Estimating the ratio of non-$\text{CO}_2$/\text{CO}_2 climate impacts of aviation

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Massachusetts Institute of Technology

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The APMT effort is managed by Maryalice Locke.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the FAA, NASA or Transport Canada.
Outline

• Intro

• Methods and assumptions

• Details on
  – Metrics
  – Social cost of carbon, SCC
  – Background scenarios
  – Damage functions
  – Scientific uncertainties

• Results

• Summary and main messages
Aviation climate impacts (30 yrs of emissions)

Effects persist long after emissions occur

Total impacts

Induced cirrus highly uncertain

CO₂ impacts shaded in gray

Change in globally-averaged surface temperature $\Delta T$ [K]

(30-year aviation scenario, result for U.S. ops only)
What is “the ratio”?

~ the ratio of total area (e.g. under the x’s) to CO₂ area (gray)
What are we seeking?

• A ratio that may be applied to an estimate of the social cost of carbon (SCC) to represent the non-CO$_2$/CO$_2$ effects of aviation

• **We are not proposing a value for such a ratio**

• Rather, we are seeking to articulate (some of) the key questions that must be answered by scientists and policy-makers in choosing such a value (or range of values)
Factors that lead to different ratio estimates

• **Choice of metric**
  RFI, GWP, ΔT-years, NPV, etc.

• **Scientific uncertainties**
  contrails/cirrus, NO\textsubscript{x} impacts, etc.

• **Economic modeling uncertainties**
  DICE, FUND, PAGE, etc.

• **Importance of long-term impacts**
  time windows, discount rates

• **Uncertain knowledge of the future**
  background emissions and GDP scenarios

• **Things not well assessed with models because they fall outside the capabilities of the models**
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  in the back-up charts

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Methods for this study

• Simplify (we lose some things when we do)
  – Adopt a globally-averaged, fleet-wide perspective

• Use a probabilistic impulse response function model (APMT) to project forward in time the results of other studies in the literature
  – Approximately replicate the behavior of different physical and economic models (e.g. MAGICC, FUND, DICE, PAGE)

• Separate prediction of the non-CO$_2$/CO$_2$ ratio from prediction of the baseline effect (e.g. the total impact of aviation on surface temperature, or the social cost of carbon)

• Run hundreds of cases for different damage functions, background scenarios, uncertain scientific parameters, discount rates, etc.

• **Determine how different uncertainties/assumptions influence estimates of the ratio of non-CO$_2$/CO$_2$ effects from aviation**
## Our assumptions

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Metrics evaluated for ratio estimates

- **GWP** for 1-yr emissions pulse
  \[ \text{GWP}_{20}, \text{GWP}_{100}, \text{GWP}_{500} \] (integrated radiative forcing with time windows*)

- **Integrated temperature change** for 1-yr emissions pulse
  \[ \text{LDP}_{20}, \text{LDP}_{100}, \text{LDP}_{500} \] (with different time windows)

- **Marginal damage** (of one new unit of emissions integrated impact over hundreds of years)
  \[ \text{NPV}_{2\%}, \text{NPV}_{3\%}, \text{NPV}_{7\%} \] (net present value with different discount rates*)

- **How sensitive are the ratios to background scenario, simplified climate model parameters, and aviation impact uncertainties?**

*Discount rates and time windows chosen to be consistent with EPA and IPCC practice, respectively*
Comparing short- and long-lived effects
time-windowing, methane GWP example

\[ \text{GWP}_{20} = 72 \]

\[ \approx 50\% \text{ of CH}_4 \text{ and } \approx 5\% \text{ of CO}_2 \]

area captured

comparises areas under curves to left of this line

\[ \text{GWP}_{100} = 25 \]

\[ \approx \text{all of CH}_4 \text{ and } \approx 30\% \text{ of CO}_2 \]

area captured

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\[ \text{GWP}_{500} = 7.6 \]

\[ \approx \text{all of CH}_4 \text{ and } \approx 90\% \text{ of CO}_2 \]

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Here the lifetimes for CO\textsubscript{2} and CH\textsubscript{4} have been used accurately, but different vertical scales have been used for the two forcing agents; the CO\textsubscript{2} effects have been multiplied to make them larger and easier to see.
Social discounting

- To express future costs and benefits in present value
- Much stronger basis in economics literature than time-windowing

\[ \text{Present Value of } \text{CO}_2 \text{ Damages} \]

\[ \approx \text{factor of 10 difference} \]
Scientific uncertainties (Lee et al., 2009)

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Radiative Forcing (W m⁻²)
Uncertainty in metrics

- If what matters is the ultimate impact (versus an intermediate scientific and/or physical parameter)
  - Then the closer the metric is to serving as a surrogate for the impact, the smaller the uncertainty in the decision
  - Often opposite to how much uncertainty there is in predicting the metric (uncertainty tends to grow as the metric becomes more relevant)

- For policy decisions, metrics that go beyond changes in radiative forcing or surface temperature—to damages—are preferred
  - In all cases quantifying the uncertainty is important
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in the back-up charts
We found:

- Estimate of non-CO$_2$/CO$_2$ ratio is less sensitive to many of the uncertainties than is the estimate of the baseline effect (e.g. the total impacts of aviation on surface temperature, or social cost of carbon)

- **Dominant parameters influencing the non-CO$_2$/CO$_2$ ratio are:**
  - Discounting and/or time-windowing (economics and policy)
  - Magnitude of climate forcing assumed for contrails and aviation-induced cirrus (science and policy)

- The ratio is less sensitive to choice of metric
  - Regardless, can use appropriate metric for the application (e.g., NPV-based ratio for SCC, GWP-based ratio for GWP)
Influences on estimates of overall impact: NPV different from influences on non-CO$_2$/CO$_2$ ratio

- Damage Coefficient
- Discount Rate
- Background CO$_2$ Scenario
- NO$_x$ Effect
- Climate sensitivity
- RF short-lived

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<td>-90% CI</td>
</tr>
<tr>
<td>7%</td>
</tr>
<tr>
<td>2K</td>
</tr>
<tr>
<td>-90% CI</td>
</tr>
</tbody>
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- Ecological and economic uncertainty
- Policymaker choice
- Alternative futures
- Uncertainty unique to aviation
- Global modeling uncertainty
- Uncertainty unique to aviation

NPV (2006 US$)
Influences on non-CO$_2$/CO$_2$ ratio: NPV metric using only the DICE damage function distribution
### Non-\( \text{CO}_2/\text{CO}_2 \) ratio by effect: NPV metric

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<tr>
<td></td>
<td>Low</td>
<td>Mid</td>
<td>High</td>
</tr>
<tr>
<td>( \text{CO}_2 )</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>( \text{NOx-total} )</td>
<td>-0.07</td>
<td>-0.09</td>
<td>-0.04</td>
</tr>
<tr>
<td>( \text{Contrails} )</td>
<td>0.00</td>
<td>0.06</td>
<td>0.22</td>
</tr>
<tr>
<td>( \text{Cirrus} )</td>
<td>0.00</td>
<td>0.21</td>
<td>0.74</td>
</tr>
<tr>
<td>( \text{Sulfates} )</td>
<td>0.00</td>
<td>-0.02</td>
<td>-0.08</td>
</tr>
<tr>
<td>( \text{Soot} )</td>
<td>0.00</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>0.00</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Total Ratio</strong></td>
<td><strong>0.9</strong></td>
<td><strong>1.2</strong></td>
<td><strong>2.0</strong></td>
</tr>
</tbody>
</table>

- Total Ratio = \( \sum_i M_i \)
Influence of scientific uncertainties, metrics, and windowing/discounting
Main messages

• Two key influences on non-CO₂/CO₂ ratio
  – Discount rate
  – Uncertainty in contrails/cirrus estimates

• Metric choice
  – If ratio is being applied to a GWP then use GWP-based ratio
  – If it is being applied to SCC, then use an NPV-based ratio

• Other factors less important
  – Background scenarios
  – Damage functions (PAGE, DICE, FUND?)
  – Scientific uncertainty in other effects (to the extent we know it)
  – Overall global modeling uncertainty (e.g. climate sensitivity)
Summary—key questions

• Given these findings, (some of) the key questions for scientists and policy-makers to arrive at an estimate for a ratio non-CO$_2$/CO$_2$ effects of aviation are:

  “What discount rate (or alternatively time-window) is appropriate?”

  “Is our understanding of climate impacts of contrails and aviation-induced cirrus cloudiness sufficient to adopt a best estimate for their effects?”

• Everyone would be more comfortable with a range of estimates (our recommendation), but for many applications a single number is needed
QUESTIONS?
Back-up charts

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Climate damages: metrics for impacts

• **CO₂ emissions** →
  → change in atmospheric CO₂ concentration
  → radiative forcing
  → change in surface temperature
  → change in health, welfare, etc.

• **Long-lived greenhouse gases** (CH₄, SF₆, N₂O, etc.)
  – IPCC convention is use of *100-yr Global Warming Potentials (GWP)*
  – CO₂ equivalent emissions = emissions of species i * GWPᵢ
  – GWP is ratio of areas under radiative forcing as a function of time curve (background and model dependent)
  – 20-, 100-, 500-year windows typically applied (in lieu of discounting)
Impacts of a new unit of CO₂ emissions

1. One new unit of emissions causes a change in atmospheric concentration that persists for a long time.

2. This change in atmospheric concentration produces a change in the Earth’s energy balance (instantaneous radiative forcing).

