Environmental Aspects of Air Transportation

Science and Technology to Achieve a Sustainable System

Dr. Terry Thompson
March/April 2011 (Part II)

Noise
Local Air Quality
Climate
Environmental Management

Metron Aviation GMU Innovation Center
Aviation and Climate
Combustion Products

- Commercial jet fuel is essentially kerosene. Although a mixture of different hydrocarbons (including iso-paraffins, napthenes, and aromatics), it can be approximated as a paraffin ($C_nH_{2n+2}$), usually $C_{10}H_{22}$.

- Main combustion process:
  \[ aC_nH_{2n+2} + bO_2 + 3.76bN_2 \rightarrow cH_2O + dCO_2 + 3.76bN_2 + \text{heat} \]

\[ C_{10}H_{22} + 15.5O_2 + 3.76(15.5)N_2 \rightarrow 11H_2O + 10CO_2 + 3.76(15.5)N_2 + 10.6 \text{ kcal/g} \]  
\[ (19.08 \text{ kBTU/lb}) \]

- The above is for complete combustion in the gaseous phase, and the process inside real engines is considerably more complex. Typical emission rates for jet aircraft (grams per kg fuel consumed) at cruise are:

- Main combustion products:
  - $CO_2$: 3200
  - $H_2O$: 1300
  - $NO_x$: 9-15
  - $SO_x$: 0.3-0.8
  - $CO$: 0.2-0.6
  - Unburned $H_xC_y$: 0-0.1
  - Particulates: 0.01-0.05

  - Produced at high T and P in combustion chamber; depends on operating conditions

  - Due to incomplete burning of fuel; produced at non-optimal operating conditions during landing, taxi, take-off and climb-out

  - Due to sulfur impurities in fuel
Global climate concerns are driven by green-house gas concentrations ($CO_2$, $O_3$, $CH_4$) and $O_3$ depletion.

- $CO_2$ molecules absorb outgoing UV radiation, and lead to warming of the troposphere (i.e., from sea level to about 10km altitude).

- $O_3$ depletion in the stratosphere (10-45km altitude) leads to increased intensity of UV radiation harmful to plant and animal life.

Aviation effects are very complex, and depend on species emitted, altitudes, atmospheric conditions, chemical reactions, etc.

Formation of contrails and contribution to cirrus cloud cover may also be a concern.
Aviation and Climate – The Basics (Cont’d)

- Overall, climate change is fundamentally related to the global carbon cycle, and to perturbations caused by fossil-fuel consumption.
Aviation and Climate – The Basics (Cont’d)

- Annual global mean energy budget shows complexity of energy flows.

Radiative Forcing (RF) – Net change in irradiance (downward minus upward) at the tropopause (altitude of 10-15km) measured in W/m².

Note that this is the TOTAL anthropogenic component.

The 2007 estimate is essentially the same.

Aviation and Climate – The Basics (Cont’d)

Aviation plays a complex role in these effects.

Sources: (a) IPCC, Aviation and the Global Atmosphere, 1999; Stern, N., Economics of Climate Change, 2006.
Aviation and Climate – The Basics (Cont’d)

- Species contributing to climate and ozone change; role and effect at Earth's surface.

<table>
<thead>
<tr>
<th>Species</th>
<th>Troposphere</th>
<th>Stratosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>Direct radiative forcing -&gt; warming</td>
<td></td>
</tr>
<tr>
<td>H2O</td>
<td>Direct radiative forcing -&gt; warming</td>
<td>Enhanced PSC formation -&gt; O3 depletion -&gt; enhanced UV-B</td>
</tr>
<tr>
<td></td>
<td>Increased contrail formation -&gt; radiative forcing -&gt; warming</td>
<td>Modifies O3 chemistry -&gt; O3 depletion -&gt; enhanced UV-B</td>
</tr>
<tr>
<td>NOx</td>
<td>O3 formation in upper troposphere</td>
<td>O3 formation below 18-20 km -&gt; reduced UV-B</td>
</tr>
<tr>
<td></td>
<td>-&gt; radiative forcing -&gt; warming</td>
<td>O3 formation above 18-20 km -&gt; enhanced UV-B</td>
</tr>
<tr>
<td></td>
<td>-&gt; reduced UV-B</td>
<td>Enhanced PSC formation -&gt; O3 depletion -&gt; enhanced UV-B</td>
</tr>
</tbody>
</table>

