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To: Directorate-General for Climate Action
European Commission, 1049 Bruxelles/Brussel, Belgium

Date: 11 December 2023

Re: Non-CO_2 MRV consultation

Dear Mr. Nikov:

In May of 2023, the European Parliament and Council issued a directive that, among other changes, will require aircraft operators to annually report the non-CO_2 aviation effects of their activities starting from January 1st, 2025. In support of this, the European Commission is to adopt a monitoring, reporting, and verification (MRV) framework by 31st August 2024. The ICCT commends the Commission on proactively fulfilling this mandate and particularly commends Deutsches Zentrum für Luft- und Raumfahrt (DLR) for their work on the scientific architecture and the data requirements as presented at the consultation meeting on the 1st of December 2023. This letter adds to their work in offering an overview of the data needs and recommends potential sources of data.

The body of this letter summarizes ICCT's understanding of what data could be collected to support the MRV system. The appendix summarizes the state of the science that led these recommendations, starting with a brief overview of the variables that impact the calculation of the non-CO_2 climate impacts of aviation. It then elaborates on each variable and the data quantities that could help improve the calculation of the non-CO_2 climate impacts. It not only considers quantities that may already be collected by aircraft operators, aircraft manufacturers, flight planning service providers, air traffic control organizations, and weather data providers, it also suggests areas where data collection could be started, expanded, or improved.

First, on the frequency of reporting the non-CO_2 impacts of an airline, we believe that an annual reporting frequency is appropriate. The uncertainty in quantifying the impact of an individual flight is higher than quantifying the overall impact of a year's worth of operations. Like existing MRV mechanisms for the European Emissions Trading Scheme (EU ETS), the MRV would require aircraft operators to monitor and report their non-CO_2 impact which is then verified by an accredited verifier. Both the reporting by airlines and the verification by the accredited verifier requires the standardization of the calculation of the non-CO_2 impacts of aviation, which is the mandate of this consultation. It is in support of this impact estimation and standardization that additional data quantities, discussed below, may be reported as part of the MRV.

The impact of a specific contrail depends on the contrail's persistence in the air, its location, and how its shape, size, and optical depth evolve over time. These phenomena are governed by local atmospheric properties, the properties of the engine exhaust, and the balance of radiation fluxes in the vicinity of the contrail. In their assessment of the scientific architecture of the MRV, DLR presented multiple mathematical models that can be used to model the climate impact at varying levels of fidelity. Every model requires (or assumes) data on flight trajectory, ice super saturated regions (ISSRs), fuel consumption, engine characteristics, and fuel quality. The appendix details how each data quantity affects the impact estimation. Replacing assumed data with reported data quantities can help reduce some of the uncertainties associated with the impact calculation.

Contrails are not the only driver of the non-CO_2 impacts of aviation, although their impact is estimated to be the biggest. NO_x, water vapor, soot, and sulfur emissions also contribute to anthropogenic climate change. The impact estimation of these is less uncertain than for contrail impact estimation and requires, at minimum, accurate data on engine emissions. That includes the fuel burn rate, the fuel quality, and the engine-specific emission indices for these pollutants. It is important to remember that these NOx, soot, and sulfur emissions also have air quality impacts that are estimated to be responsible for 16,000 premature deaths globally and the importance of quantifying these emissions extends beyond just evaluating their climate impact.[1]

Table 1 summarizes the data quantities that should be considered under this MRV. It provides a reason for the reporting requirement and offers two possible sources of the data, the ideal solution, and a second-best option in case collecting the ideal solution is not possible. Below is a succinct discussion of each data quantity. Please refer to the appendix for a more detailed discussion.

Table 1. Summary of the data quantities that should be considered under the MRV.

Quantity	**Reason for reporting**	**Best solution**	**2nd best option**
Flight trajectory	Accurate positioning data informs all aspects of modeling the non-CO_2 impacts	GPS trajectory data directly from the aircraft	Satellite-based ADS-B data
Humidity and temperature data	High quality humidity and temperature data is required to correctly observe ISSR and model contrail impacts	Incentivising the deployment of high-quality meteorological sensors for data reporting.	Improved observational data coverage through LIDAR and satellite data

[1] Yim, Steve H. L., Gideon L. Lee, In Hwan Lee, Florian Allroggen, Akshay Ashok, Fabio Caiazzo, Sebastian D. Eastham, Robert Malina, and Steven R. H. Barrett. "Global, Regional and Local Health Impacts of Civil Aviation Emissions." *Environmental Research Letters* 10, no. 3 (February 2015): 034001. https://doi.org/2020031315113099.

Fuel burn rate	The fuel burn rate, fuel quality, and engine specific emission indices dictate the exhaust properties which impact contrail formation and the emission of NOx, nvPM, sulfuric particulates, and water vapor	Instantaneous fuel burn rate from flight sensors	Reporting the fuel burned per flight
Fuel quality		Daily fuel quality report from each airport includes naphthalene and sulfur content.	Relying on ReFuelEU MRV for fuel quality per batch delivered to the airport
Engine specific emissions		Fleet information reported by the airline that lists the engines used on each aircraft.	Using fleet data from a secondary data provider
Wind Conditions	Wind conditions govern the evolution of the contrail over its lifetime	Meteorological reanalysis data	
Cloud cover	Clouds impact the radiative forcing from contrails	Meteorological reanalysis data and satellite data	

The direct reporting of flight trajectory data, which is already collected by aircraft operators, would eliminate uncertainties in positioning information. Satellite based ADS-B data might provide enough geographical coverage, but data would have to be purchased from Aireon which is the sole provider of satellite-based ADS-B data that has sufficient geographical coverage. [2]

A network of aircraft carrying humidity and temperature sensors to improve meteorological datasets and numerical weather prediction models would help identify ISSRs. Incentivizing widescale sensor deployment should be considered as a low cost and more accurate alternative (per observation) to radiosonde data.[3] Assimilating LIDAR measurements from the ground and satellite observations of contrail formation could also improve the identification of ISSRs.

