Date of publication: 24 December 2019
Updated: 9 January 2020

Author: Rogier Lieshout

Airneth report 23:
Non-CO_2 climate impacts of aviation

Seminar
10 December 2019
7AM, The Hague

Non-CO_2 climate impacts of aviation

This document summarizes the Airneth seminar entitled "The non-CO_2 climate impacts of aviation" held on December 10th 2019 in The Hague. The views and opinions expressed during the seminar do not necessarily correspond with those of Airneth, the KiM Netherlands Institute for Transport Policy Analysis or the Dutch Ministry of Infrastructure and Water Management. The presentations held during the seminar are available on the Airneth website.

1. Key takeaways

- Aviation contributes to global warming and climate change in various ways;
- The combined contribution of non-CO_2 species, such as NO_x (nitrogen oxides), H_2O (water vapour), SO_2 (sulphur dioxide), soot, contrails and induced cloudiness is potentially large;
- The individual contributions differ and depend on various flight parameters and situational factors as well as the lifetimes of the various non-CO_2 species;
- CO_2, NO_x (in an indirect way) and contrails contribute most to radiative forcing;
- The impact of NO_x is especially large when emitted at high (cruise) altitude; the impact of contrails mainly depends on location and time of day;
- When the actual flight parameters and situational factors for a specific flight are known (ex-post) the non-CO_2 impacts can be modelled in a detailed fashion, though uncertainties remain;
- For ex-ante impact assessments such as SCBAs the actual flight parameters and prevailing situational factors are unknown and simplifying assumptions are necessary and possible;
- A globally uniform multiplier on CO_2 is considered too simple by academics as it fails to take the driving factors (quantity of emissions in cruise mode and geographical location) of the non-CO_2 impacts into account;
- Modelling the non-CO_2 impacts based on a multiplier differentiated by destination (region) appears to provide a good estimation of the total climate impact under mean conditions;
- The relative impact of CO_2 and non-CO_2 species on radiative forcing or temperature can be measured with various metrics, such as GWP, GWP*, GTP and ATR;
- The non-CO_2 impacts of aviation can be reduced by (amongst other things): optimization of cruise speeds and altitudes, avoidance of climate sensitive regions, inclusion of non-CO_2 species in cap-and-trade or offsetting schemes and through the use of Sustainable Aviation Fuels;
- Due to their relatively short lifetimes, non-CO_2 species have a relatively large impact on the climate over a relatively short period of time. This means that aviation's climate impact can be reduced in the short-term by reducing non-CO_2 species. However, if this goes at the expense of CO_2 reduction, more CO_2 needs to be reduced in later years.

2. Introduction

Aviation is currently responsible for 2.4% of global CO_2-emissions. The amount of CO_2 emitted by the aviation industry can be estimated with accuracy, as CO_2-emissions are directly related to fuel consumption. The impacts of these CO_2-emissions on global warming and climate change are also well understood by science.

The impacts of other types of emissions, such as NO_x (nitrogen oxides), H_2O (water vapour), SO_2 (sulphur dioxide) and soot on climate change are less well understood. The same holds for the impact of condensation trails (contrails) and induced cloudiness. Estimating the impact of these non-CO_2 species is more difficult, because (1) some non-CO_2 emissions (such as NO_x)

have an indirect impact, (2) the size of the impacts depends on many factors such as altitude, location, time of the day, atmospheric composition and meteorological conditions, and (3) the species have very different lifetimes, ranging from minutes (contrails) to decades (CH_4).

Although most of the individual impacts of NO_x, H_2O, SO_2, soot and contrails on the climate are believed to be smaller than the impact of CO_2, their combined impact may be substantial. Previous studies indicate that the total impact of aviation on global warming could be a factor 1.3 to 4.8 larger than the impact of CO_2 alone (Lee, 2009, 2010; IPCC, 1999; Scheelhaase, 2019). The large bandwidth reflects the uncertainties that remain in estimating the impacts of the non-CO_2 species. Due to these uncertainties, some studies either refrain from estimating the non-CO_2 impacts or use a generic multiplier on the CO_2-impacts. As the non-CO_2 species most likely make a net contribution to climate change, ignoring them would underestimate the total climate impact of aviation. Using a multiplier on the CO_2-impacts ensures that the non-CO_2 impacts are accounted for. However, a generic multiplier might be too simple to account for (1) the range of factors that determine the size and locally sometimes even the sign of the non-CO_2 impacts and (2) the lifetimes of the various species and their impacts.