Aviation and Climate – The Basics (Cont’d)

- Species contributing to climate and ozone change; role and effect at Earth's surface.

SOxO and H2SO4  Troposphere
  Enhanced sulfate aerosol concentrations
  Direct radiative forcing -> cooling
  Contrail formation -> radiative forcing -> warming
  Increased cirrus cloud cover -> radiative forcing -> warming

  Modifies O3 chemistry

Stratosphere
  Modifies O3 chemistry

Soot  Troposphere
  Direct radiative forcing -> warming
  Contrail formation -> radiative forcing -> warming
  Increased cirrus cloud cover -> radiative forcing -> warming

  Modifies O3 chemistry

Stratosphere
  Modifies O3 chemistry

Aviation and Climate – The Basics (Cont’d)

- Estimates of aviation contributions (note vertical scale differences):

1999 estimate of 1999 levels

2005/6 estimate of 2000 levels

Sources: (a) IPCC, Aviation and the Global Atmosphere, 1999; (b) JPDO and PARTNER, Workshop on the Impacts of Aviation on Climate Change, 2006.
Aviation and Climate – The Basics (Cont’d)

- There are significant uncertainties in the magnitudes of different aviation effects.

Source: IPCC, Aviation and the Global Atmosphere, 1999
Metrics – Fuel Efficiency

- **Fuel only** – This metric considers only the fuel used, independent of size of aircraft, carrying capacity, or distance traveled.

- **Fuel modulated by flight distance** – This metric considers flight distance per unit of fuel used.

- **Fuel modulated by seat distance** – This metric considers seat distance flown per unit of fuel used, regardless of whether the seat was occupied. Seat distance is the product of the number of seats times the distance flown by the aircraft. For cargo operations, payload can be converted to a number of seats by dividing by the average weight of a passenger and baggage (typically 100kg).

- **Fuel modulated by occupied seat distance** – This metric considers seat distance flown per unit of fuel used, only for occupied seats. Occupied seat distance is the product of the number of occupied seats times the distance flown by the aircraft.
**Metrics – Fuel Efficiency (Cont’d)**

Fuel Efficiency = \( \frac{F}{C \times D} \)

where
- \( F \) is the mass in kg of fuel burned
- \( C \) is the seat capacity of the aircraft in number of seats
- \( D \) is the ground-track distance traveled in km

Fuel Burned (\( F \)) = \( t_m \times R_m \)

where:
- \( t_m \) is the time in minutes for mode of operation \( m \)
- \( R_m \) is the rate of fuel flow in kg/minute for mode of operation \( m \)

BADA fuel-flow values are expressed in kg/sec for the aircraft during the phases of climb, cruise, and descent at different altitudes. EDMS fuel flow is expressed in kg/sec for each engine of the aircraft during the phases of taxi/idle, takeoff (to 1000 feet AGL), climb (1000 feet AGL to 3000 feet AGL), and approach (3000 feet AGL to touchdown).

When we aggregate across flights, this equation becomes:

\[ \text{Aggregate Fuel Efficiency} = \sum_i F_i \Big( \frac{1}{\sum_i(C_i \times D_i)} \Big) \]

The fuel efficiency for a group of \( N \) flights could also be expressed as the average of the individual flights, as follows:

\[ \text{Averaged Fuel Efficiency} = \frac{1}{N} \sum_i F_i \Big( \frac{1}{C_i \times D_i} \Big) \]
Sensitivities – Fuel Efficiency

- Aircraft and engine type
- Seating capacity


Sensitivities – Fuel Efficiency (Cont’d)

- Averages by aircraft type for a given day of operation at LGA.