Knowing the instantaneous fuel burn rate during all phases of the flight would reduce the uncertainty on the quantity of the emissions of the various pollutants, improving the

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[2] Aireon. (n.d.). *The Executive Reference Guide: Space-based ADS-B*. Retrieved November 29, 2023, from https://aireon.com/wp-content/uploads/2020/02/Aireon_ExecRefGuide_Brochure_Q12020_00h_web.pdf

[3] Bell, Meredith. “WVSS and TAMDAR Status and Business Models.” Presented at the WMO Workshop on Aircraft-based Water Vapor Measurements for Forecasting and Aviation Application, December 7, 2023.

estimation of their warming impact. However, reporting the fuel burned for each flight, an established practice in Brazil since 2000, would be sufficient for the purpose of this MRV.[4]

Daily reports of fuel quality, particularly aromatic, naphthalene, and sulfur content, at each airport would provide the most accurate picture of the emissions profile of aircraft engines. The MRV requirement in ReFuelEU requires the reporting of the relevant quantities for each batch of fuel delivered to the airport. Relying on this data should be sufficient for the purpose of quantifying non-CO_2 impacts. The emissions indices of different engines vary, even for the same aircraft model, and knowing exactly which engine is used for each flight would improve the characterization of emissions. The most accurate source of this data would be self-reported by airlines, however fleet information can be bought from data providers as well. ICAO’s engine emissions databank (EEDB) provides the most complete aircraft engine testing data but does not cover the cruise condition. Collecting addition data for typical cruise throttle levels would reduce interpolation error.[5]

Finally, wind and cloud cover data from existing meteorological sources and satellites is sufficient for the purpose of this MRV. To improve the meteorological data, direct reporting of temperature and wind conditions from the aircraft to the data providers should be encouraged through the World Meteorological Organization’s Aircraft Meteorological Data Relay (AMDAR) observing system.[6]

In closing, the ICCT commends the commission on undertaking the design of this MRV and appreciates the opportunity to comment on it. We thank the opportunity to provide these initial thoughts, which we expect to refine over time into concrete recommendations as the science progresses. Please reach out to Dr. Jayant Mukhopadhaya (j.mukhopadhaya@theicct.org) or by phone at +49 1522 818 6094.

Best regards,

Dan Rutherford

Dan Rutherford, Ph.D.

Aviation Director, International Council on Clean Transportation

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[4] Agência Nacional de Aviação Civil (ANAC). (2023, October 18). *Microdados*. Agência Nacional de Aviação Civil (ANAC). https://www.gov.br/anac/pt-br/assuntos/regulados/empresas-aereas/Instrucoes-para-a-elaboracao-e-apresentacao-das-demonstracoes-contabeis/envio-de-informacoes/microdados

[5] European Union Aviation Safety Agency (EASA). (n.d.). *ICAO Aircraft Engine Emissions Databank*. EASA. Retrieved November 17, 2023, from https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank

[6] World Meteorological Organization (WMO). “What Is AMDAR.” Accessed December 8, 2023. https://community.wmo.int/en/activity-areas/wmo-iata-collaborative-amdar-programme/amdar.

Appendix

Climate impact of contrails

There are several factors that affect the radiative forcing of contrails. Contrails are formed by the interaction between the aircraft engine's plume and the atmosphere. They form when certain temperature and humidity conditions, as defined by the Schmidt-Appleman criterion, are met.[7] Under such conditions water can nucleate around exhaust particulates and ambient aerosols and freeze to form the ice crystals that make up contrails.[8,9] The exhaust particulates depend on the fuel quality, the fuel burn rate, and the emission indices of the specific aircraft engine. A recent global analysis suggests that roughly 35% of flight distance over the 2019-2021 period formed contrails.[10]

However not all contrails persist in the atmosphere for long enough to have a meaningful impact on the Earth's climate. They persist when formed in ice supersaturated regions (ISSRs) where the ambient relative humidity with respect to ice (RH_i) is greater than 100%. Their lifetime depends on several factors including RH_i, turbulent interactions of the aircraft wake and the atmosphere, and ice crystal losses within the contrail.[11] It is estimated that roughly 5% of the flight distance over the 2019-2021 period resulted in persistent contrail formation and the average lifetime of a persistent contrail was greater than 2 hours.[10]

When contrails do persist in the atmosphere, they alter the balance of incoming solar radiation and outgoing terrestrial radiation fluxes.[12] These interactions are affected by the time of day, the optical depth of the contrails, the nearby cloud cover, and the geospatial location of the contrails.[13] While they can have a cooling or warming effect, on average the

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[7] Schumann, U. (1996). On conditions for contrail formation from aircraft exhausts. *Meteorologische Zeitschrift*, *5*, 4–23. https://elib.dlr.de/32128/1/mz-96.pdf

[8] Petzold, A., Gysel, M., Vancassel, X., Hitzenberger, R., Puxbaum, H., Vrochticky, S., Weingartner, E., Baltensperger, U., & Mirabel, P. (2005). On the effects of organic matter and sulphur-containing compounds on the CCN activation of combustion particles. *Atmospheric Chemistry and Physics*, *5*(12), 3187–3203. https://doi.org/10.5194/acp-5-3187-2005

[9] Kärcher, B. (2018). Formation and radiative forcing of contrail cirrus. *Nature Communications*, *9*(1), Article 1. https://doi.org/10.1038/s41467-018-04068-0

[10] Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S., & Stettler, M. (2023). Global aviation contrail climate effects from 2019 to 2021. *EGUsphere*, 1–32. https://doi.org/10.5194/egusphere-2023-1859

[11] Kleine, J., Voigt, C., Sauer, D., Schlager, H., Scheibe, M., Jurkat-Witschas, T., Kaufmann, S., Kärcher, B., & Anderson, B. E. (2018). In Situ Observations of Ice Particle Losses in a Young Persistent Contrail. *Geophysical Research Letters*, *45*(24), 13,553-13,561. https://doi.org/10.1029/2018GL079390

[12] Meerkötter, R., Schumann, U., Doelling, D. R., Minnis, P., Nakajima, T., & Tsushima, Y. (1999). Radiative forcing by contrails. *Annales Geophysicae*, *17*(8), 1080–1094. https://doi.org/10.1007/s00585-999-1080-7

[13] A contrail's optical depth is a measure of the scattering and absorption of radiation as it travels through the contrail.

effect is estimated to be strongly warming.[14] In the 2019-2021 period, it is estimated that of the flights that produced persistent contrails, 30% of them produced net cooling contrails while 70% of them produced net warming ones.[10]

Based on the various physical phenomena that dictate the formation, persistence, and resulting radiative forcing of contrails, **Figure 1** presents a taxonomy of data that could be reported or collected to help quantify the radiative forcing from contrails. Flight trajectory is mentioned once, under atmospheric conditions, but it informs every aspect of the modeling.