National and supranational climate goals encompass not only CO_2-emissions, but total greenhouse gas (GHG) emissions. However, regulation is still very much focused on CO_2-emissions. Due to the large potential climate impact of the other species, it is not unlikely that these shall be regulated in the near future. On the 27th of March 2019 the Dutch Minister of Infrastructure and Water Management announced that she would like to take the non-CO_2 impacts of aviation into account in future policy.[1] Against this background the Ministry commissioned Airneth to organize a seminar on the subject.

Airneth invited three renowned academics in the field of non-CO_2 impacts. Dr. Peter van Velthoven provided an introduction into the climate impacts of aviation. Prof. Dr. Volker Grewe presented the warming and cooling impacts of CO_2 and non-CO_2 species and discussed various options to reduce or mitigate the non-CO_2 impacts of aviation. Dr. Janina Scheelhaase from DLR showed how the non-CO_2 impacts of aviation could be translated into CO_2-equivalents. Their presentations were followed by a discussion with the audience on how non-CO_2 impacts could be taken into account in (economic) impact assessments such as Social Cost-Benefit Analyses (SCBAs). This report summarizes the various presentations and the discussion.

3. Presentations

3.1 Keynote I: Impacts of non-CO_2 emissions from aviation on climate: an introduction

Dr. Peter van Velthoven (Royal Netherlands Meteorological Institute, KNMI)

Dr. Van Velthoven introduced the various non-CO_2 species of aviation, described their warming or cooling impacts and showed which factors determine the size of the impacts.

- **NO_x (nitrogen oxides):** NO_x is a combination of NO and NO_2. NO_x acts as a catalyst for the oxidation of methane (CH_4) which leads to the production of ozone (O_3) and water vapour. Although NO_x itself is not a greenhouse gas, ozone, water vapour and methane are. This means that NO_x has an indirect impact on the climate through the production of ozone (warming) and the oxidation of methane (cooling). The warming impact is likely larger than the cooling impact, which means that NO_x has a net warming impact.

  NO_x emissions from aviation have a relatively larger climate impact than similar emissions from other sectors. First, NO_x emitted at cruise altitude has a much longer lifetime than NO_x emitted at the surface, and therefore many more ozone molecules are produced per

---

[1] Tweede Kamer 2018-2019, 31936 nr. 585. Brief van de Minister van Infrastructuur en Waterstaat van 27 maart 2019.

emitted NO_x molecule. Secondly, ozone at cruise altitude has a larger warming impact than ozone at other altitudes.

- **Water vapour:** Water vapour is produced directly by aircraft engines and indirectly through the oxidation of methane (see above). In the tropopause/troposphere water vapour has a relatively short lifetime of around one week as it is removed as rain or snow. The lifetime increases with altitude in the stratosphere as it first needs to be transported back into the troposphere which is a slow process. Therefore the warming impact of water vapour is larger when emitted (higher) in the stratosphere.

  As the altitude of the stratosphere differs by location, the warming impact of water vapour also differs by location. Near the North Pole the stratosphere starts at an altitude of around 8 kilometres, whereas it starts at an altitude of around 16 kilometres near the equator. The warming impact of water vapour emitted at cruise altitudes is therefore larger near the North pole than near the equator.

- **Contrails:** Condensation trails (contrails) occur when the hot moist air from aircraft exhausts mixes with cold dry environmental air without clouds. As the relative humidity in the atmosphere differs by location, the risk of contrails and their persistence also differ by location. The warming impact of contrails also depends on the time of day. Only during daytime contrails reflect solar radiation (cooling), whereas during both daytime and night-time they absorb infrared radiation emitted by the earth's surface and atmosphere (warming). The net effect will in general be warming.

  When contrails persist, they may transform into cirrus clouds. Such clouds are also known as contrail-cirrus or aviation cirrus. Although such aviation induced cloudiness reduces natural cloudiness, globally the net impact will still be warming. There remains much uncertainty however on the amount of warming by contrail-cirrus clouds. This is partly due to the difficulty of detecting aviation induced clouds from natural clouds.

