Aviation Emissions

SYST 460/560
Lance Sherry (Ph.D.)

Jet Engine Fuel Burn Chemistry

CnHm+ S + N + O →

***CO + H O + N + O +** NOx + CO + SOx + Soot +UHC*

- **Fuel**
- **Air**
- **Products of Ideal Combustion**
- **Products of Non-ideal Combustion**

Type of Emissions

- Aircraft emit a complex mixture of air pollutants
- Local Air Quality emissions:
  - CO
  - Nox
  - Sox
  - unburnt HCs
  - PM (particulate matter)
- Atmospheric effects that contribute to Global Warming
  - CO2
  - water vapor

Effects of Emissions

- Atmospheric chemistry and physics of these emissions complex
- Effects of the different emissions on flora, fauna, and human health are complex and not fully understood

Inventory vs. Dispersion

- Inventory model
  - quantification net amounts of pollutants at an airport based on annual landing/takeoff (LTO) cycles
  - quantification net amounts of pollutants enroute based on time and thrust level in each phase
- Dispersion model
  - spatio-temporal concentrations of pollutants

Inventory vs. Dispersion

<u>Emissions Inventory Metrics</u>

- Quantify total amount of pollutants produced in period
- Criteria pollutants are CO, HC, NOx, SOx, PM(x)
- Not sensitive to lateral track location
- Sensitive to altitude, aircraft type, state

<u>Emissions Dispersion Metrics</u>

- Quantify concentration in time period
- Pollutant concentrations modeled at point locations
- Sensitive to track location, altitude, aircraft type, state
- <u>*National Ambient Air Quality Standards*</u> sets threshold concentrations

Regulations

- Clean Air Act and amendments (1963, 1970, 1977, 1990) have resulted in a broad regulatory framework.
- EPA’s National Ambient Air Quality Standards (NAAQS) set primary and secondary standards to protect public health (primary) and public welfare (secondary).
- States are required to submit State Implementation Plans (SIPs) for monitoring and controlling each pollutant in the NAAQS to EPA
  - EPA has approval authority.

Regulations - NAAQS

- EPA has set National Ambient Air Quality Standards for six principal pollutants, which are called "criteria" pollutants. Units of measure for the standards are parts per million (ppm) by volume, parts per billion (ppb) by volume, and micrograms per cubic meter of air ($\mu g/m^3$).
- Areas or regions violating these limits are designated to be in <u>non-attainment areas</u>

Regulations - NAAQS

Pollutant [final rule cite]		Primary/ Secondary	Averaging Time	Level	Form
Carbon Monoxide [76 FR 54294, Aug 31, 2011]		primary	8-hour	9 ppm	Not to be exceeded more than once per year
			1-hour	35 ppm	
Lead [73 FR 66964, Nov 12, 2008]		primary and secondary	Rolling 3 month average	0.15 µg/m^3 [1]	Not to be exceeded
Nitrogen Dioxide [75 FR 6474, Feb 9, 2010] [61 FR 52852, Oct 8, 1996]		primary	1-hour	100 ppb	98th percentile, averaged over 3 years
		primary and secondary	Annual	53 ppb [2]	Annual Mean
Ozone [73 FR 16436, Mar 27, 2008]		primary and secondary	8-hour	0.075 ppm [3]	Annual fourth-highest daily maximum 8-hr concentration, averaged over 3 years
Particle Pollution [71 FR 61144, Oct 17, 2006]	$PM_{2.5}$	primary and secondary	Annual	15 µg/m^3	annual mean, averaged over 3 years
			24-hour	35 µg/m^3	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24-hour	150 µg/m^3	Not to be exceeded more than once per year on average over 3 years
Sulfur Dioxide [75 FR 35520, Jun 22, 2010] [38 FR 25678, Sept 14, 1973]		primary	1-hour	75 ppb [4]	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		secondary	3-hour	0.5 ppm	Not to be exceeded more than once per year

as of October 2011

Inventory Modeling – High Altitude

- Inventory above 3000 feet uses complex
- technique,
  - Methodology under development
- Boeing Method 2 uses fuel flow at altitude and modifies the standard ICAO emission indices

Inventory Modeling – Low Altitude

- Low-altitude methodology is well established, and is based on times in *operational mode*, fuel rates, and emission indices

