A Note on How to Internalize Aviation’s Climate Impact of Non-CO$_2$ Effects

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**CO₂ is not equivalent to climate impact**

Climate impact depends on:
- **Species** of emission
- **Amount** of emission
- **Locus** of emission
- **Time** of emission
- **Weather** conditions

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**Aviation Radiative Forcing Components in 2005**

<table>
<thead>
<tr>
<th>RF Terms</th>
<th>Spatial scale</th>
<th>LO SU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>0.0280</td>
<td>High</td>
</tr>
<tr>
<td>Ozone production</td>
<td>-0.0125</td>
<td>Med-Low</td>
</tr>
<tr>
<td>Methane reduction</td>
<td>-0.0184</td>
<td>Med-Low</td>
</tr>
<tr>
<td>NOX</td>
<td>0.0138</td>
<td>Med-Low</td>
</tr>
<tr>
<td>Water vapour</td>
<td>0.0026</td>
<td>Low</td>
</tr>
<tr>
<td>Sulphate aerosol</td>
<td>-0.0048</td>
<td>Low</td>
</tr>
<tr>
<td>Soot aerosol</td>
<td>0.0034</td>
<td>Low</td>
</tr>
<tr>
<td>Linear contrails</td>
<td>0.0118</td>
<td>Low</td>
</tr>
<tr>
<td>Induced cirrus cloudiness</td>
<td>0.033</td>
<td>Very Low</td>
</tr>
<tr>
<td>Total aviation (Excl. induced cirrus)</td>
<td>0.055</td>
<td>Global</td>
</tr>
<tr>
<td>Total aviation (Incl. induced cirrus)</td>
<td>0.078</td>
<td>Global</td>
</tr>
</tbody>
</table>

Lee et al. (2009)

Aviation responsible for approximately 3.5 % of all anthropogenic radiative forcing in 2005
Overview of Climate Impact Mitigation Options

Changing **kind** of emissions

Possible **climate** reductions

Minimizing **amount** of emissions

Changing **time** of emissions

Changing **locus** of emissions

Operational mitigation approaches e.g. climate-optimized trajectories

electric / hydrogen drive, ...

Novel engine concepts
Modification of aircraft design
Climate-Optimized Trajectories

Lührs et al. (2016)

monetary weighting 1.000
climate weighting 0.000
COC 0.973
ATR 1.044
fuel 0.960
flight time 0.979
mean altitude 11,252 m
Climate-Optimized Trajectories

Lührs et al. (2016)

monetary weighting 0.736
climate weighting 0.264
COC 0.998
ATR 0.700
fuel 1.002
flight time 0.994
mean altitude 10,461 m
Climate-Optimized Trajectories

- eco-efficient
- cost-optimized
- great circle
- climate-optimized

- Climate weighting
- Monetary weighting
- COC
- ATR
- Fuel
- Flight time
- Mean altitude

Lührs et al. (2016)
Climate-Optimized Trajectories

Cost-optimal ≠ Climate-optimal

monetary weighting: 0.000
climate weighting: 1.000
COC: 1.086
ATR: 0.502
fuel: 1.106
flight time: 0.982
mean altitude: 10,430 m

Lührs et al. (2016)
Key Findings

- Climate impact of non-CO₂ effects is highly dependent on locus and time of emission
- Climate-optimal operation ≠ cost-optimal operation

Aviation Industry

Airlines are exclusively driven by economy

→ Monetization of external effects are necessary
→ Climate optimal operation ≠ cost optimal operation

Climate Impact

Environmental economics
Research Questions

(i) How to include aviation's climate impact of non-CO$_2$ effects adequately into an environmental policy measure?

(ii) What is a reasonable „shadow price“ for global warming?
Overview of Instruments of Environmental Policy

- Voluntary Approaches
  - Contractual Arrangements (Coase Theorem)
  - Personal Interest
  - Social Standards
  - Helpfulness

- Market-based Approaches
  - Price-based Instruments i.a. subsidies, environmental taxes and charges.
  - Quantity-based Instruments i.a. tradeable permits.