- **Particles:** Sulfate aerosols are sulfur-rich particles which may reflect sunlight and therefore have a (small) cooling impact. Soot resulting from incomplete combustion of aviation fuel has both a direct and indirect impact. Soot may absorb infrared radiation which has a direct warming impact. Indirectly soot may also contribute to cloudiness. Soot particles can act as ice nuclei onto which water vapour can condense, if the air is cold and moist enough, to form cloud crystals. When the density of soot particles increases (through aircraft emissions), more ice nuclei can be formed which likely increases the climate impact of the induced cirrus.

The lifetimes of the various climate impacts vary from centuries (CO_2), decades (CH_4), weeks/months (O_3, H_2O), hours (contrail cirrus) to minutes (contrails).

Metrics
Various metrics are available to estimate the total climate impact of aviation on the climate:[2]

- **Global Warming Potential (GWP)** measures the contribution of non-CO_2 species to radiative forcing over a longer time period, relative to the contribution of CO_2.[3] If the relative contribution is measured over a longer period of time, the metric will emphasize the importance of longer-lived greenhouse gases such as CO_2 itself. Traditionally a time

---

[2] Dr. Scheelhaase presented another metric (ATR), which is discussed in section 3.3.

[3] This implicitly means that the GWP for CO_2 is standardised to one.

period of 100 years is taken (GWP100). A variation on GWP, GWP*, has recently been suggested that tries to account for the difference in lifetimes. It is an attempt to account for this by comparing the effect of the rate of emissions of short-lived greenhouse gases with that of accumulated emissions of long-lived GHGs.

- **Global Temperature change Potential (GTP)** measures the temperature change of a specific greenhouse gas at a certain (future) point in time compared to CO_2.

Since both the GWP and the GTP are expressed relative to CO_2, they can be used for weighting emissions to obtain CO_2-equivalents. The main differences are that (1) GWP is measured in terms of accumulated radiative forcing, whereas GTP measures is in terms of temperature and (2) GWP measures the relative contribution over a longer period of time, whereas GTP measures the relative contribution at one moment in time.

The values of both metrics are very dependent upon the time horizon chosen. Which metric is most appropriate depends on the application.

3.2 Keynote II: Aviation non-CO_2 effects and climate mitigation options

Prof. Dr. Volker Grewe (DLR & TU Delft)

On average non-CO_2 species account for more than 50 percent of aviation’s climate impact. NO_x-emissions (through the production of ozone) and contrails are the non-CO_2 species that contribute most to radiative forcing. Uncertainties are relatively large with respect to the impacts of ozone, methane and aviation induced cirrus clouds.

Multiple options are available to reduce the climate impact of aviation. Three options are described in more detail:

- **Cruise altitude and speed:** Modelling results show that the climate impacts of aviation can be reduced by altering cruise altitude and speed. There is however a trade-off between the climate impact and airline costs. This means that cost-optimal speeds and altitudes differ from climate-optimal speeds and altitudes. Estimations show that the climate impact for an Airbus A330 can be reduced by 30% against a 5% cost increase. Larger climate impact reductions are more costly. A 64% reduction of the climate impact for instance increases airline costs by 32%. Aircraft designs can be optimised for alternative cruise altitudes and speeds which lead to lower cost increases for the airlines.

- **Avoidance of climate sensitive regions:** As mentioned above, the climate impact of aviation depends (among other things) on location. Avoiding climate sensitive regions may reduce the climate impact. An illustration for the transatlantic market shows that the avoidance of sensitive regions leads to relatively large benefits against a modest cost increase. In other words, flight trajectories only need small adjustments to minimize the climate impact.

- **Carbon offsetting:** Market-based measures such as EU ETS and CORSIA are currently focused at reducing or stabilizing CO_2-emissions. CORSIA for instance aims to stabilize CO_2-emissions at 2020 values (for international flights between states participating in the program). Stabilizing CO_2-emissions means that CO_2 keeps accumulating in the atmosphere due to its long lifetime. This means that even when CO_2 emissions are stabilized the warming impact increases.

  Non-CO_2 species have a shorter lifetime than CO_2. This means that reducing the non-CO_2 species offers a possibility to reduce aviation’s climate impact over the short-term. The non-CO_2 effects may be included in market-based measures via CO_2-equivalents (see below).

