Impacts of Aviation Emissions

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Aviation Environmental Portfolio Management Tool (APMT)
www.apmt.aero

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA, NASA or Transport Canada.
Focus of discussion

• Choices exist to mitigate environmental impacts (fuels, operations, technology, policies)

• What matters and why?
  – Climate, air quality, noise, energy use, economy, national security

• Articulating the relationship between emissions and impacts
  – To better understand the value of different mitigation options
Impact of Aviation Emissions & Noise

Combustion Emissions

- CO₂: 71%
- Water: 28%
- CO, HC, NOₓ, SOₓ, Primary PM₂.₅: < 1%

Aircraft Noise

Atmospheric Chemistry and Physics

- SOₓ
- NOₓ
- UHC
- CO
- O₃
- H₂O
- CH₄
- δO₂

Global Climate Change

- Cooling Effects
- Warming Effects

Emissions from Fuel Production

Population Exposure and Health Impacts
Alternative fuels: importance of life-cycle

Fuel processing and land-use assumptions dominate assessment of the mitigation value

Life cycle GHG results from CAAF/09-IP/6 “Comparison of Life Cycle GHG Emissions from Select Alternative Jet Fuels”
Complexities of interactions among aviation technology-operations-policy-environment

• NOx certification stringency as an example
  – Many different uncertain pathways for environmental impacts (climate, air quality, skin cancer, noise)
  – Many different uncertain pathways for costs (manufacturer development risks, aircraft prices, fuel burn penalties, operating penalties, ticket prices, etc.)
  – Many different uncertain pathways for improvement (combustor, engine, airframe, fuels, operational procedures, operational usage)

• How should we decide what level of NOx emissions certification stringency is appropriate?
  – Despite complexity and uncertainty, we make decisions (2010 CAEP/8 NOx ≈ $2B-$22B? decision)
Some environmental effects of NOx reductions

• Surface ozone in urban areas may increase -- health costs

• Surface ozone in rural and suburban areas decreases -- health benefits

• Surface secondary ambient particulate matter decreases -- health benefits

• Atmospheric ozone decreases in areas where aircraft fly
  – Increased skin cancer -- health costs
  – Decreased positive climate forcing -- environmental benefits

• Atmospheric methane increases globally
  – Increased positive climate forcing -- environmental costs

• May have increased fuel burn associated with technology trades
  – Increased noise -- environmental costs
  – Increased positive climate impacts from CO₂ -- environmental costs
  – Increased costs to consumers and operators

Is increased NOx stringency good or bad? How do we
Aviation Environmental Tool Suite

Policy scenarios
- Certification stringency
- Market-based measures
- Land-use controls
- Sound insulation

Market scenarios
- Demand
- Fuel prices
- Fleet

Environmental scenarios
- CO₂ growth

Technology and operational advances
- CNS/ATM, NGATS
- Long term technology forecasts

Cost-effectiveness
- $/kg NOx reduced
- $/# people removed from 65dB DNL
- $/kg PM reduced
- $/kg CO₂ reduced

Benefit-cost
- Health and welfare impacts
- Change in societal welfare ($)

Distributional analyses
- Who benefits, who pays
- Consumers
- Airports
- Airlines
- Manufacturers
- People impacted by noise and pollution
- Special groups
- Geographical regions

Global, Regional, Airport-local

Focus of presentation

New Tool Suite
(FAA+NASA +Transport Canada)

Inputs

Cost-effectiveness

Outputs

Benefit-cost

Distributional analyses

Environmental Tool Suite

Policy and Scenarios
Including Alternative Fuels and outputs from Simulation Tools as appropriate

Environmental Design Space (EDS)
What are the aircraft design characteristics?

APMT Economics
What are the airline supply & consumer demand effects?

Aviation Environmental Design Tool (AEDT)
What are the noise, emissions and fuel burn outputs?