- Regulatory Approaches
  - Restrictive Instruments i.a. environmental limits and standards
  - Coordinating Instruments i.a. single European sky

Create financial incentive for airlines for climate impact mitigation
Types of Market-based Measures (MBMs)

In the aviation context, three types of MBMs have been considered:

- **Levies**
  - Focus on $\text{CO}_2$ emissions reduction only instead of climate impact mitigation.

- **Emission Trading**

- **Offsetting**
Concept of Climate Charged Airspaces (CCA)
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CONCEPT **FOCUSSES ON MOST SENSITIVE AIRSPACES WITH RESPECT TO CLIMATE CHANGE**
Concept of Climate Charged Airspaces (CCA)

CONCEPT FOCUSES ON LOCATION AND TIME DEPENDENCY OF NON-CO2 EFFECTS INSTEAD OF EMISSION REDUCTION ONLY
Concept of **Climate Charged Airspaces (CCA)**

**INTRODUCTION OF CLIMATE CHARGES** FOR OPERATORS THAT FLY IN HIGHLY CLIMATE SENSITIVE AREAS
Concept of **Climate Charged Airspaces (CCA)**

**INTRODUCTION** OF CLIMATE CHARGES FOR OPERATORS THAT FLY IN HIGHLY CLIMATE SENSITIVE AREAS
Concept of **Climate Charged Airspaces (CCA)**

THE CONCEPT GENERATES A **FINANCIAL INCENTIVE** TO **REDUCE EMISSIONS** WITHIN THESE AREAS.
Concept of **Climate Charged Airspaces (CCA)**

Climate charges are levied for operators per kilometer flown within these areas.
Concept of **Climate Charged Airspaces (CCA)**

Introduction of climate charges \( (C_{cj}) \) for flights through \( \text{CCA}_j \):

\[
C_{cj} = U_{cj} \cdot \left( \frac{\text{MTOW}}{k_1} \right)^{k_2} \cdot d_j \cdot I_{AC}
\]

- **Charge as function of maximum take-off weight**
- **Incentive factor for green technologies**
- **Unit cost per km flown \( [$/km] \)**
- **Distance flown in \( \text{CCA}_j \) \( [km] \)**

In analogy to en-route charges \( (C_{ei}) \):

\[
C_{ei} = U_{ei} \cdot \left( \frac{\text{MTOW}}{k_1} \right)^{k_2} \cdot d_i
\]
Concept of **Climate Charged Airspaces (CCA)**

CONCEPT **FOCUSSES FIRST** ON MOST SENSITIVE AIRSPACES WITH RESPECT TO CLIMATE CHANGE
Concept of Climate Charged Airspaces (CCA)

CCA with varying unit charges per km flown

CONCEPT CAN BE ADAPTED TO CURRENT
LEVEL OF SCIENTIFIC UNDERSTANDING (LOSU) ANY TIME
How navigation charges can influence traffic patterns

Global Unit Rates applicable from 01/01/2016 according to Eurocontrol (2016)

\[ C_{ei} = U_{ei} \cdot \left( \frac{MTOW}{k_1} \right)^{k_2} \cdot d_i \]

“If an airline chooses to fly a longer route around an expensive airspace, it’s relatively cheap these days, in terms of additional fuel burn, to do this.”

Flemming Nyrup,
Performance Manager at MUAC
First Results
Climate Weighting

- Climate charge: 0.000 $/km
- COC: 1.000
- ATR: 1.000
- fuel: 1.000
- flight time: 1.000
- mean altitude: 11,645 m
variables

**Climate Optimized Trajectories > Benchmark**

- Charged Volume Fraction 0.0 %
- Climate charge $\infty \$/km

- COC 1.000
- ATR 1.000
- fuel 1.000
- flight time 1.000
- mean altitude 11,645 m
Climate Weighting

Climate charge 0.000 $/km
COC 1.020
ATR 0.821
fuel 1.051
flight time 0.994
mean altitude 10,374 m
Charged Volume Fraction $41.5 \%$

*Climate charge* $\infty$ $$/km$

- COC: 1.020
- ATR: 0.834
- fuel: 1.055
- flight time: 0.990
- mean altitude: 11,012 m
Climate Optimized Trajectories

