Aviation Emissions

SYST 460/560

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Jet Engine Fuel Burn Chemistry

\[ CnHm + S + N + O \rightarrow CO + H_2O + NOx + CO + SOx + Soot + UHC \]

- 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

**Emissions Inventory Metrics**
- 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

**Emissions Dispersion Metrics**
- Quantify concentration in time period
- Pollutant concentrations modeled at point locations
- Sensitive to track location, altitude, aircraft type, state
- *National Ambient Air Quality Standards* 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 (µg/m³).

• Areas or regions violating these limits are designated to be in non-attainment areas
# Regulations - NAAQS

<table>
<thead>
<tr>
<th>Pollutant [final rule cite]</th>
<th>Primary/Secondary</th>
<th>Averaging Time</th>
<th>Level</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide [76 FR 54294, Aug 31, 2011]</td>
<td>primary</td>
<td>8-hour</td>
<td>9 ppm</td>
<td>Not to be exceeded more than once per year</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-hour</td>
<td>35 ppm</td>
<td></td>
</tr>
<tr>
<td>Lead [73 FR 66964, Nov 12, 2008]</td>
<td>primary and secondary</td>
<td>Rolling 3 month average</td>
<td>0.15 µg/m³ (1)</td>
<td>Not to be exceeded</td>
</tr>
<tr>
<td>Nitrogen Dioxide [75 FR 6474, Feb 9, 2010] [61 FR 52852, Oct 8, 1996]</td>
<td>primary</td>
<td>1-hour</td>
<td>100 ppb</td>
<td>98th percentile, averaged over 3 years</td>
</tr>
<tr>
<td></td>
<td>primary and secondary</td>
<td>Annual</td>
<td>53 ppb (2)</td>
<td>Annual Mean</td>
</tr>
<tr>
<td>Ozone [73 FR 16436, Mar 27, 2008]</td>
<td>primary and secondary</td>
<td>8-hour</td>
<td>0.075 ppm (3)</td>
<td>Annual fourth-highest daily maximum 8-hr concentration, averaged over 3 years</td>
</tr>
<tr>
<td>Particle Pollution [71 FR 61144, Oct 17, 2006]</td>
<td>PM₂.₅</td>
<td>Annual</td>
<td>15 µg/m³</td>
<td>Annual mean, averaged over 3 years</td>
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<tr>
<td></td>
<td>primary and secondary</td>
<td>24-hour</td>
<td>35 µg/m³</td>
<td>98th percentile, averaged over 3 years</td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>primary and secondary</td>
<td>24-hour</td>
<td>150 µg/m³</td>
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<tr>
<td>Sulfur Dioxide [75 FR 35520, Jun 22, 2010] [38 FR 25678, Sept 14, 1973]</td>
<td>primary</td>
<td>1-hour</td>
<td>75 ppb (4)</td>
<td>99th percentile of 1-hour daily maximum concentrations, averaged over 3 years</td>
</tr>
<tr>
<td></td>
<td>secondary</td>
<td>3-hour</td>
<td>0.5 ppm</td>
<td>Not to be exceeded more than once per year</td>
</tr>
</tbody>
</table>
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 = $N_{\text{eng}} \times \text{t}_{\text{mode}} \times \text{fuellflow}_{\text{mode}} \times \text{EImode}$

• Pollutant inventory = $\sum_{\text{all_flights}} ($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)

<table>
<thead>
<tr>
<th>ENG_NAME</th>
<th>MODE</th>
<th>CO_EI</th>
<th>HC_EI</th>
<th>NOX_EI</th>
<th>SOX_EI</th>
<th>PART_EI</th>
<th>FUEL_KG/S</th>
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</thead>
<tbody>
<tr>
<td>CFM56-7B20</td>
<td>1</td>
<td>3,200000</td>
<td>0,10000</td>
<td>9,500000</td>
<td>1,000000</td>
<td>0,000000</td>
<td>0,274000</td>
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<tr>
<td>CFM56-7B20</td>
<td>2</td>
<td>0,500000</td>
<td>0,10000</td>
<td>17,400000</td>
<td>1,000000</td>
<td>0,000000</td>
<td>0,761000</td>
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<tr>
<td>CFM56-7B20</td>
<td>3</td>
<td>0,600000</td>
<td>0,10000</td>
<td>20,500000</td>
<td>1,000000</td>
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<td>0,913000</td>
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<tr>
<td>CFM56-7B20</td>
<td>4</td>
<td>25,900000</td>
<td>3,10000</td>
<td>4,300000</td>
<td>1,000000</td>
<td>0,000000</td>
<td>0,100000</td>
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</tbody>
</table>
Inventory Modeling – Fuel Flow Rates

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

<table>
<thead>
<tr>
<th>Altitude (FL)</th>
<th>Fuel Rate (kg/min)</th>
<th>Cruise</th>
<th>Climb</th>
<th>Descent</th>
</tr>
</thead>
<tbody>
<tr>
<td>B772</td>
<td>20 XXX</td>
<td>319.1</td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td>B772</td>
<td>30 93.0</td>
<td>315.0</td>
<td>31.9</td>
<td></td>
</tr>
<tr>
<td>B772</td>
<td>40 93.1</td>
<td>311.7</td>
<td>31.4</td>
<td></td>
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<tr>
<td>B772</td>
<td>60 98.7</td>
<td>303.4</td>
<td>30.3</td>
<td></td>
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<tr>
<td>B772</td>
<td>80 98.8</td>
<td>292.3</td>
<td>29.3</td>
<td></td>
</tr>
<tr>
<td>B772</td>
<td>100 98.9</td>
<td>281.2</td>
<td>28.2</td>
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<tr>
<td>B772</td>
<td>120 99.0</td>
<td>274.6</td>
<td>27.1</td>
<td></td>
</tr>
<tr>
<td>B772</td>
<td>140 99.1</td>
<td>263.5</td>
<td>26.1</td>
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<tr>
<td>B772</td>
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<td>280 120.6</td>
<td>188.4</td>
<td>18.6</td>
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<tr>
<td>B772</td>
<td>290 120.4</td>
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<tr>
<td>B772</td>
<td>310 120.0</td>
<td>172.8</td>
<td>17.0</td>
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<td>B772</td>
<td>330 115.4</td>
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<td>350 110.1</td>
<td>150.9</td>
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<tr>
<td>B772</td>
<td>410 100.2</td>
<td>119.0</td>
<td>11.7</td>
<td></td>
</tr>
</tbody>
</table>
Inventory Modeling

Aircraft Performance Data-base

Scheduled (or Actual) Arrivals and Departures (with aircraft type)

Arrival and departure profiles (i.e. modes)

Emissions Calculator

Emissions Inventory
Improving Emissions

Reducing Airport Emissions

Technological
- Alternative (cleaner) fuel sources
  - Engine
    - Newer/Cleaner
    - Retrofit Options (High pressure turbine, Steam injection, upgraded gas turbine)
- Design (Aerodynamics)

Operational
- Decrease Taxi-Out Time (TOT)
- Reducing Power Output during taxi
  - Fleet
    - Increase Load Factor
    - Upgrade / Decrease Frequency
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

• CO2 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 CO2 into atmosphere (2010)
  – 1700 CO2 in atmosphere 280 parts per million
  – 1900 CO2 300 ppm
  – 1990 CO2 390 ppm
  – 2015 CO2 estimate – 400 ppm
  – 2025 CO2 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 CO2 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

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