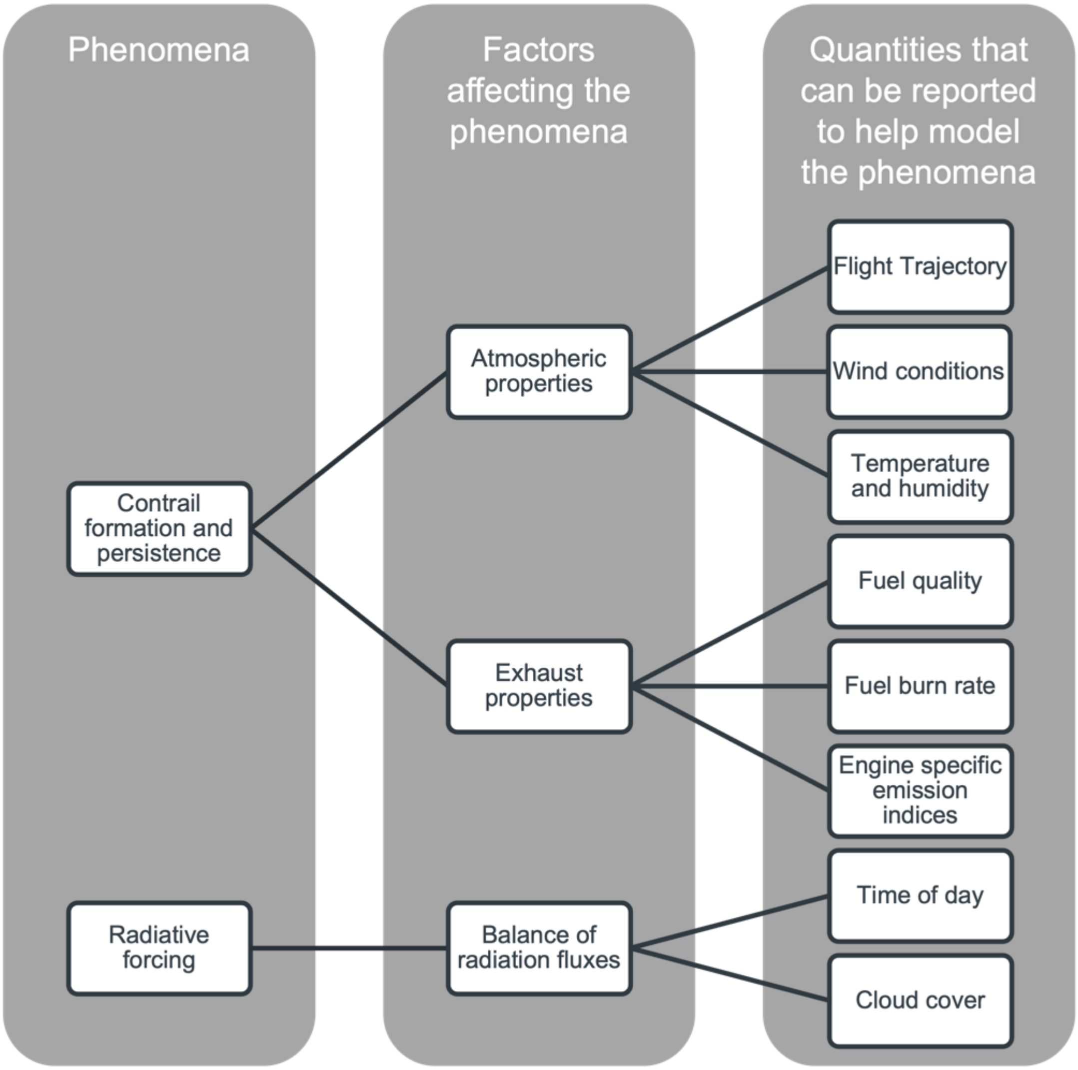

Figure 1. A taxonomy of the various quantities whose collection could help model the formation, persistence, and radiative forcing of contrails.

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[14] Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., … Wilcox, L. J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, *244*, 117834. https://doi.org/10.1016/j.atmosenv.2020.117834

This taxonomy does not include an emerging avenue of research: measuring contrail formation and persistence using satellite imagery.[15,16,17] By training a neural net using human-labeled satellite imagery from geostationary satellites, it is possible to automate the monitoring and reporting linear persistent contrails.[18] If this contrail detection were perfect, there wouldn't be a need for modeling the contrail formation and persistence over areas where these satellite images are available.

The current state-of-the-art (Ng et al.) uses the GOES-16 satellite, a geostationary satellite with 2km spatial resolution and 10-minute temporal resolution that orbits over the Americas. The model has higher precision than recall, meaning that while pixels that the algorithm labels as containing contrails have a high likelihood of containing contrails, it does miss some contrails completely. The contrails also cannot yet be tracked for the entirety of their lifetime as the contrail detection algorithms cannot detect them once they diffuse to form contrail-cirrus clouds, which is also when a larger proportion of the warming is said to occur.[19]

The ability to do this detection depends on the availability of geostationary imaging. For the MRV in Europe, a satellite with similar specifications to the GOES-16 is already in orbit over Europe.[20] . Between when a contrail is formed and when it is detected by satellite images, the contrail can move through the atmosphere, a phenomenon known as advection, due to the wind. To link a detected contrail to a specific flight, precise trajectory information and local wind speeds are required. This allows for the modeling of the contrail advection between the flight segment that produces the contrail and the location of the contrail that is detected.