Benchmark

Cost Optimized Trajectories for CCA Concept

Climate Weighting

- Climate charge: $0.000 /km
- COC: 1.106
- ATR: 0.652
- fuel: 1.228
- flight time: 1.010
- mean altitude: 8,910 m
<table>
<thead>
<tr>
<th>Charged Volume Fraction</th>
<th>Climate Optimized Trajectories &gt; Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost Optimized Trajectories for CCA Concept</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Climate charge</th>
<th>∞ $/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>COC</td>
<td>1.071</td>
</tr>
<tr>
<td>ATR</td>
<td>0.678</td>
</tr>
<tr>
<td>fuel</td>
<td>1.191</td>
</tr>
<tr>
<td>flight time</td>
<td>0.969</td>
</tr>
<tr>
<td>mean altitude</td>
<td>8.932</td>
</tr>
</tbody>
</table>

88.8 %
Conclusion & Outlook
Conclusion

• Climate Charged Airspaces (CCA) are a policy instrument to operationalize the eco-efficiency of climate-optimized trajectories (COT)

• CCA are introduced to generate a financial incentive to minimize the total climate impact of aviation

• First results of the CCA concept with infinite climate unit costs show large climate impact reduction potentials in the same order of magnitude as COT

• Focusing on highly climate sensitive areas seems to be very effective

• High mitigation efficiencies are reachable for small cost increments

• Optimizing for maximum climate impact reduction leads to disproportional rise in monetary costs
Outlook

**Improvement of Environmental Economics**
- Add variations of climate unit costs
- Replacement of hard restriction

**Improvement of flight simulations**
- Add constraints to optimization
- More realistic results

Trade-off studies

Recommendations for Policy Planning
Annex
Concept of **Climate Charged Airspaces (CCA)**

\[
CCA_j(x) = \begin{cases} 
    U_{cj} & \text{if } CCF_{tot}(x) \geq c_{thr} \\
    0 & \text{if } CCF_{tot}(x) < c_{thr}
\end{cases}
\]

climate-charged airspace

cost-optimized

time-optimized

climate-optimized

short-term
How *navigation* charges can influence traffic patterns

<table>
<thead>
<tr>
<th>Route charges</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>€ 74</td>
<td>€ 68</td>
<td>€ 72</td>
<td>€ 71</td>
</tr>
<tr>
<td>Netherlands</td>
<td>€ 66</td>
<td>€ 66</td>
<td>€ 67</td>
<td>€ 67</td>
</tr>
<tr>
<td>Germany</td>
<td>€ 74</td>
<td>€ 77</td>
<td>€ 77</td>
<td>€ 90</td>
</tr>
<tr>
<td>France</td>
<td>€ 65</td>
<td>€ 65</td>
<td>€ 66</td>
<td>€ 70</td>
</tr>
<tr>
<td>Switzerland</td>
<td>€ 99</td>
<td>€ 97</td>
<td>€ 100</td>
<td>€ 111</td>
</tr>
<tr>
<td>UK</td>
<td>€ 85</td>
<td>€ 85</td>
<td>€ 87</td>
<td>€ 100</td>
</tr>
</tbody>
</table>

Jet fuel (gallons) average price

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2015’</th>
</tr>
</thead>
<tbody>
<tr>
<td>% distribution of traffic on available routes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>UK-France</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>2</td>
<td>Germany-Netherlands-Belgium-France</td>
<td>61%</td>
<td>64%</td>
<td>65%</td>
<td>70%</td>
</tr>
<tr>
<td>3</td>
<td>Germany-Belgium-France</td>
<td>14%</td>
<td>14%</td>
<td>13%</td>
<td>11%</td>
</tr>
<tr>
<td>4</td>
<td>Germany (MUAC)-Switzerland-France</td>
<td>17%</td>
<td>14%</td>
<td>12%</td>
<td>12%</td>
</tr>
<tr>
<td>5</td>
<td>Germany-Switzerland-France</td>
<td>3%</td>
<td>4%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>Other</td>
<td>Germany-Hannover-Belgium-France</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Eurocontrol (2016)