![Average Taxi Fuel Efficiency As Function of Number of Seats](image)

*NOTE: POINTS LYING ON X AXIS ARE FOR AIRCRAFT TYPES NOT REPRESENTED IN THE SAMPLE DAY.*
“Passenger Fuel Efficiency” (mJ/kg*km) varies with trip distance and aircraft type.

Alternative Fuels May Be Feasible

- Various types of alternative fuels are being investigated:

  **Drop-in replacement**
  - Very low sulfur Jet-A
  - Jet-A from Canadian tar sands
  - Jet-A from Colorado oil shale
  - Fischer-Tropsch synthetic fuels from biomass, coal, natural gas

  **More significant changes**
  - « Biojet » from large variety of sources
  - Cryogenic fuels such as hydrogen or methane

- Full production/consumption cycle being evaluated (production, transportation, and use) from the perspectives of impacts on air quality, exposure to hazardous material, climate effects, etc.

- Current world-wide consumption of jet fuel is approximately 200 million gallons/day

Convergences and Complications

Aviation’s climate impact – While aviation’s impact is perhaps 5-10% of the overall transport impact, depending on the measure used, this is a substantial and very visible proportion. The IPCC reports that international transport (aviation and marine) contributed about 0.8 Gt of CO2 to global CO2 emissions in 2004, while road transport contributed 5.4 Gt and electricity plants contributed 10.4 Gt (IPCC-WG3, 2007, Ch.1, p.13).

Carbon costs - Cap-and-trade systems for carbon or CO2 will induce greater desire for operational efficiency throughout the system, specifically including airport operations and air-traffic management (Stern, 2006, Chapter 22).

Goals likely to be stringent – In the carbon area, goals recently set include California’s goal to reduce CO2 emissions by 80% from 1990 levels by 2050. The UK has set targets of by 20% from 1990 levels by 2050, and by 60% from 2000 levels by 2050 (Stern, 2006, p. 516).

Rising fuel costs - Fuel costs were approximately 20% of overall aviation operating costs (ICAO, 2005), and are rising significantly.
Competing technical goals - Improvements in engine fuel efficiency can lead to worsening of NOx emissions, since higher pressure ratios are better for fuel efficiency, but the increased combustion temperature creates more NOx.

Fleet technology insertion relatively slow - Noise and safety requirements add complexities that require relatively long times for improvements to enter the operational fleet. Furthermore, aircraft have a useful service life measured in decades, further slowing the insertion of new technology into the fleet.

Local and regional priorities may differ - Local ambient air-quality standards and EPA-designated non-attainment areas for different pollutants can lead to different regional priorities for environmental impact. Local noise-impact concerns differ across communities, as well.
Northwest Airlines – « EarthCares » Program

- Started in 2007, and aimed at fuel efficiency and CO₂ reduction. Main principles:
  
  - Support IATA goal of 25% improvement in fuel efficiency by 2020, and US ATA goal of 30% by 2025, and support engine and airframe technology improvements to meet these goals.
  
  - Support alternative fuels to reduce CO₂, provided that they are safe, can be produced economically, and can be shown to have positive environmental effects over the complete production/consumption cycle.
  
  - Support ATM improvements via U.S. NextGen and European SESAR programs.

- 2007 CO₂ emissions were 5% below 1990 levels, primarily due to fleet modernization.

  - A330s, 76-seat RJs, and A319s 30-35% more fuel-efficient than corresponding DC-10s, DC-9s, and B727-200s. B787s due to enter fleet in 2009, with additional 20% improvement relative to older aircraft of similar size.
  
  
  - Average fleet fuel efficiency of 53 passenger-miles per gallon.