3.3 Keynote III: Economic impacts of regulating aviation’s full climate impact: insights from the AviClim research project

Dr. Janina Scheelhaase (DLR)

Dr. Scheelhaase presented the findings of a study which looked into the most cost-efficient way to reduce the total climate impact of aviation. Various options were considered: (1) a climate tax on all relevant emissions, (2) a climate tax on NO_x emissions combined with a CO_2 trading scheme and climate-optimal trajectories and (3) the inclusion of CO_2, NO_x, H_2O and contrails in an emissions trading scheme. For each option various scenarios were considered with respect to geographical coverage.

The climate impacts of non-CO_2 emissions were converted into CO_2-equivalents by calculating the Average Temperature Response (ATR) over a time period of 20 and 50 years compared to CO_2. The ATR metric can therefore be seen as a combination of the GWP and GTP metrics presented by Van Velthoven (see above). The ATR takes a longer time period into account (like the GWP metric) and estimates the relative impact on temperature (like the GTP metric).

In the options with emissions trading (2 and 3) it is assumed that 85% of the allowances are allocated for free. These options are therefore less costly to airlines than a climate tax. The relative high costs of a climate tax leads to large reductions in demand and fuel consumption. A global emissions trading scheme for CO_2 and non-CO_2 (option 3) would be most cost-effective. The second-best solution would be a combination of market-based measures and operational measures (option 2).

A follow-up study investigated how the most relevant non-CO_2 species (NO_x, H_2O and contrails) could be included in the EU ETS. The idea is to (1) translate the non-CO_2 species into CO_2-equivalents for each individual flight, (2) sum the CO_2-emissions and CO_2-equivalents to determine the total amount of allowances required for the flight and (3) price these allowances against the ETS-price for carbon to obtain the total cost for complying with the extended EU ETS.

The CO_2-equivalents were calculated by weighing the CO_2 and non-CO_2 species for each individual flight with their respective ATRs. The ATR for NO_x was differentiated by altitude, location (latitude and longitude) and time. The ATRs for CO_2, H_2O and contrails were only dependent on location. This allows one to calculate the CO_2-equivalents for each flight when actual flight trajectories are known (ex-post).

The approach was illustrated for a set of routes ranging from short-haul (AMS-CDG: 248 miles) to long-haul (CDG-LAX: 5670 miles) routes. The total warming impact of the CO_2 and non-CO_2 species was found to be 1.5 to 4.6 times higher than of CO_2-emissions alone. The factor increases with distance, which indicates that the flight time at cruise level is a determining factor for the non-CO_2 impacts.

Including non-CO_2 species into EU ETS incentivizes airlines (and manufacturers) to reduce the non-CO_2 impacts of aviation. As the non-CO_2 impacts increase more than proportionally with distance, airlines operating relatively many long-haul flights will need many allowances and therefore face the largest cost increase. To avoid competitive distortions it is important to include all departing flights to and from Europe in the system.

The studies were commissioned by the German government. The German government is considering taking the non-CO_2 impacts of aviation into account in future policy. It has not been decided however how the non-CO_2 impacts should be measured.

4. Discussion

The presentations show that the non-CO_2 impacts of aviation depend on a range of factors such as altitude, temperature, location, atmospheric composition, time of the day and meteorological conditions. The non-CO_2 impacts of individual flights can be estimated ex-post, when the actual flight trajectories and prevailing atmospheric and meteorological conditions are known.

Impact assessments, such as Social Cost-Benefit Analyses (SCBAs), estimate the long-term impacts of policy measures. In the Netherlands, SCBAs generally consider a time period of up to 100 years. How can non-CO_2 impacts be best predicted for future flights? Should we try to estimate each determining factor separately or focus on the driving factors and assume averages for the other factors? And what are the most appropriate metrics to use? The discussion mainly focused on best practices to include non-CO_2 impacts in ex-ante studies.

4.1 Differentiating the multiplier for non-CO_2 impacts based on destination (region)

The driving factors behind the non-CO_2 impacts are latitude, altitude, flight distance, aircraft and engine type. There is however a trade-off between accuracy and complexity. A previous study by DLR has shown that taking an estimation based on latitude and distance gives a good estimation of the total climate impact under mean climatological conditions over the year.