Other non-CO2 impacts

Contrails are not the only driver of the non-CO_2 impacts of aviation, although their impact is estimated to be the biggest. NO_x, water vapor, soot and sulfur emissions also contribute to

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[15] Meijer, Vincent R., Luke Kulik, Sebastian D. Eastham, Florian Allroggen, Raymond L. Speth, Sertac Karaman, and Steven R. H. Barrett. "Contrail Coverage over the United States before and during the COVID-19 Pandemic." *Environmental Research Letters* 17, no. 3 (March 2022): 034039. https://doi.org/10.1088/1748-9326/ac26f0.

[16] McCloskey, Kevin, Scott Geraedts, Christopher Van Arsdale, and Erica Brand. "A Human-Labeled Landsat-8 Contrails Dataset." In *Climate Change AI*. Climate Change AI, 2021. https://www.climatechange.ai/papers/icml2021/2.

[17] Ng, Joe Yue-Hei, Kevin McCloskey, Jian Cui, Vincent R. Meijer, Erica Brand, Aaron Sarna, Nita Goyal, Christopher Van Arsdale, and Scott Geraedts. "OpenContrails: Benchmarking Contrail Detection on GOES-16 ABI." arXiv, April 20, 2023. https://doi.org/10.48550/arXiv.2304.02122.

[18] Geostationary satellites stay in orbit over the same location on Earth and can take high resolution infrared images.

[19] Teoh, Roger, Ulrich Schumann, Edward Gryspeerdt, Marc Shapiro, Jarlath Molloy, George Koudis, Christiane Voigt, and Marc E. J. Stettler. "Aviation Contrail Climate Effects in the North Atlantic from 2016 to 2021." *Atmospheric Chemistry and Physics* 22, no. 16 (August 29, 2022): 10919–35. https://doi.org/10.5194/acp-22-10919-2022.

[20] EUMETSAT. "MTG-I FCI Instrument Status and Calibration | EUMETSAT," February 23, 2022. https://www.eumetsat.int/mtg-i-fci-instrument-status-and-calibration.

the total anthropogenic climate forcing from aviation. The discussion of the impacts here are primarily informed by Lee et al. which presents the state-of-the-art in the analysis of the impact of these pollutants.[21]

The study estimates the warming impact for these pollutants differently than how it calculates it for contrails. For each of these pollutants, a literature review is used to calculate a best estimate for the warming impact per unit mass of pollutant. This best estimate is then scaled by the mass of the pollutant emitted over the year. Consequently, accurately calculating the radiative forcing of these pollutants requires estimating the mass of pollutant that is emitted. This is affected by the fuel burn rate, the fuel quality, and the engine-specific emission indices for these pollutants. In other words, it depends on the exhaust properties as listed in **Figure 1**. In contrast, the radiative forcing of contrails requires the modeling of its formation, persistence, and evolution, as discussed in the previous section.

Data requirements

With this background in the factors affecting non-CO_2 impacts of aviation, we now discuss data and specific quantities that would help improve our ability to quantify the non-CO_2 impacts of aviation.

Flight Trajectory

Flight trajectory here refers to the latitude, longitude, and altitude of the aircraft at each moment in time, also known as the 4-dimensional (4D) flight trajectory. Knowing the precise trajectory is essential for every aspect of the contrail impact calculation. It determines the atmospheric and wind conditions, the fuel burn rate of the aircraft, and the local balance of radiation fluxes at the time of contrail formation. Flight trajectory information is also essential to attribute detected contrails to specific flights if satellite imagery is being used to observe contrails.

The current best practice in estimating contrail formation is to use Automatic Dependent Surveillance – Broadcast (ADS-B) data to model the aircraft trajectory. Most aircraft are required to broadcast their position, and this can be picked up by receivers that are on the ground and, more recently, by satellites orbiting the Earth.[22] Ground-based receivers have poor coverage over water and cover about 62% of the total area operated by European Air Navigation Service Providers (ANSP).[23] Flights within the EU remain mostly over land and therefore get good coverage with the ADS-B data. However, flights leaving continental Europe can suffer from missing trajectory information for huge portions of their flight. **Figure 2** shows the trajectory of Delta Airlines' flight DL141 from Brussels to New York City on the

[21] Lee, D.S., D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, et al. "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018." *Atmospheric Environment* 244 (January 2021): 117834. https://doi.org/10.1016/j.atmosenv.2020.117834.

[22] The regulations for what aircraft are required to have on-board ADS-B transmitters varies between countries. For example, the US mandates ADS-B transmitters on all aircraft that fly above 18,000 feet.

[23] Eurocontrol. (n.d.). *Automatic dependent surveillance – broadcast (ADS-B) | EUROCONTROL*. Retrieved November 17, 2023, from https://www.eurocontrol.int/service/automatic-dependent-surveillance-broadcast

20th of November 2023 from FlightRadar24.[24] The solid line represents parts of the trajectory where ADS-B data was received, while the dashed line represents interpolated parts of the flight trajectory. Soon after leaving Europe, ADS-B coverage is lost. It is recovered for a short duration over the Labrador Sea but is lost soon after. Coverage is continuous once the flight reaches mainland North America. For this flight, 37% of the flight has no flight trajectory information. This severely impacts the ability to accurately model the non-CO_2 impact of the flight.

