Jointly regulating jet fuel aromatic and sulfur content: A near-term strategy for public health and climate benefits

By Pedro Piris-Cabezas (Environmental Defense Fund – EDF & ICSA)

Introduction

Aircraft engines combust fuel imperfectly and incompletely, emitting combustion side products derived from fuel impurities and high-temperature reactions with air. Among these products, fine particulate matter with aerodynamic diameters of 2.5 microns and below ($PM_{2.5}$) have an outsized impact on regional air quality, public health and the climate.

Aromatic compounds, which can constitute up to 25% by volume of jet fuel, are responsible for substantial non-volatile $PM_{2.5}$ formation, a primary or direct source of particulate matter.[1] Low levels of sulphur compounds in jet fuel are responsible for sulphur dioxide (SO_2) formation, a volatile particulate matter (vPM) that is the precursor of sulphate aerosols, a potent secondary $PM_{2.5}$.[2]

Interventions focused on jointly reducing jet fuel aromatic and sulphur content present an opportunity to significantly reduce $PM_{2.5}$ emissions from both new and in-service aircraft, delivering significant public health and climate benefits in the near term. Furthermore, a swift focus on cleaning jet fuel could also facilitate the development of advanced aircraft engine combustor technologies designed to reduce NO_x emissions,[3] which continue to be a key gaseous pollutant of concern for aviation.

Regulating jet fuel aromatic content to reduce non-volatile particulate matter (nvPM) is widely recognized as a valid and complementary strategy to aircraft engine standards. However, to date, there is no regulation tapping on its outstanding potential for reducing these emissions. ICAO adopted nvPM emission standards for aircraft engine design in 2017 and 2020. These standards focus not only on particulate matter (PM) mass concentration but also PM number, emphasizing ultrafine particulate (UFP) matter. These technology-following standards were not designed to improve air quality or reduce non-CO_2 climate impacts, but rather to prevent backsliding without impacting in-service aircrafts.

Studies have demonstrated that blending synthetic alternative fuels, free of aromatics, with conventional jet fuel can significantly reduce non-volatile PM emissions, with reductions proportional to the change in aromatic content. These reductions are markedly greater at low to medium thrust conditions[4] (e.g., on the ground when idle or taxiing or during cruise and landing) than at high thrust levels. For instance, a blend comprising 32% synthetic fuel

1 ASTM International, 2021
2 Lee et al., 2020
3 Holladay et al., 2020
4 Schripp et al. 2022

and 68% conventional jet fuel has been shown to lower non-volatile PM emissions by an average of 25% in mass and 20% in number on average during landing and take-off; the same blend at low thrust conditions achieved as much as 60% decrease in PM concentrations.[5] A 50:50 blend of conventional jet fuel and synthetic fuel reduced PM number and mass emissions immediately behind a cruising aircraft by 50 to 70%.[6] The exact reduction for any given flight is difficult to pinpoint, as PM reductions are influenced by factors such as engine class and age, engine thrust settings and the aromatic content in the conventional jet fuel used in the blend.

Existing jet fuel specifications limit sulphur content to no more than 3,000 parts per million (ppm) by mass, primarily to prevent the formation of corrosive compounds that can damage turbine metal parts.[7] Regulations for road transport diesel, implemented over the last few decades in countries and regions such as the European Union, China, India, Canada, Japan or the United States mandate a maximum sulphur content of 10 or 15 ppm to lower emissions of harmful particulate matter and sulphur oxides. For reference, according to the U.S. Environmental Protection Agency, unregulated diesel in the United States contained as much as 5,000 ppm of sulphur. Many other countries have already adopted or are quickly moving towards ultra-low sulphur diesel (ULSD) regulations. These regulatory efforts offer a potential model for regulatory advancement in the aviation sector, which should also tap on synergies with ULSD production to expedite the transition to ultra-low sulphur jet fuel.

While individual Member States could unilaterally implement measures to regulate sulphur and aromatic content in jet fuel, such interventions would primarily apply to fuel uplifted within their own jurisdictions. As a result, they would presumably only cover domestic aviation and the departing leg of international flights, leaving emissions from arriving flights unaddressed. Given the need for coordinated action to achieve the greatest reductions in PM emissions across the full scope of international aviation, ICAO stands as the most appropriate body to facilitate such cooperation and ensure meaningful, global outcomes.