Pollutant mass per flight =

Neng * tmode * fuelflowmode * EImode

- Pollutant inventory = Σall_flights (pollutant mass per flight)

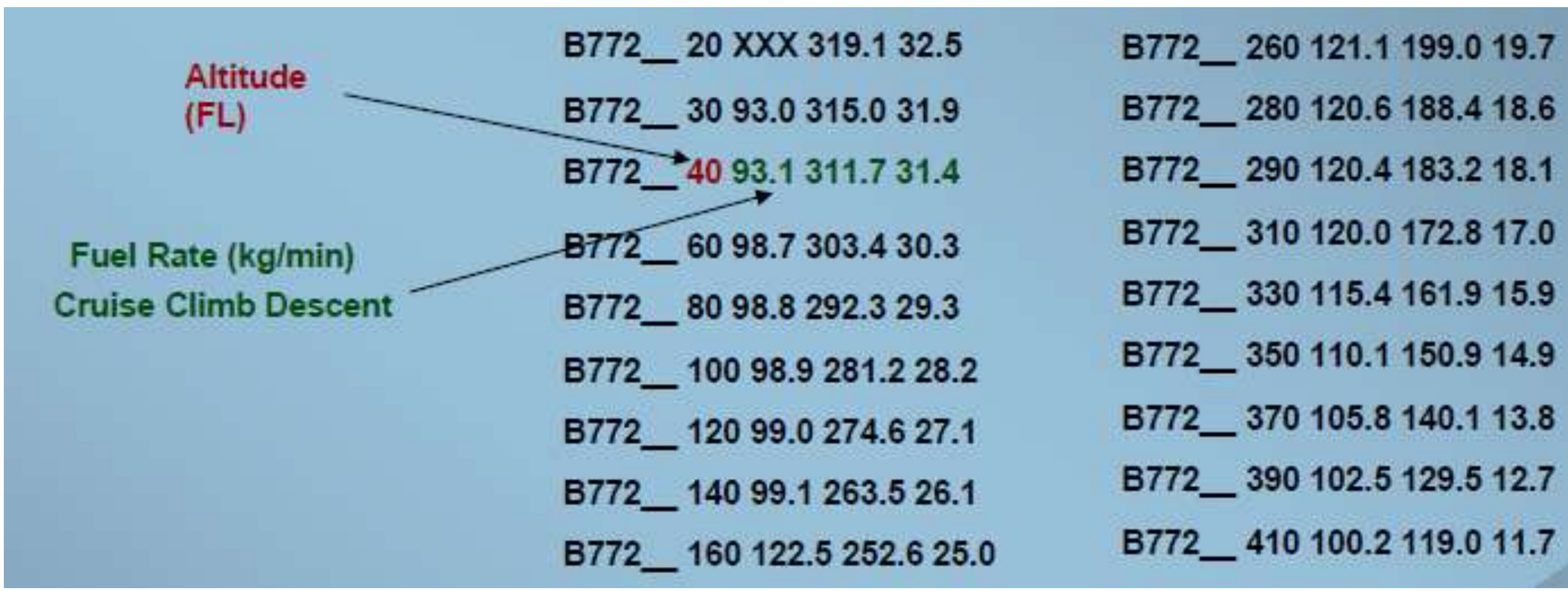
Inventory Modeling – Emissions Index

Different pollutant production rates for engines by mode of operation (one engine from about 470 in EDMS 4.1) (modes: 1=approach; 2=climb-out; 3=takeoff; 4=taxi/idle)