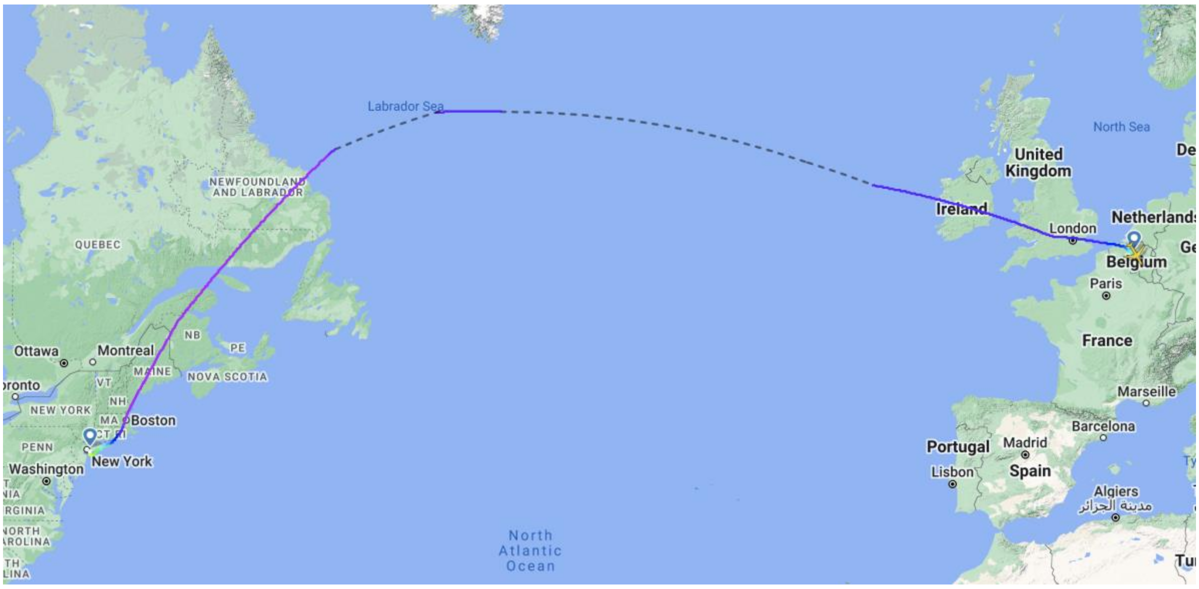

Figure 2. ADS-B based trajectory of flight DL141 from Brussels to New York City on 20th of November 2023

Satellite-based ADS-B data is not limited by the ground-based ADS-B receiver network. Its global coverage varies depending on the data provider. One such provider, Aireon, uses Iridium's 66 satellite network to provide global ADS-B monitoring.[25] They have seen investment from ANSPs around the world.[26] Eurocontrol has integrated Aireon's satellite ADS-B data into their network operations system.[27] Using Aireon's data would be an improvement over using ground-based ADS-B data but may incur data purchasing costs.

[24] Flightradar24. "Live Flight Tracker - Real-Time Flight Tracker Map." Flightradar24. Accessed November 21, 2023. https://www.flightradar24.com/data/flights/dl141.

[25] Aireon. (n.d.). *The Executive Reference Guide: Space-based ADS-B*. Retrieved November 29, 2023, from https://aireon.com/wp-content/uploads/2020/02/Aireon_ExecRefGuide_Brochure_Q12020_00h_web.pdf

[26] Investing ANSPs include Naviair, Irish Aviation Authority, ENAV, NAV Canada, and NATS which are responsible for Danish, Irish, Italian, Canadian, and UK airspace, respectively.

[27] Eurocontrol. "EUROCONTROL's Deployment of Aireon's Space-Based ADS-B for Flow Management," May 19, 2021. https://www.eurocontrol.int/event/eurocontrols-deployment-aireons-space-based-ads-b-flow-management.

The best source of flight trajectory data would be from the aircraft themselves. The exact 4D trajectory of the flight is collected by the aircraft operators and should be reported as part of the MRV. This will eliminate any data gaps in the ADS-B data. It would improve the modeling the contrail's formation, persistence, and climate impact by providing certainty in the time and location of the aircraft which impacts the local atmospheric conditions that are used in modeling calculations. It will also help improve the satellite detection and attribution of contrails.

Atmospheric conditions

Global contrail impact studies often depend on climate reanalysis data, an assimilation of past weather observations, to provide a complete weather map of the atmosphere.[10,28] The RH_i is of particular interest as it indicates the occurrence of ISSRs which drives the behavior of persistent contrails. However, the reanalysis data have been shown to be overpredicting ISSR regions when compared to radiosonde measurements and underpredicting ISSR regions when compared to in-situ water vapor measurements from humidity sensors attached to aircraft.[29,30] Correcting the humidity profiles from the reanalysis data using in-situ measurements is essential as without the correction, contrail impacts maybe underestimated by much as 78%.[10]

These discrepancies highlight the need for a better source of data for humidity. For this, in-situ measurements with high quality water vapor sensors carried on in-service aircraft, would be ideal. The In-Service Aircraft for a Global Observation System (IAGOS) fleet has such sensors on board, but the fleet is only 9 active aircraft globally.[31] The sensors are technologically mature but require frequent calibration (every 600-800 hours).[32] This is roughly the same frequency as a required maintenance check (an A-check), although the exact frequency of the maintenance check varies between aircraft models.[33] Increasing the number of aircraft with such sensors on-board will significantly improve our understanding of the distribution of ISSRs globally and our ability to predict the climate impact of contrails.

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[28] Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., Silva, A. M. da, Gu, W., … Zhao, B. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *Journal of Climate*, *30*(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

[29] Agarwal, A., Meijer, V. R., Eastham, S. D., Speth, R. L., & Barrett, S. R. H. (2022). Reanalysis-driven simulations may overestimate persistent contrail formation by 100%–250%. *Environmental Research Letters*, *17*(1), 014045. https://doi.org/10.1088/1748-9326/ac38d9

[30] Reutter, P., Neis, P., Rohs, S., & Sauvage, B. (2020). Ice supersaturated regions: Properties and validation of ERA-Interim reanalysis with IAGOS in situ water vapour measurements. *Atmospheric Chemistry and Physics*, *20*(2), 787–804. https://doi.org/10.5194/acp-20-787-2020

[31] In-Service Aircraft for Global Observing System (IAGOS). (n.d.). *IAGOS Fleet – IAGOS*. Retrieved November 20, 2023, from https://www.iagos.org/iagos-fleet/

[32] Smit, Herman G.J. "Standard Operation Procedure for the IAGOS Capacitive Hygrometer (ICH) (Part of IAGOS-CORE-Package 1)." Research Centre Juelich GmbH, January 2017. https://wp1.aeris-data.fr/wp-content-aeris/uploads/sites/66/2017/04/SOP_IAGOS_CORE_ICH_05-Jan-2017.pdf.

[33] Qantas. "The A, C and D of Aircraft Maintenance." Qantas News Room, July 18, 2016. https://www.qantasnewsroom.com.au/roo-tales/the-a-c-and-d-of-aircraft-maintenance/.