3. This change in energy balance leads to a change in globally-averaged surface temperature.

4. The change in surface temperature produces damages that can be estimated economically.
Uncertainty in metrics

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- To express future costs and benefits in present value
- Much stronger basis in economics literature than time-windowing

Approximately a factor of 10 difference
US EPA guidance on social cost of carbon*

- “For incremental emissions reductions, it is conceptually appropriate to use an approach that estimates the marginal value of changes in climate change impacts over time as an estimate for the monetized marginal benefit of the GHG emissions reductions projected for the proposal.”
  - Almost everything from aviation is incremental with respect to the background

- “The marginal value of GHG emissions is equal to the net present value of climate change impacts over hundreds of years of one additional net global metric ton of GHGs emitted to the atmosphere at a particular point in time. This marginal value is sometimes referred to as the social cost of carbon.”
  - Typically a pulse of emissions in a simplified climate model
  - This is the method used in the FAA Environmental Tool Suite/APMT

*Technical Support Document on Benefits of Reducing GHG Emissions U.S. Environmental Protection Agency (June 12, 2008)
SCC ranges: US EPA* and APMT-Impacts

- SCC estimates have wide ranges in EPA study and other literature
- **APMT produces $/tC estimates comparable to EPA analyses**

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<td>-11</td>
<td>249</td>
<td>583</td>
</tr>
<tr>
<td><strong>FUND global</strong></td>
<td>-22</td>
<td>323</td>
<td>2548</td>
</tr>
<tr>
<td><strong>APMT-Impacts</strong></td>
<td>49</td>
<td>211</td>
<td>1389</td>
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“Meta global” & “FUND global” are EPA studies based on Tol 2006

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**US Interagency Working Group**
**SCC for Regulatory Impact Analysis**

- **APMT can be used as a surrogate for other models/assumptions**
- Five background scenarios: Stanford Energy Modeling Forum
- $/tC values for 2010 (in 2007 dollars) at 3% discount rate

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<tr>
<td></td>
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<tr>
<td></td>
<td>Mid</td>
<td>95th</td>
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</tr>
<tr>
<td>IMAGE</td>
<td>131</td>
<td>260</td>
<td>156</td>
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<tr>
<td>MERGE</td>
<td>81</td>
<td>154</td>
<td>109</td>
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<td>109</td>
<td>215</td>
<td>131</td>
</tr>
<tr>
<td>MiniCam</td>
<td>106</td>
<td>212</td>
<td>133</td>
</tr>
<tr>
<td>550 Avg</td>
<td>91</td>
<td>186</td>
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• APMT model has flexibility to be used as a surrogate to approximately replicate the assumptions and results of other models
  – DICE, FUND, PAGE, MAGICC, etc.
  – Probabilistic or deterministic

• Aviation-specific effects represented

• Set-up for the different assumptions of the recent US SCC study and then estimated ratio of non-CO$_2$/CO$_2$ effects for aircraft
  – While using different assumptions for aircraft effects representing low, mid, and high estimates from literature
Background scenarios used in our study
CO₂ emissions shown, also used matched GDP scenarios from same sources

IPCC SRES
Used in many studies
Extension beyond 2100 a question

EMF-22
Used in the US Interagency Study on SCC
Damage functions
as used in US Interagency SCC study
Scientific uncertainties (Lee et al., 2009)

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Influences on non-CO₂/CO₂ ratio: GWP metric

- **Time window**
  - 500 years
  - 100 years
  - 20 years

- **Background CO₂ scenario**
  - A1B
  - A2

- **Noₓ effect**
  - Stevenson
  - Wild

- **RF short-lived**
  - Low
  - High

- **Ecological and economic uncertainty**

- **Alternative futures**

- **Uncertainty unique to aviation**
Influences on non-CO$_2$/CO$_2$ ratio: $\Delta T$-yrs metric

- **Time window**: 500 years, 100 years, 20 years
- **Background CO$_2$ scenario**: A1B, A2
- **No$_x$ effect**: Stevenson, Wild
- **Climate sensitivity**: 2K, 4.5K
- **RF short-lived**: Low, High

- Ecological and economic uncertainty
- Alternative futures
- Uncertainty unique to aviation
- Global modeling uncertainty
- Uncertainty unique to aviation
Influences on non-CO2/CO2 ratio: NPV metric using APMT as a surrogate for USG SCC cases

Nominal case

- Damage function
- Discount rate
- Background CO2 scenario
- Climate sensitivity
- RF short-lived

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

Economic Ratio

- Low
- High
Influence of scientific uncertainties, metrics, and windowing/discounting (using APMT as a surrogate for USG SCC cases)
Ratio and SCC change over time

- Annual growth rate on NPV ratios for analyses into the future
  - Additional units of CO₂ have less radiative forcing due to increased background concentration of CO₂ → denominator decreases

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<tr>
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<td>1.1%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Low</td>
<td>Mid</td>
<td>High</td>
</tr>
<tr>
<td>0.2%</td>
<td>1.0%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

- US NHTSA recommends annual SCC growth rate of 2.4% for a discount rate of 3%*

- IPCC suggests increase of 2% to 4% per year on SCC

- APMT analysis suggests the following growth rates ought to be applied on the SCC as a function of discount rate:

<table>
<thead>
<tr>
<th>2% Discount Rate</th>
<th>3% Discount Rate</th>
<th>7% Discount Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3%</td>
<td>1.6%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>