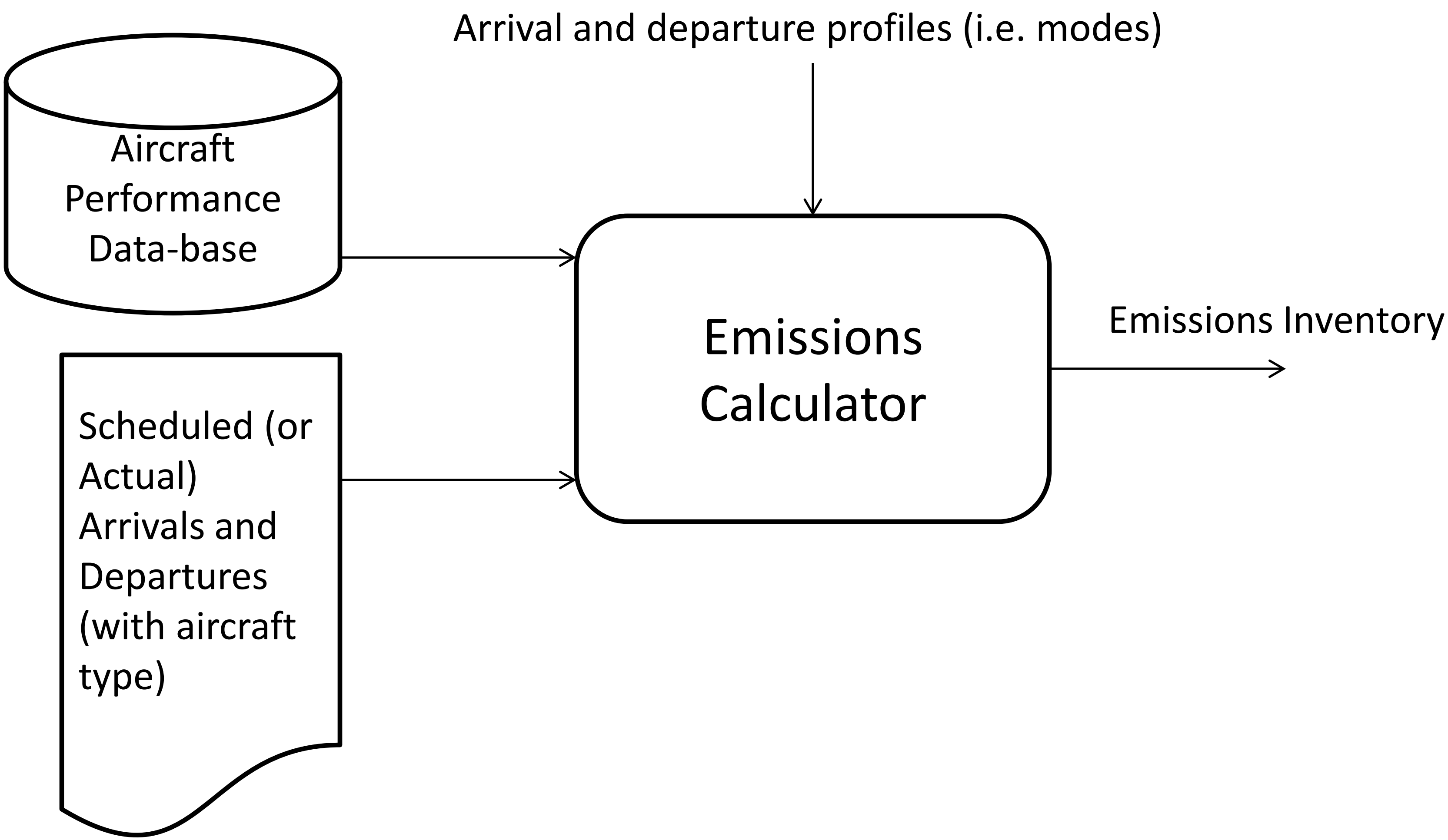
ENG_NAME	MODE	CO_EI	HC_EI	NOX_EI	SOX_EI	PART_EI	FUEL_KG/S
CFM56-7B20	1	3,200000	0,100000	9,500000	1,000000	0,000000	0,274000
CFM56-7B20	2	0,500000	0,100000	17,400000	1,000000	0,000000	0,761000
CFM56-7B20	3	0,600000	0,100000	20,500000	1,000000	0,000000	0,913000
CFM56-7B20	4	25,900000	3,100000	4,300000	1,000000	0,000000	0,100000