Since these sensors are not widely used in aircraft currently, the first step in collecting this data would be incentivizing or mandating their installation on in-service aircraft. There are two main incentive mechanisms that could work in this regard. The first is one that can improve the supply of these sensors. The EU Innovation Fund in its most recent call for proposals has expanded the definition of eligible projects to include those that address non-CO_2 impacts of aviation. However, the funding hinges on projecting reductions in CO_2-equivalents and that would require proposals from airlines that not only develop these sensors, but also include non-CO_2 mitigation procedures.

The second mechanism could be a combination of a mandate and an incentive that can improve the demand for these sensors. It would be prudent to start with an incentive to promote the adoption and development of these sensors. This incentive offset the performance penalty that is experienced by the aircraft for having the sensor and the data acquisition system on board.[34] The incentive could be scaled to reflect the added fuel consumption due to the additional components as the airline would have to pay into the EU ETS for the additional fuel that is used. Once the benefit of extending the sensor network is established, a mandate for their installation on new aircraft and, if required, existing aircraft fleets should be considered.[35]

Improving our ability to identify ISSRs through a more accurate characterization of the relative humidity in the upper atmosphere is essential for the MRV and for any mitigation measures that are taken by airlines to avoid non-CO_2 impacts. It should be considered the highest priority to reduce the uncertainty in the reported non-CO_2 impacts. In-lieu of incentivizing or mandating on-board sensors, expansion of observational data through ground-based LIDAR or satellite ISSR observation should be considered.[36]

Other atmospheric properties that are important are the ambient temperature and the local cloud cover. While temperature readings from existing sensors on the aircraft may not be accurate enough for research purposes, they are accurate enough that their reporting would help improve the modeling of the formation and persistence of contrails. Local cloud cover data is readily available from the same meteorological data sources mentioned above and satellites.

Fuel burn rate

The amount of fuel being burned determines the thermodynamic state of the engine which in turn impacts the formation and persistence of the contrails. It also impacts the emission of particulates and therefore affects the formation of the contrails. The fuel burn rate is a quantity that is well known to aircraft operators and their flight planning partners as it is a key metric to optimize the fuel load for a flight. Researchers that model contrail formation do not

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[34] The performance penalty could be from the added mass of the sensor and data acquisition system, and from the changed aerodynamics from having a sensor that changes the external contour of the aircraft.

[35] Depending on the sensor design, requiring it on existing aircraft may need supplemental type certifications which is a non-trivial process that would add monetary, engineering, and administrative burden.

[36] Raymetrics SA. "Advanced Operational LIDARS for Challenging Applications: Temperature and Humidity LIDAR." March 2019. https://raymetrics.com/wp-content/uploads/2021/05/Temp%20and%20Humidity%20Lidar_4x3.pdf.

have access to this data and must estimate the fuel burn. Recent bottom-up global inventories that take stock of aviation's CO_2 emissions by modeling the fuel usage per flight and summing annually, are within 5% of each other.[37,38,39] However these inventories fall short of IEA's top-down estimate of global jet fuel consumption partly owed to unmodeled aviation activity, or absence of trajectory data.

Modeling flight-level fuel burn with accuracy requires using an aircraft performance model to model the forces on an aircraft, data on flight trajectories and local wind conditions, and engine performance models that provide fuel burn values at different thrust conditions. There are multiple sources for each aspect of the modeling, however lets focus on the modeling by Teoh et al. to highlight some of the data gaps that exist.[10] They use ADS-B data to model the aircraft trajectory, the short-comings of which have already been discussed. Wind conditions are estimated using freely available data from the European Center for Mid-range Weather Forecast,[40] however on-board sensors can give real-time wind information for better modeling. To model the aircraft's performance The Base of Aircraft Data (BADA), which is maintained by Eurocontrol, is used to estimate the forces on the aircraft.[41] Additionally, the mass of the aircraft, an input into BADA, is not known and must be estimated. The engine thrust output from BADA is then converted into a fuel burn using ICAO's engine emissions databank (EEDB) which only contains engine operation information for 4 throttle settings: takeoff, climb out, approach, and idle.[42] No such data for the cruise condition is included in this databank.

This modeling exercise can be skipped if the instantaneous fuel burn rates over the course of a flight trajectory were reported by aircraft operators. An equivalent option would be to report the engine thrust settings at each point in the flight trajectory as the fuel burn rate could be interpolated using the ICAO EEDB. Another would be to fill the gaps in the data sources by reporting accurate trajectory, wind, and mass data from the aircraft and increasing the granularity of the thrust settings used for the EEDB.

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[37] Graver, B., Rutherford, D., & Zheng, S. (2020). *CO2 emissions from commercial aviation: 2013, 2018, and 2019*. International Council on Clean Transportation. https://theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/

[38] Quadros, F. D. A., Snellen, M., Sun, J., & Dedoussi, I. C. (2022). Global Civil Aviation Emissions Estimates for 2017–2020 Using ADS-B Data. *Journal of Aircraft*, *59*(6), 1394–1405. https://doi.org/10.2514/1.C036763

[39] Teoh, Roger, Zebediah Engberg, Marc Shapiro, Lynnette Dray, and Marc Stettler. "A High-Resolution Global Aviation Emissions Inventory Based on ADS-B (GAIA) for 2019–2021." Preprint. Gases/Atmospheric Modelling and Data Analysis/Troposphere/Chemistry (chemical composition and reactions), June 1, 2023. https://doi.org/10.5194/egusphere-2023-724.

[40] Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.bd0915c6

[41] Nuic, A., Poles, D., & Mouillet, V. (2010). BADA: An advanced aircraft performance model for present and future ATM systems. *International Journal of Adaptive Control and Signal Processing*, *24*(10), 850–866. https://doi.org/10.1002/acs.1176

[42] European Union Aviation Safety Agency (EASA). (n.d.). *ICAO Aircraft Engine Emissions Databank*. EASA. Retrieved November 17, 2023, from https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank

The least data-intensive option would be to report the total fuel burn for each flight which could be incorporated in the fuel burn modeling to scale the instantaneous fuel burn rates by the ratio of the modeled and reported fuel burn. Such a reporting requirement could also support the Environmental Labelling Scheme that was introduced in ReFuelEU to allow customers to make an environmentally informed choice regarding their aviation activity.

