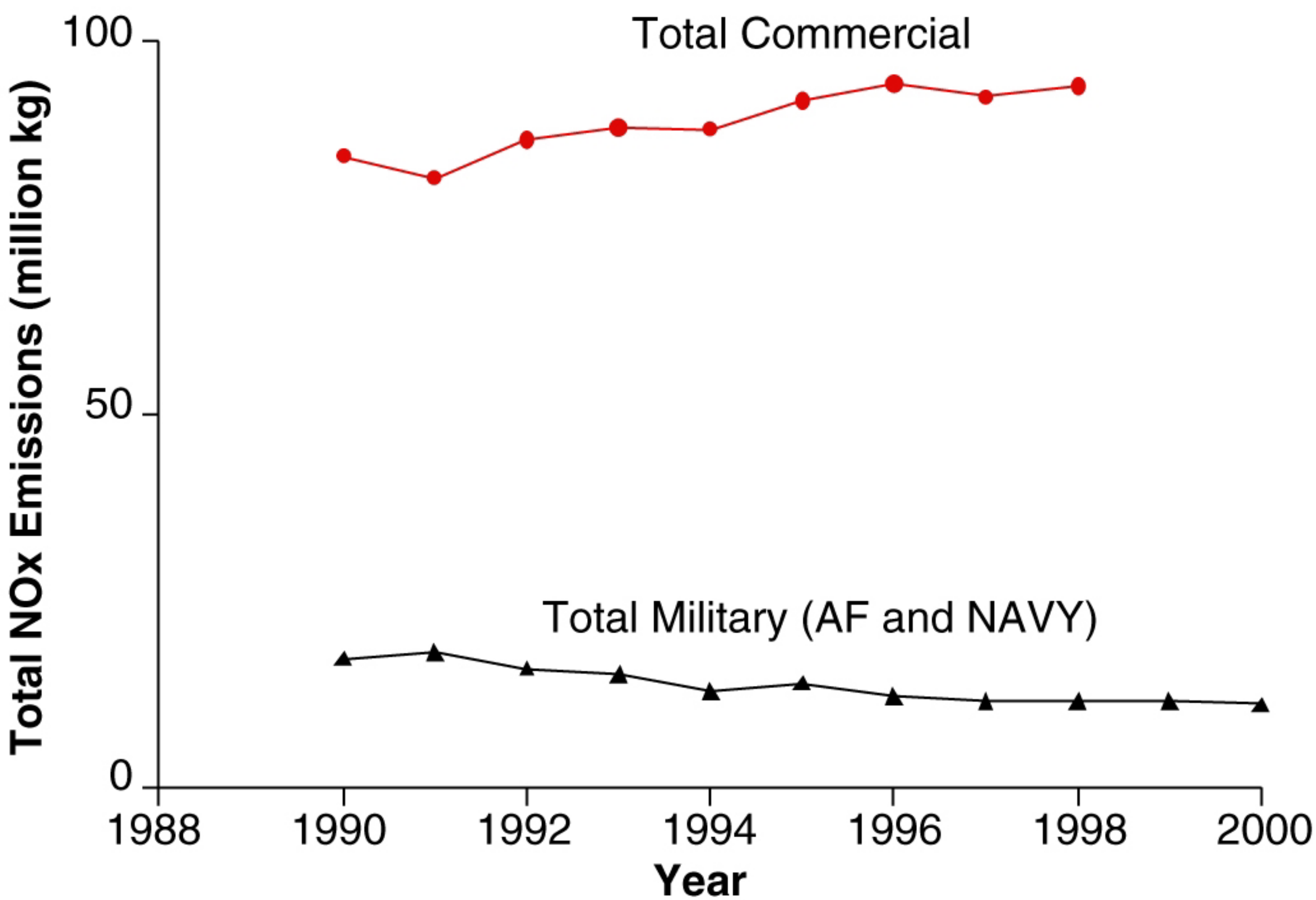
High energy conversion per unit volume (high temperatures and pressures) → **High NO_x**