Source: Northwest Airlines, « EarthCare Program », available at www.nwa.com/corpinfo/aircares/
Environmental Management and Optimization
Environmental Management

- As environmental constraints grow, there is likely to be increased pressure to manage environmental effects.

- This will be a complex balance of operational factors and environmental impacts in both noise and emissions.
Zurich

- Arrival and departure management
- Resource management: gate, stand, refueling, catering, etc.
- Noise and emissions monitoring
- Environmental management system and ISO 14000 process
- Emissions-related component of landing fees, differentiated by aircraft class
- Strong regulatory framework from Swiss government
- Regional interactions with regional traffic and environmental conditions
### Seattle/Tacoma

**TABLE III-1  SUMMARY OF GREENHOUSE GAS EMISSIONS ASSOCIATED WITH SEA-TAC AIRPORT ACTIVITY (2006)**

<table>
<thead>
<tr>
<th>User/Source Categories</th>
<th>CO2 (Metric tons/year)</th>
<th>Percent of User</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Port of Seattle owned/controlled</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facilities/Stationary Sources</td>
<td>46,636</td>
<td>16.7%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Ground Support Equipment (on- and off-road)</td>
<td>2,750</td>
<td>1.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Ground Access Vehicles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger Vehicles (airport roads)</td>
<td>21,233</td>
<td>7.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Hotel &amp; Parking Shuttles (airport roads)</td>
<td>178,341</td>
<td>73.3%</td>
<td>5.5%</td>
</tr>
<tr>
<td>Port Employee Commute (on-airport)</td>
<td>263</td>
<td>1.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Port-owned Vehicles (off-road)</td>
<td>0</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Ground Access Vehicles Total</td>
<td>199,837</td>
<td>82.2%</td>
<td>3.9%</td>
</tr>
<tr>
<td>Port of Seattle-owned/controlled Total</td>
<td>242,363</td>
<td>100.0%</td>
<td>4.8%</td>
</tr>
<tr>
<td><strong>Aircraft/Stationary-owned/controlled</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft Approach</td>
<td>49,722</td>
<td>1.9%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Total/Idle/Delay</td>
<td>158,812</td>
<td>64.8%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Taxi/Off</td>
<td>81,806</td>
<td>33.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Clerks/Crew/Airline Crew</td>
<td>47,854</td>
<td>19.4%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Ground Access Vehicles</td>
<td>2,671,095</td>
<td>99.7%</td>
<td>7.7%</td>
</tr>
<tr>
<td>Aircraft Total</td>
<td>3,428,698</td>
<td>100.0%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Ground Support Equipment (on-airport)</td>
<td>42,705</td>
<td>1.0%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Ground Access Vehicles (on-airport)</td>
<td>4,843</td>
<td>0.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Tenant Ground Access Vehicles</td>
<td>2,353</td>
<td>0.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Port-owned Vehicles (off-airport)</td>
<td>7,196</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Ground Access Vehicles Total</td>
<td>0</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>**Airline/Stationary-owned/controlled Total</td>
<td>2,760,082</td>
<td>100.0%</td>
<td>23.8%</td>
</tr>
<tr>
<td>Public-owned/controlled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port and Tenant Employee Commuter (off-airport)</td>
<td>46,122</td>
<td>4.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Passenger Vehicles (off-airport roads)</td>
<td>322,644</td>
<td>55.7%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Hotel &amp; Parking Shuttles (off-airport roads)</td>
<td>211,017</td>
<td>36.3%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Public-owned/controlled Total</td>
<td>598,803</td>
<td>100.0%</td>
<td>14.4%</td>
</tr>
</tbody>
</table>