Inventory Modeling – Fuel Flow Rates

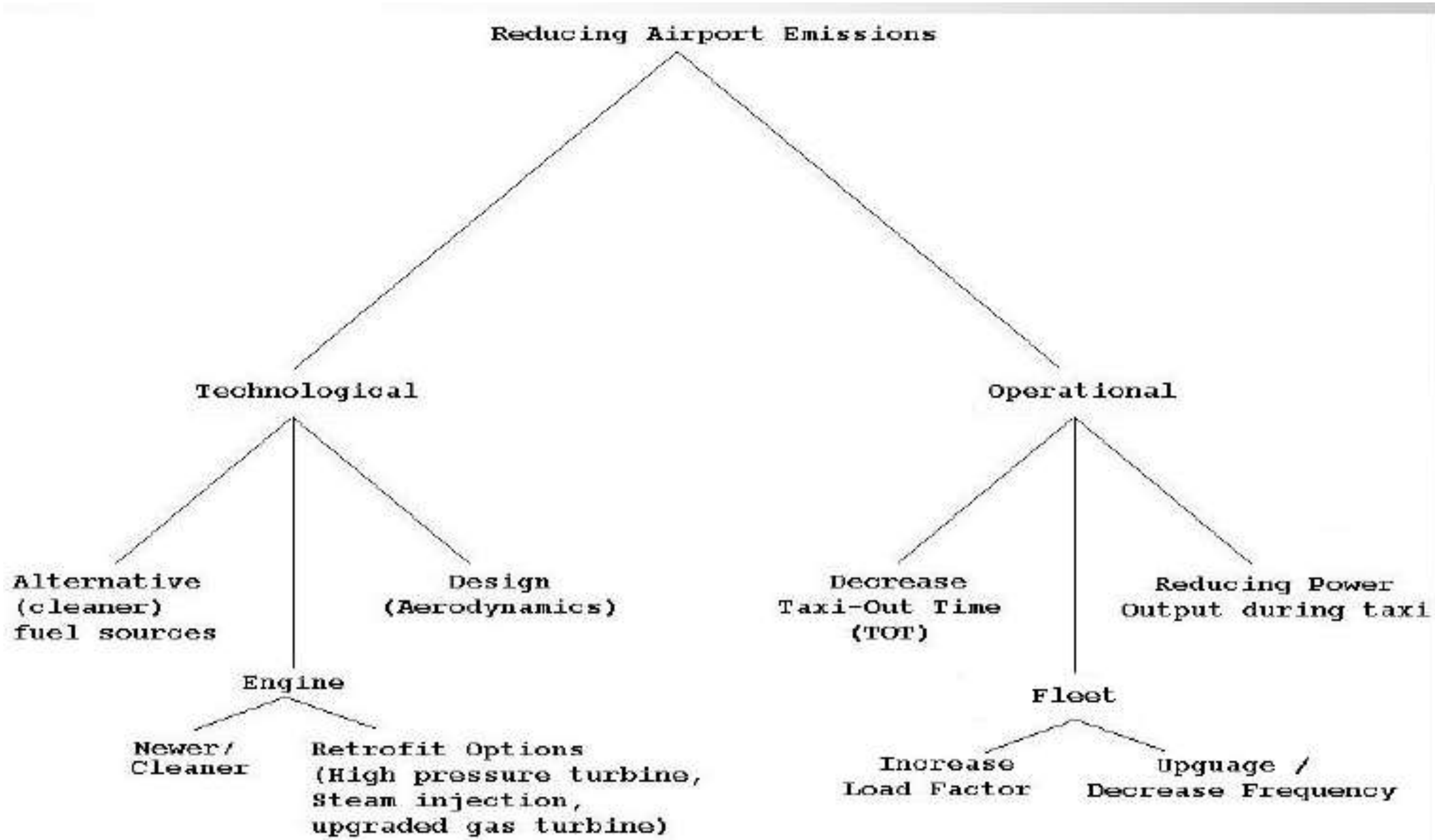
- **Different fuel rates by altitude and mode (data from BADA; about 90 aircraft types)**