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

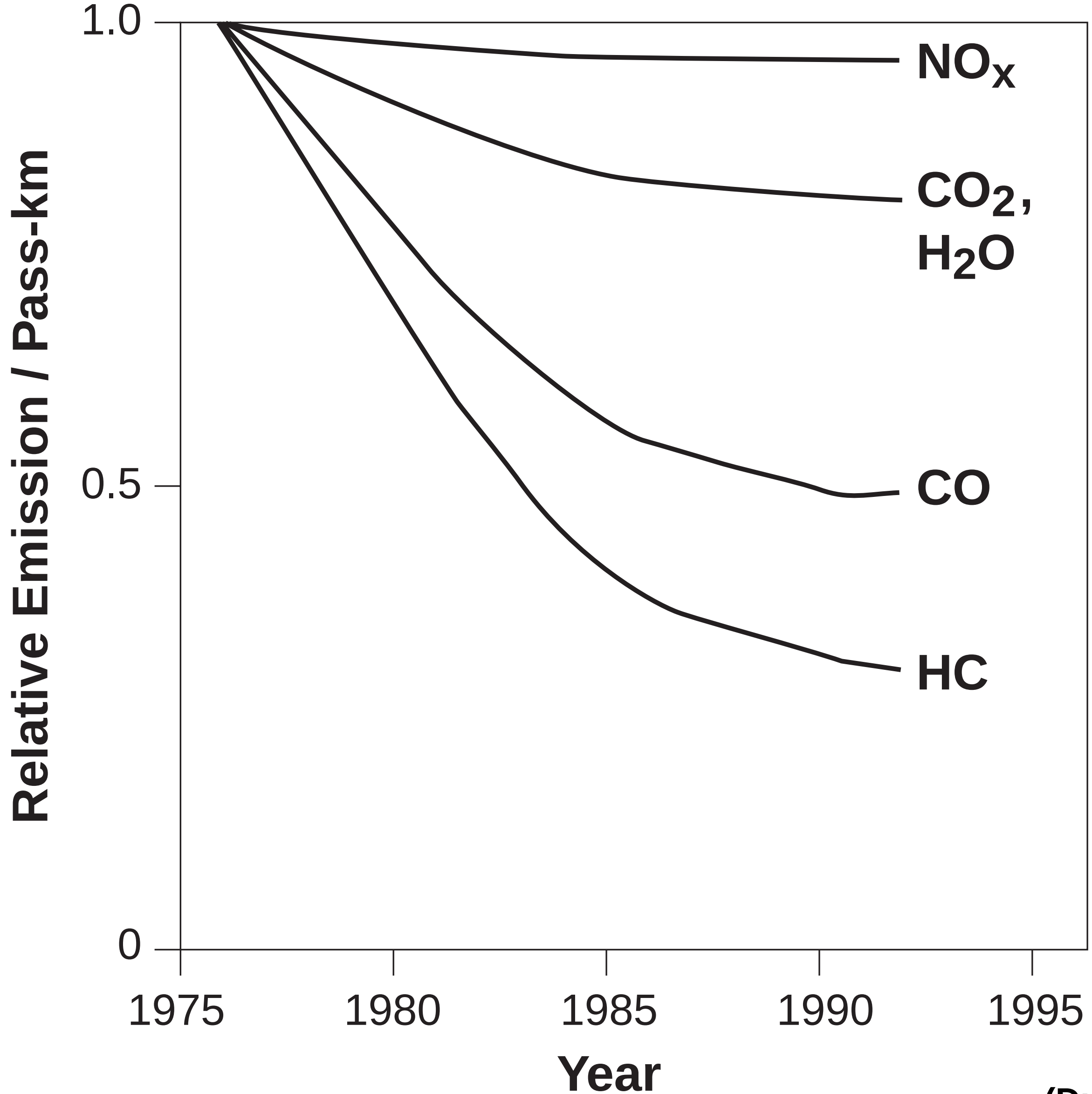
NO_x EMISSIONS TECHNOLOGY TRENDS



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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