**Greenhouse Gas Emissions Summary for Local, Regional, and Worldwide Tracking**

*For Sea-Tac Airport Activity (2006)*

- **Port of Seattle owned/controlled**: 243,203 metric tons CO2/year (4.8% of total)
- **On-Airport Total Emissions**: 641,000 approx. (12.5% of total)
  - This includes POS, hotel/shuttles, passenger vehicle on-airport, aircraft approach, takeoff, taxi and ground support vehicles.
- **Total Regional Emissions**: 1.2 million approx. (24% of total)
  - This includes on airport emissions plus emissions from vehicles driving to and from airport.
- **Aircraft Cruise Altitude Emissions**: 3.8 million approx. (76% of total)
  - This includes aircraft emissions above 3,000 feet to its destination and beyond, until fuel loaded at Sea-Tac is completely burned off.
- **Worldwide Emissions**: 5.09 million approx. (100% of total)
  - Includes all activities associated with Sea-Tac worldwide, including eventual burning of fuel to an aircraft’s destination and beyond, until fuel loaded at Sea-Tac is completely burned off.

**Current Sea-Tac Airport Greenhouse Gas Reduction Programs**

- **Ramp Control Tower** – established to increase efficiency of aircraft handing during taxing to gates. For every one minute reduction of taxing time, an airline operating a Boeing 737 saves almost four gallons of fuel – a Boeing 747 will reduce jet fuel consumption by 15 gallons in that same four minute period.
- **Gate electrification** – this provides airlines the option to power their on-aircraft electrical needs (lighting, instruments, etc.) at nearly all Sea-Tac gates. The emission savings on average is nearly 20 pounds of CO2 for every one minute of gate electricity used.
- **Electric Ground Support Equipment** – using electric pushback tractors to move aircraft away from gates saves about 150 pounds of CO2 per day, versus using traditional diesel tractors.
- **Underground fuel hydrant system** – jet fuel is delivered directly to the gate via an underground system, eliminating the need to have diesel-powered trucks deliver fuel to aircraft.
- **Compressed Natural Gas (CNG) fuelling station** – The Port partnered with Clean Energy to build the first large CNG fuelling station open to the public in Washington.
- **CNG powered vehicles** – Port operations reduce air emissions by using 16 buses, two sweepers and 60 light-duty vehicles powered by natural gas.
- **CNG powered taxis** – in 2007, all taxis serving Sea-Tac were converted to natural gas. And, 25 hybrid Toyota Prius models are now in service, as part of a pilot program.
- **Over the past five years, energy consumption has been reduced** by 25% per square foot through lighting retrofits, providing 300% more light while using 50% less energy.
- **Since October 2006, 25% of electrical power purchased for the airport is in the form of Renewable Energy Credits or “green power.”**

**FIGURE III-1  Port of Seattle Aviation Division CO2 Emissions (2006)**

- Port-owned vehicles only reflect on-airport travel
- On-road vehicles only reflect on-airport travel
- Port employee commute 16.2%
- Facilities & Stationary 1.1%
- GSE 0.7%
- Stationary 8.0%
- Port-owned vehicles (off-airport) 6.0%
Amsterdam Schiphol

- Balance DNL noise load at ~35 enforcement points
- Runway-use problem being addressed via stochastic dynamic programming.
- Strong governmental and societal pressure.

Source: Meerburg, 2007
## Examples of Current U.S. Environmental Constraints

<table>
<thead>
<tr>
<th>Noise</th>
<th>Southern California</th>
<th>Atlanta Area</th>
</tr>
</thead>
</table>
| **LAX**                | Noise-abatement procedures shift arriving night traffic over ocean, place departing turns beyond shoreline, and enforce engine-off towing restrictions (Imperial Terminal)  
- Preferred runways and taxiways at night  
- Restrictions on engine run-up and APU use, especially at night  
- Over 6000 dwelling units insulated and nearly 3000 acquired (as of 12/05) | **ATL**  
- Noise-abatement tracks in use at all times  
- Noise/track-monitoring system in place E and W of airport  
- Preferred departure runways  
- 10,150 homes insulated and 2720 acquired (as of 3/01) |
| **SAN**                | Voluntary noise-abatement procedures  
- Noise curfew for departures 2330-0630, with fines for violations  
- Engine run-ups above idle prohibited at night  
- More than 500 homes insulated within 70dB CNEL contour (as of 8/04) | |

| Emissions              | - Portions of the Los Angeles Basin are in non-attainment for ozone, PM-2.5, and PM-10.  
- Portions of the San Diego area are in non-attainment for ozone. | - Portions of the Atlanta area are in non-attainment for ozone and PM-2.5 |
**Examples of Current U.S. Environmental Constraints (Cont’d)**