There is already precedence for this kind of reporting in Brazil where the Agência Nacional de Aviação Civil (ANAC) has required all Brazilian airlines to report the fuel burned for each flight. This MRV requirement has been in place since 2000 and the data is published publicly and hosted on their website.[43] This dataset can be used to show the variance in per-flight fuel burn and compare it to the results of a fuel burn model that is less sophisticated than the one discussed above. **Figure 3** compares the reported fuel burn for two of the world's most popular aircraft, the Airbus A320 and the Boeing 737-800. The blue dots represent the fuel burn reported to ANAC and line represents the results of the European Environment Agency's fuel burn calculator. This model uses the great circle distance between two airports (does not use actual trajectories), it does not account for wind conditions, it assumes a single payload for each aircraft type, and uses only one engine model for each aircraft type. By ignoring these effects, the fuel burn estimate is reduced to the single line while the reported fuel burn showcases nearly 25-30% variation in the fuel burned for the same aircraft between the same two airports, over the course of a year.

[43] Agência Nacional de Aviação Civil (ANAC). (2023, October 18). *Microdados*. Agência Nacional de Aviação Civil (ANAC). https://www.gov.br/anac/pt-br/assuntos/regulados/empresas-aereas/Instrucoes-para-a-elaboracao-e-apresentacao-das-demonstracoes-contabeis/envio-de-informacoes/microdados

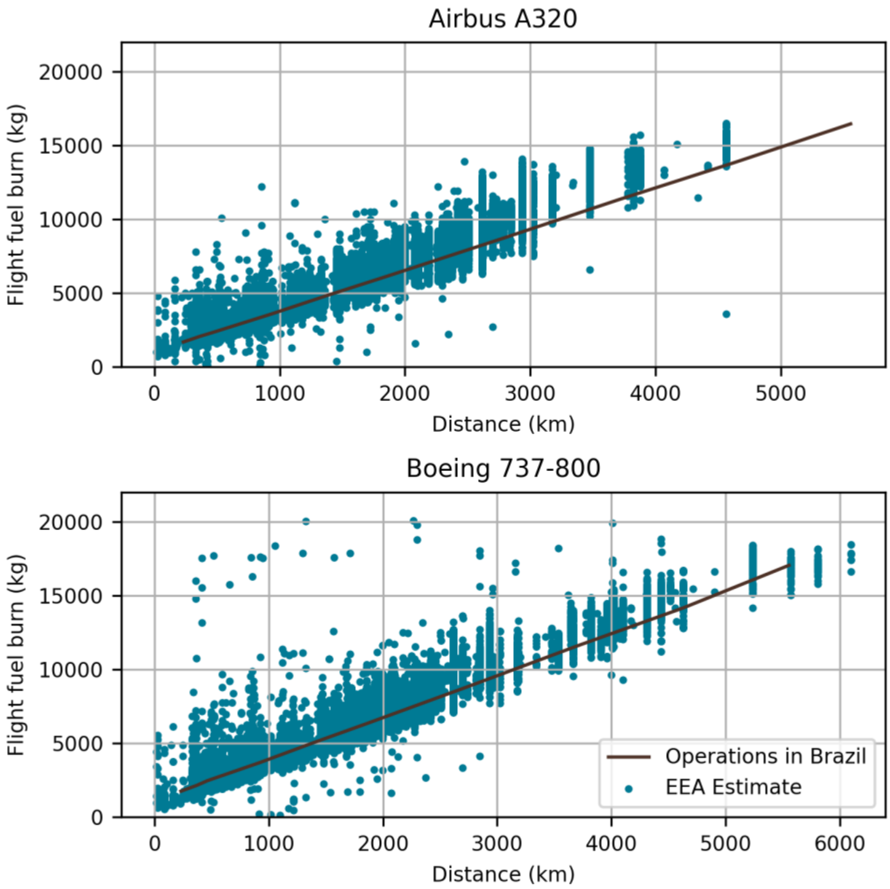

Figure 3. Reported fuel burn data from ANAC in 2019 for the Airbus A320neo and the Boeing 737-800, compared to the EEA's fuel burn model.

Fuel Quality

The fuel quality refers to the chemical composition of the jet fuel that is burned in the aircraft's engine. There are international standards that govern the properties of jet fuel.[44] However, the chemical composition can vary depending on the crude oil that was refined to produce the jet fuel.[45] The composition of the fuel impacts soot emissions which, along with ambient aerosols, act as nucleation points for ice crystal formation. Flight tests blending low-aromatic SAF with Jet A-1 have shown a reduction in ice crystal number and optical depth of

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[44] Kelechava, B. (2022, August 3). Jet Fuel Specifications. *The ANSI Blog*. https://blog.ansi.org/jet-fuel-specifications-astm-d1655-aviation/

[45] MathPro, Inc. (2023). *Techno-economic assessment of process routes for naphthalenes control in petroleum jet fuel*. International Council on Clean Transportation. https://theicct.org/publication/naphthalene-control-jet-fuel-mar23/

contrails when the hydrogen content of the fuel is reduced.[46,47] However, the full extent of the impact of reducing soot, for example with lean combustor designs and using 100% sustainable aviation fuel (SAF), and the role of sulfur in ice nucleation, is still being researched.[8,9]

For the consideration of this MRV, it is important to note that fuel quality metrics are already set to be reported under the ReFuelEU Aviation regulation that has been adopted by the EU.[48] Specifically, Article 10 states that aviation fuel suppliers must report starting in 2025, among other things, "content of aromatics and naphthalenes by percentage volume and of sulphur by percentage mass in aviation fuel supplied per batch, per Union airport". Often, especially for bigger airports, fuel from multiple suppliers get mixed into a single fuel reservoir. The fuel that enters an aircraft may be different from the individual batches reported by the supplier. Daily fuel quality reports from each airport would give the most complete information to characterize the fuel that is used in an aircraft. However, in absence of this information, the fuel quality reporting mandates as part of the ReFuelEU regulation would be sufficient and should be incorporated into this MRV.