Differentiating the multiplier on the CO_2 impacts by destination or destination region might therefore be a way to limit complexity and at the same time increase the accuracy of the impact estimations compared to using a generic multiplier. DLR is currently working on simple formulas that can be used to estimate the non-CO_2 impacts of aviation.

4.2 Comparison with other sectors

The non-CO_2 impacts of aviation are likely higher than of other sectors, for instance due to the risk of contrails and cloudiness and the fact that NO_x at high altitudes is a stronger catalyst for the production of ozone than at lower altitudes. This means that average multiplication factors for aviation are likely higher than for ground based installations and surface transport. Nevertheless, it is important to also take the non-CO_2 impacts of other sectors into account to combat climate change and to prevent market distortions.

4.3 Sensitivity of non-CO_2 impact on flight parameters

The non-CO_2 impacts can be quite sensitive to the flight parameters. Intermediate stop operations (ISOs) for instance may reduce fuel consumption and CO_2-emissions on long-haul routes, as less fuel needs to be taken on board during the first flight leg. This reduces the aircraft’s weight during the first flight leg, which allows it to fly at a higher altitude. However, as indicated above, more ozone is produced at higher altitudes, which might fully counter the benefit of the reduced CO_2-emissions of ISOs.

4.4 Sustainable Aviation Fuels

The non-CO_2 impacts of Sustainable Aviation Fuels (SAFs) may be smaller than for conventional fuels due to reduced sulphur and aromatic content which leads to less emissions of fine particles impacting contrail properties. Production capacity for SAFs is currently still limited which translates into a high price. More investments are needed to expand production capacity and to bring the price down to a level at which SAFs become a viable alternative for airlines to use.

4.5 Metrics

Various metrics were suggested in the presentations (GWP/GWP*, GTP and ATR) to estimate the relative impacts of the non-CO_2 species to the impact of CO_2. Which metric is most appropriate depends on the type of application. For SCBAs, which generally consider a time period of up to 100 years, the GWP* and ATR seem most appropriate as they take the long term impacts of the non-CO_2 species into account.

5. Literature and suggested further reading

Fahey, D., Baughcum, S., Gupta, M., Lee, D., Sausen, R., Van Velthoven, P. (2013). Aviation and climate: state of science. Chapter in ICAO Environmental Report 2013.

Grewe, V. (2019). Addressing non-CO_2 effects of aviation. ICSA’s Aviation Decarbonization Forum, Montreal, Canada.

Grewe, V., Matthes, S., Dahlmann, K. (2019). The contribution of aviation NO_x emissions to climate change: are we ignoring methodological flaws. Environmental Research Letters 14.

Grewe,, V., Matthes, S., Frömming, C., Brinkop, S., Jöckel, P., Gierens, K., Champougny, T., Fuglestvedt, J., Haslerud, A., Irvine, E., Shine, K. (2017). Feasibility of climate-optimized air traffic routing for trans-Atlantic flights. Environmental Research Letters 12.

IPCC (1999). Aviation and the Global Atmosphere.

Lee, D., Fahey, D., Forster, P., Newton, P., Wit, R., Lim, L., Owen, B., Sausen, R. (2009). Aviation and global climate change in the 21st century. Atmospheric Environment, 43, p. 3520-3537.

Lee, D., Pitari, G., Grewe, V., Gierens, K., Penner, J., Petzold, A., Prather, M., Schuman, U., Bais, A., Berntsen, T., Iachetti, D., Lim, L., Sausen, R. (2010). Transport impacts on atmosphere and climate : Aviation. Atmospheric Environment, 44 (37), p. 4678 - 4734.

Lee, D. (2018). The current state of scientific understanding of the non-CO_2 effects of aviation on climate. Commissioned by the UK Department for Transport. December 2018.

Scheelhaase, J., Dahlmann, K., Jung, M., Kiemel, H., Nieße, H., Sausen, R., Schaefer, M., Wolters, F. (2016). How to best address aviation’s full climate impact from an economic policy point of view? – Main results from AviClim research project. Transportation Research Part D, 45, p. 112-125.

Scheelhaase, J. (2019). How to regulate aviation's full climate impact as intended by the EU council from 2020 onwards. Journal of Air Transport Management, 75, p. 68-74.