Aviation environmental Portfolio Management Tool (APMT) for Impacts

Emissions
Climate Impacts

Emissions
Air Quality Impacts

Noise
Noise Impacts

Monetized impacts

APMT Cost Benefit
What are the monetized benefits of decision alternatives?
Aircraft emissions & air quality

Emissions:
- CO, HC, NO\textsubscript{x}, SO\textsubscript{x}, Primary PM\textsubscript{2.5} < 1%

Atmospheric Chemistry & Physics:
- CO\textsubscript{2}: 71%
- Water: 28%
- CO, HC, NO\textsubscript{x}, SO\textsubscript{x}, Primary PM\textsubscript{2.5} < 1%

Population Exposure and Health Impacts:
- Primary PM\textsubscript{2.5}
- Secondary PM\textsubscript{2.5}
- Ozone
- SO\textsubscript{x}
- NO\textsubscript{x}
- UHC
- CO

(a simplified view)
Variation in air quality (movie of simulation)
Aircraft contributions to ambient PM concentration (emissions below 3000 ft AGL only)

- Aircraft contribution to PM concentration less than 0.1% on average
- National ambient air quality standard is 15 $\mu$g/m$^3$
- Strong regional differences in impacts
- 18% of health impacts in LA county, 40% in top 10 counties
- Health risk estimated to be ~64 to 270 yearly premature deaths
- ~$1B/yr$ damage costs in U.S.
- SOx, NOx dominant sources, followed by primary PM

<table>
<thead>
<tr>
<th></th>
<th>With aircraft emissions ($\mu$g/m$^3$)</th>
<th>With aircraft emissions removed ($\mu$g/m$^3$)</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Attainment Areas</td>
<td>17.76</td>
<td>17.75</td>
<td>-0.06%</td>
</tr>
<tr>
<td>All Counties</td>
<td>12.60</td>
<td>12.59</td>
<td>-0.08%</td>
</tr>
</tbody>
</table>
Apportionment of AQ impacts
(US-only commercial aviation, CAEP/8 scenario, large engines only, fixed NEI 2001 background, emissions < 3000’, SMAT’d)
Cruise emissions impacts on surface air quality
(Barrett, Britter and Waitz, in review)
Surface air quality

- Aviation contributions to U.S. criteria pollutant emissions inventories (below 3000 ft) typically 1% or less
- Dominant air quality concerns are particulate matter (PM) and ozone
  - Studies show PM is responsible for about 95% of the health costs (typical of other sources)
  - There are many health impacts, but premature risk of death in areas of high concentrations of ambient PM dominates the valuations
  - Sources: direct emissions of soot + gaseous precursors that form volatile aerosols later (SOx, NOx, and hydrocarbons)
  - There are well-established practices for evaluating these impacts
- New research suggests cruise emissions impacts on surface air quality may be important
Aircraft emissions & climate change

CO, HC, NOx, SOx, Primary PM2.5: < 1%

CO2: 71%

Water: 28%

(a simplified view)
## Radiative forcing from aviation

(A point-in-time metric, use care in interpreting; includes accumulated effects, but not future effects of past emissions)

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>(W m(^{-2}))</th>
<th>Spatial scale</th>
<th>LO SU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>0.0280 (0.0253)</td>
<td>Global</td>
<td>High</td>
</tr>
<tr>
<td>Ozone production</td>
<td>0.0263 (0.219)</td>
<td>Continental</td>
<td>Med-Low</td>
</tr>
<tr>
<td>Methane reduction</td>
<td>-0.0125 (-0.0104)</td>
<td>hemispheric</td>
<td>Med-Low</td>
</tr>
<tr>
<td>Total NO(_x)</td>
<td>0.0138 (0.0115)</td>
<td>Global</td>
<td>Med-Low</td>
</tr>
<tr>
<td>Water vapour</td>
<td>0.0028 (0.0020)</td>
<td>Hemispheric</td>
<td>Low</td>
</tr>
<tr>
<td>Sulphate aerosol</td>
<td>-0.0048 (-0.0035)</td>
<td>to global</td>
<td>Low</td>
</tr>
<tr>
<td>Soot aerosol</td>
<td>0.0034 (0.0025)</td>
<td>Local to</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</td>
<td>0.0118 (0.010)</td>
<td>Local to</td>
<td>Low</td>
</tr>
<tr>
<td>Induced cirrus cloudiness</td>
<td>0.033</td>
<td>to hemispheric</td>
<td>Very Low</td>
</tr>
<tr>
<td>Total aviation (Excl. induced cirrus)</td>
<td>0.055 (0.0478)</td>
<td>Global</td>
<td>Low</td>
</tr>
<tr>
<td>Total aviation (Incl. induced cirrus)</td>
<td>0.078</td>
<td>Global</td>
<td>Low</td>
</tr>
</tbody>
</table>