Engine specific emission indices

The only available aircraft engine testing data is the ICAO EEDB. It contains engine-specific emission intensities of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), water, and non-volatile particulate matter (nvPM). It covers 557 unique engines, representing roughly 75% of all flights and over 90% of total flight distance flown.[39]

The nvPM emissions are of particular interest for the formation and persistence of contrails and having engine-specific information is essential for accuracy. A sensitivity analysis on the effect of nvPM emissions on the warming impact of contrails suggests that if a constant emission index for nvPM is assumed for all engines, the net radiative forcing is overestimated by 20%.[10] The same study also found that using the default engine assignments for all aircraft (defaults that are specified in BADA) would overestimate the contrail radiative forcing by 18% compared to when the emissions are adjusted based on the specific engine that is mounted on the aircraft.

NOx is considered to generate the second-highest warming of the non-CO_2 impacts that have been quantified. Of specific interest is the NOx emissions at the cruise condition of the engine. The EEDB only contains emission indices for 4 different thrust levels: takeoff, climb

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[46] Voigt, C., Kleine, J., Sauer, D., Moore, R. H., Bräuer, T., Le Clercq, P., Kaufmann, S., Scheibe, M., Jurkat-Witschas, T., Aigner, M., Bauder, U., Boose, Y., Borrmann, S., Crosbie, E., Diskin, G. S., DiGangi, J., Hahn, V., Heckl, C., Huber, F., … Anderson, B. E. (2021). Cleaner burning aviation fuels can reduce contrail cloudiness. *Communications Earth & Environment*, *2*(1), 1–10. https://doi.org/10.1038/s43247-021-00174-y

[47] Bräuer, T., Voigt, C., Sauer, D., Kaufmann, S., Hahn, V., Scheibe, M., Schlager, H., Huber, F., Le Clercq, P., Moore, R. H., & Anderson, B. E. (2021). Reduced ice number concentrations in contrails from low-aromatic biofuel blends. *Atmospheric Chemistry and Physics*, *21*(22), 16817–16826. https://doi.org/10.5194/acp-21-16817-2021

[48] Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation), European Parliament and Council (2023). https://eur-lex.europa.eu/eli/reg/2023/2405/oj

out, approach, and idle.[49] No such data is collected for the cruise condition, which is critical for the quantification of the NOx impact. Requiring the reporting of emission indices at the cruise condition would help prevent reliance on interpolation between engine conditions.

Figure 4 shows the difference in the fuel burn rate and the emissions of NOx, nvPM, and sulfuric nvPM for the LEAP-1A26 and PW1127G-JM engines from the EEDB. Both engines are used on Airbus A320neo aircraft. There is an order of magnitude difference in the mass of the nvPM emissions and roughly a 2x difference in the NOx emissions at higher throttle levels between the two engines. Additionally, there is a non-linearity in the emissions behavior with respect to engine throttle level, which indicates the need for a cruise condition point for the databank.

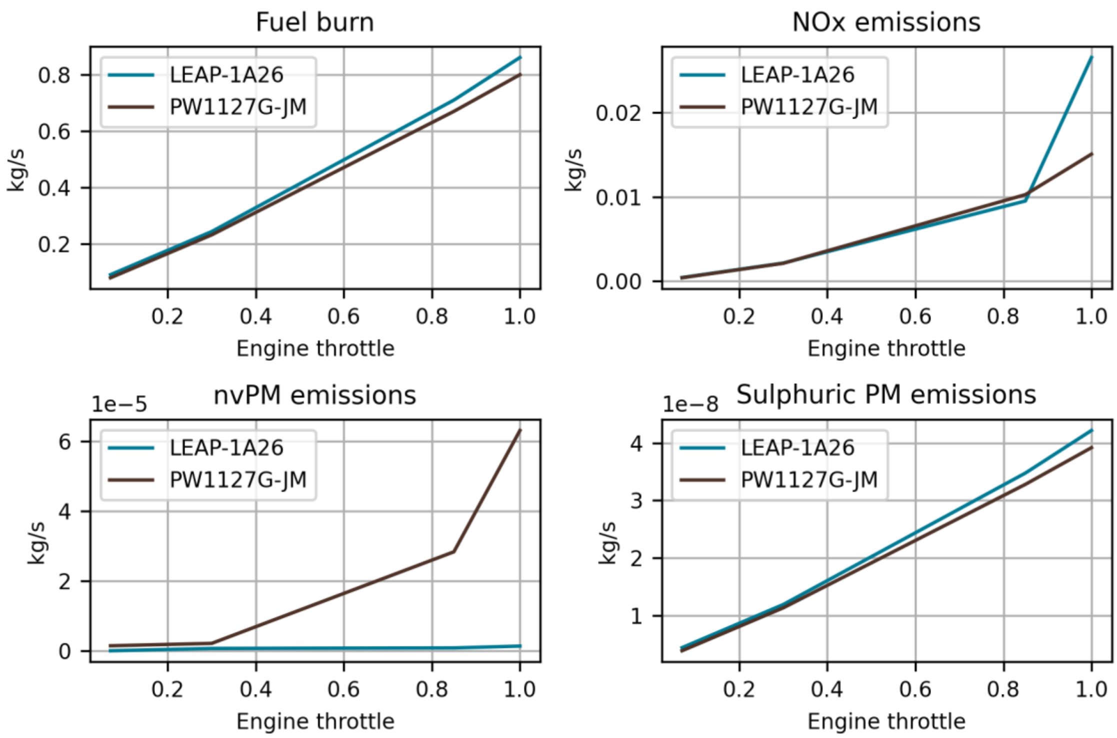

Figure 4. Differences in the fuel burn (top left), NOx emissions (top right), nvPM emission (bottom left), and Sulfuric PM emissions (bottom right) for two different engines for the Airbus A320neo.

Including the impact of engine-specific emission indices will require the reporting of the engine associated with each aircraft that is operated by an airline. This data should be reported directly by the aircraft operator as that would be the most complete and up-to-date source of data. A fallback option would be to buy fleet data from data providers.

[49] It does also include the maximum nvPM production, however, provides no information about the engine thrust that achieves this maximum production state.