<table>
<thead>
<tr>
<th>Noise</th>
<th>Northern California</th>
</tr>
</thead>
</table>
| **SFO** | - Noise regulations in effect, including fines for violations  
- Fly Quiet Program encourages operator compliance with tracks/procedures via scoring shared with public  
- Noise/track-monitoring system in place N, NW, and SE of airport  
- Preferred departure runways, especially 2200-0700  
- Engine run-up and APU restrictions, especially at night  
- Over 15,000 homes insulated (80% FAA AIP funds, 20% from SFO general revenue) |

| Emissions | |
|-----------| - Portions of the San Francisco area are in non-attainment for ozone. |
Current Environmental Constraints – Assembling Local Data from Around the World

NOISE ABATEMENT PROCEDURES
Airport Noise Regulation (Resolution No. 01-0354, As Amended)

In order to reduce the noise impacts surrounding the San Francisco International Airport, the City and County of San Francisco developed a Noise Abatement Regulation to provide aircraft operators guidance for operating at SFO. Specific noise abatement procedures are as follows:

To reduce the impacts of aircraft noise in surrounding communities, particularly between the hours of 2300 and 0700, the airport encourages the use of the following procedures:

1) Weather and traffic conditions permitting, aircraft are requested to use the over water departure and arrival runways (Arrivals on Runways 28 L/R and Departures on Runways 10 L/R).

2) When departing on Runway 28L/R, use the Shoreline Departure procedure whenever possible.

3) When departing straight out on Runway 28L/R use the appropriate ICAO A or AC 91-53A noise abatement climb procedure to reduce noise impacts on communities close to the airport.

4) Use the Quiet Bridge Approach to Runway 28L/R

Sanctions:
Violations of any provision of the City and County of San Francisco Airport Commission’s Rules and Regulations (Article I, Rule 1.12.0) Noise Abatement Regulation Resolution No. 88-0016 as amended shall be punishable in the following manner:

1) 1st violation in a 12 month period - letter of admonishment from the Airport Director.
2) 2nd violation in a 12 month period - a fine in the amount of $1,000.
3) 3rd violation in a 12 month period - a fine in the amount of $2,000.
4) Additional violations in a 12 month period - a fine in the amount of $3,000.

Variances:
1) Upon the effective date of this regulation, requests by operators for a variance from any provision of this regulation must be made in writing to the Airport Director at least 60 days prior to the date of the requested variance. Every request for a variance shall be reviewed by the Airport Director or his designated representative. Among other factors, the noise impact on the surrounding community and the fairness to other operators, which are in compliance with this regulation, shall be considered in determining whether a variance should be granted.

2) The Airport Director shall notify the operator in writing whether a variance is granted and include any instructions or restrictions pertaining to the waiver.

Fly Quiet Program:
To help pilots understand the rules and regulations for noise abatement at SFO, the Fly Quiet Program
Other Impacts
Impacts Beyond Noise, Air Quality, and Climate

- De-icing fluids
  - Based on glycols, potassium acetate, and other compounds
  - Aircraft: ten to several thousand gallons per aircraft depending on size
  - Runways and taxiways
- Storage-tank leakage of fuels and other agents
- Stormwater management
- Relevant U.S. regulations:
  - Clean Water Act
  - Occupational Safety and Health Administration (OSHA) rules
  - National Pollutant Discharge Elimination System (NPDES) permits

Background Reading and Additional References
**Background Reading**


- Federal Interagency Committee on Noise (especially 1992 report on airport noise analysis).