(Le et al., *Atmos. Env. 2009*)
Contrail-induced cirrus cloudiness

- Warm, moist exhaust can mix with colder, less humid ambient air, triggering ice particles to nucleate and form contrails.
- Under some conditions, contrails lead to larger areas of cirrus than would occur otherwise.
- Correlation with air traffic activity is certain.
- Net impact on radiative forcing is uncertain.

*Image from H. Mannstein, DLR, TAC Conference, 2006*
Aviation climate impacts (30 years of emissions)

Effects persist long after emissions occur

Induced cirrus highly uncertain

CO₂ impacts shaded in gray

(30-year aviation scenario, result for U.S. ops only)
Influence of uncertainties and policy-maker preferences (30 year scenario, impacts of U.S. ops only)

Valuation:
- Damage Coefficient
- Discount Rate

Scientific:
- Background CO₂ Scenario
- NOₓ Effect
- Climate sensitivity
- RF* short-lived

Ecological and economic uncertainty
Policymaker choice
Alternative futures
Uncertainty unique to aviation
Global modeling uncertainty
Uncertainty unique to aviation

Nominal case
- 0.5x
- 7%
- A2
- Stevenson
- 2K
- -90% CI

- 3%
- A1B
- Wild
- 3K
- +90% CI

- 2x
- 2%
- 2x
- 4.5K

NPV (2005 US$ x 10³)
Putting it all together is a challenge

We use a range of inputs and assumptions (within probabilistic simulations)

Note: blue line signifies distribution, blue box signifies discrete value used with lens
Revisiting increased engine certification stringency for NO\textsubscript{x}

For an illustrative sample case; impacts of U.S. ops only
Revisiting increased engine certification stringency for NO$_x$

For an illustrative sample case; note that results are very sensitive to climate, manufacturing cost, and fuel penalty assumptions; impacts of U.S. ops only
Baseline impacts and some potentially important factors not accounted for

These results are for one particular set of assumptions and scenarios: they are not general.

- Direct health impacts of noise (unknown)
- Broader economic impacts of noise, e.g., through delayed airport expansion (unknown)
- Impacts on rental units (factor of 2)
- Impact of cruise emissions on surface air quality (factor of 2-10?)
- Some localized effects very close to airport (factor of 2?)
- Long-term climate feedbacks, threshold events (unknown)
- Regionalized impacts (factor of 2?)

![Graph showing impacts]

2005 US$ x 10^9

- Noise
- Air Quality
- Climate
Status of our work

• FAA has made a commitment to use these tools
  – to inform their decision-making for the ICAO/CAEP meeting in 2010 (NOx stringency)
  – to assess options for the U.S. Next Generation Air Transportation System (NextGen)
  – to consider low sulfur fuels, cap-trade, CO₂ standards, NASA technology portfolio, alternative fuels

• Our methods are under continual review, development, and improvement

• Our purpose
  – is not to provide “one answer” or a single “best estimate”
  – but to provide a framework that may be used to communicate potential outcomes and uncertainties using a variety of metrics, under a variety of assumptions and scenarios
Questions?

Thank you to the many graduate students and researchers whose work I presented.