Inventory Modeling



Improving Emissions

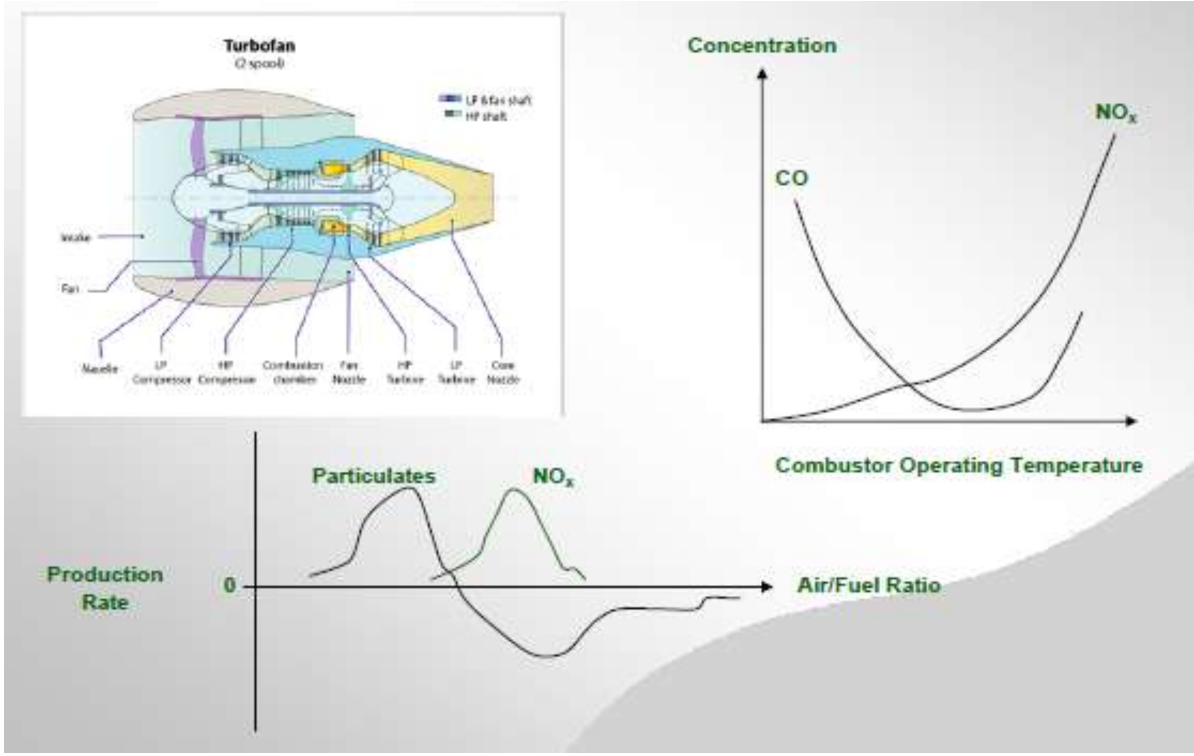


Improving Emissions

- Time in Mode
  - Operational
    - Better prediction of taxi out behavior -> better management of taxi-way/gate resources -> reduced taxi out time.
- Number of Engines
  - Operational
    - More judicious use of engine power during taxi mode.
- Emissions Index
  - Technological
    - Better engines
    - Better fuel
- Fuel Flow
  - Operational
    - Derated takeoff thrust
    - Idle-thrust descents
  - Technology
    - Engine technology innovations

Engine Innovations

- Engine design cannot be optimized for all emissions
- Design tradeoffs form an active area of research and development



Climate Change

Climate Change

- CO_2 is greenhouse gas
  - Produce a lot of it
  - Effects long-lasting (i.e. decades)
    - Methane disperses in a decade

- Human activity put ~ 37 billion tons of CO_2 into atmosphere (2010)
  - 1700 CO_2 in atmosphere 280 parts per million
  - 1900 CO_2 300 ppm
  - 1990 CO_2 390 ppm
  - 2015 CO_2 estimate – 400 ppm
  - 2025 CO_2 estimate – 420 ppm

Aviation Contribution

- 2% emitted by aviation (2010)
  - Potentially more harmful cos emitted at altitude
- Aviation traffic expected to grow
  - 1990 – 2003 aviation's output of greenhouse gas emissions in Europe + 80%
- Emissions Inventory = Neng * Fuel Burn Rate * Time
  - *CO2 emissions from aviation fuel* are 3.15 grams per gram of fuel

Example CO_2 Calculations (Metric)

Boeing 747 - 400

- Distance: 5556 km
- Fuel used: 59.6 tonnes
- Seats: 416
- Seat occupancy: 80%
- Fuel use: 32.2 g per passenger km
- CO2 emissions: 101 g per passenger km
- Cruising speed: 910 km per hour
- CO2 emissions: 92 kg CO2 per hour

Boeing 737-400

Distance of 926 km,

Fuel used 3.61 tonnes

Seating capacity of

Average seat occupancy 65%

Fuel use of 36.6 g per passenger km.

CO2 emissions from aviation fuel are 3.15 grams per gram of fuel [

CO2 emissions: 115 g per passenger km

Cruising speed of 780 km per hour

CO2 emissions: 90 kg CO2 per hour