Figure based on Sausen et al., Aviation Radiative Forcing in 2000: An update on IPCC (1999), *Met. Z.*, 2005

Background

- Overall radiative forcing from aircraft is a factor of 2 to 4 times greater than forcing from aircraft CO$_2$ alone
- The severity of climate impacts due to non-CO$_2$ emissions depends strongly on altitude
  - NO$_x$ emissions near the tropopause are more effective at producing ozone than emissions at the surface
  - Aircraft cruise in the narrow altitude band where contrail persistence conditions are most likely

Figure adapted from Radel and Shine, Radiative Forcing Due to Contrails, *J. Geophysical Research*, 2008
Background

• An aircraft’s climate impact varies with altitude due to several effects

  – There is an optimal altitude for minimum fuel burn

  – NO\textsubscript{x} emissions index varies with throttle setting and ambient conditions

  – The magnitude of radiative forcing per emissions varies with altitude for NO\textsubscript{x} and contrail and cirrus cloud formation
Method

- Developed a simple climate model which captures altitude dependence
- Climate model integrated with conceptual design tool PASS (Program for Aircraft Synthesis Studies)
- PASS design code includes engine model which accounts for changes to efficiency, weight, and drag with varying bypass ratio
- Design studies are performed to compare economic and environmental performance of aircraft configurations
Climate Model

- Climate model accounts for time variation of long-lived and short-lived emissions
- Similar climate models have been used to examine aircraft emissions (Lee, Grewe, Marais, Wit, Ponater)
- This model has added dependence of climate impact on altitude
- Following Shine and Egelhofer, $\Delta T_{s,100}$ is used as a climate change metric for comparing aircraft designs

Shine et al., Alternatives to the Global Warming Potential for Comparing Climate Impacts, *Climatic Change*, 2005
Climate Model

- For sustained emissions of 1 kg CO$_2$ per year, and 1 nautical mile per year stage length:
Climate Model

Emissions (E) are predicted from fuel burn and emissions index (EI):

\[ E_i = E I_i W_{\text{fuel}} \]

EIs for CO\(_2\), H\(_2\)O, soot, and sulfate are constants

EI(NO\(_x\)) is calculated for varying engine throttle setting using a fuel flow correlation with sea-level certification data
Climate Model

Based on quantity of emissions, radiative forcing is computed for each species.

Altitude-dependence of radiative forcing is taken into account with forcing factors:

\[ RF_i(t, h) = RF_{\text{avg}, i}(t) s_i(h) \]
Climate Model

- NO$_x$ and contrails RF per emissions vary with altitude
- All other RFs are assumed constant with altitude
- Plot shows factor of relative RF per kg NO$_x$ or mile compared with overall fleet average

Aircraft Design Optimization

• Study: Find the aircraft configurations with best economic and/or environmental performance
  – 162 passenger, 3000 nmi max range, narrowbody aircraft

• For each optimization, fuselage layout and cross-section remain constant and wing and engine design parameters are varied

• Design variables: Max takeoff weight, sea-level static thrust, engine bypass ratio, wing area, wing aspect ratio, wing sweep, wing thickness, cruise Mach, and initial/final cruise altitudes

• Designs are constrained to have the same range, takeoff, approach, and climb performance
Aircraft Optimization

• Optimization problem
  – Gradient based optimizer used
  – 16 design variables
  – 24 constraints

• Constraints:
  – Design range > 3,000 nautical miles
  – Takeoff field length < 7,500 ft
  – Landing field length < 5,500 ft
  – Stability Margin > 0.1

• Objectives: total operating cost, fuel burn, NO\textsubscript{x} emissions, and 100-year global warming
Optimization Results
Optimization Results

Min Cost
- MTOW: 157,500 lbs
- Thrust: 22,900 lbs
- AR: 9.1
- Mach: 0.85
- Init/Final Altitudes: 37,000 / 39,000 ft
Optimization Results

Min Fuel  (Min Cost)

- MTOW: 157,700 lbs (157,500 lbs)
- Thrust: 17,600 lbs (22,900 lbs)
- AR: 19.5 (9.1)
- Mach: 0.61 (0.85)
- Init/Final Altitudes: 36,000 / 37,000 ft (37,000 / 39,000 ft)
Optimization Results

Min $\text{NO}_x$ (Min Cost)

- MTOW: 188,800 lbs (157,500 lbs)
- Thrust: 39,700 lbs (22,900 lbs)
- AR: 19.9 (9.1)
- Mach: 0.51 (0.85)
- Init/Final Altitudes: 34,000 / 35,000 ft (37,000 / 39,000 ft)
Optimization Results

Min Global Warming (Min Cost)

- MTOW: 158,900 lbs (157,500 lbs)
- Thrust: 17,900 lbs (17,600 lbs)
- AR: 19.3 (9.1)
- Mach: 0.45 (0.85)
- Init/Final Altitudes: 18,000 / 18,000 ft (37,000 / 39,000 ft)
Cost-Climate Tradeoff
Effect of Climate Model Uncertainty

- CO₂ effects are well-understood, but uncertainty is high for NOₓ and cloud impacts (especially cirrus).
- Cost-climate impact tradeoff evaluated for four different scenarios with NOₓ and cloud impacts are either greater or less than current best estimates.
- Bounds are based on 2/3 confidence intervals from IPCC (1999) and Stordal.

- Low net NOₓ: 1/3 x RF(O₃)+RF(CH₄)
- High net NOₓ: 3 x RF(O₃)+RF(CH₄)
- Low clouds: no RF(contrails), 1/3 x RF(cirrus)
- High clouds: 6 x RF(contrails), 2.7 x RF(cirrus)

Stordal et al., Is there a trend in cirrus cloud cover due to aircraft traffic?, Atm. Chem. & Phys., 2005.
Effect of Climate Model Uncertainty

Contrails & Cirrus

Net NO$_x$

low

high

A

B

C

D

100 Year Global Warming vs. Cost
Summary

• Only about 1/3 of aircraft global warming is attributable to CO$_2$ emissions, and the remaining effects are strongly dependent on emissions altitude.

• Designing an aircraft to have low fuel burn or low emissions leads to global warming reductions of 5-10%.

• Larger benefit in global warming is attained by designing aircraft for lower cruise altitudes:
  – 30% lower global warming at 1% increase in cost (M 0.77, 29,000 ft)
  – 50% lower global warming at 1.5% increase in cost (M 0.75, 26,000 ft)
  – 70% lower global warming at 2.3% increase in cost (M 0.71, 22,000 ft)

• Uncertainty in modeling impacts from NO$_x$ and contrails/cirrus is high; even if these forcings are much greater or less than current best estimates, a range of 16-50% reduction in global warming impacts is possible for 1% increase in cost (approx. M 0.76, 28,000 ft).
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Questions?