Public health effects

Human exposures to ambient $PM_{2.5}$ are associated with several adverse health effects. There is “causal relationship” between long- and short- term exposures to $PM_{2.5}$ and mortality and cardiovascular effects; “likely causal relationship” between long- and short- term $PM_{2.5}$ exposures and respiratory effects, nervous system effects and cancer.[8] These risks are present even at dosages in compliance with regulatory limits, meaning that compliance does not yet guarantee safety from pollution-related harms. A recent research program in Canada, Europe, and the United States reported associations between mortality and long-term exposure to low levels of ambient pollution satisfying each jurisdiction’s clean air laws.[9]

Due to the confluence of transport modes and associated industrial infrastructure at major metropolitan hubs, the pollution footprint of aviation activity often overlaps with that of truck, train, and ship traffic. Even then, turbine engine aircraft contribute a potentially more acute risk to the mix: source-differentiating studies of aviation’s effect on air quality consistently show elevated UFP matter in and around airports.[10] When compared to particle size distributions from other mobile sources, aircraft’s fingerprint tends toward the sub-20-nanometre end of the $PM_{2.5}$ range.[11] UFP may pose greater danger than larger $PM_{2.5}$ fractions. Some literature suggests that sub-100 nanometre UFP deposits deeper in the lung during inhalation, has a high surface area-to-mass ratio, and can permeate through the alveolar membrane into the blood stream.[12]

5 Durdina et al., 2021
6 Moore et al., 2017
7 ASTM International, 2021
8 EPA, 2019
9 Health Effects Institute, 2016-2022
10 Austin et al., 2019; Hsu et al., 2013; Lammers et al., 2020; Lopes et al., 2019; E. A. Riley et al., 2016; K. Riley et al., 2021; Stacey, 2019; Westerdahl et al., 2008
11 Austin et al., 2019; E. A. Riley et al., 2016; Stacey, 2019
12 Bendtsen et al., 2021; Lammers et al., 2020

Airport workers are facing a major occupational hazard. Proximity to running jet engines is associated with heightened exposure to nano-sized particles and volatile organic compounds (VOCs), and in turn with increased risks of disease, hospital admissions and self-reported lung symptoms.[13] Communities adjacent to aircraft landing and take-off activity are also exposed to concentrated pollutant release from flightpaths directly overhead.[14]

On a global scale, aviation-attributable $PM_{2.5}$ and ozone (O_3) have been estimated to be responsible for approximately 16,000 premature mortalities each year and, of those, around a third occur within 20 km of an airport due to aviation-attributable $PM_{2.5}$.[15] This suggests that, in addition to the contributions of $PM_{2.5}$ emissions to regional air quality, impacts on public health in the vicinity of airports are an important public health concern.[16] A recent re-evaluation of that study, using greater resolution and updated epidemiological data, finds that the aviation's global air quality impacts due to aviation-attributable $PM_{2.5}$ and O_3 are greater than previously estimated, increasing the total premature mortalities attributable to 74,300 each year globally. Of those, $PM_{2.5}$ emissions account for around 21,200 premature mortalities.[17]

A study focused on China employing high-resolution emissions inventories and chemical transport modelling based on the actual trajectory of all aircraft flights estimated that aviation-attributable ambient $PM_{2.5}$ and O_3 exposures were responsible for around 67,000 deaths in China alone, with populous coastal regions in Eastern China suffering the most due to the dense aviation activity.[18] Another study based on 24-hour average $PM_{2.5}$ concentration of airport aircraft activities in China estimated that around 21,200 deaths in 2023 were due to aviation-attributable $PM_{2.5}$ emissions.[19]

Non-CO_2 climate impacts

In addition to delivering air quality improvements in and around airports and at the regional and global scale, controlling PM pollution can also reduce aviation's non-CO_2 climate impacts.[20] The non-CO_2 climate impacts of aviation constitute a significant portion of aviation's current net climate effect,[21] with persistent aircraft condensation trail (contrail) cirrus clouds being one of the primary drivers.[22] Where there are still knowledge gaps regarding contrails and contributions from various carbonaceous or non-carbonaceous PM types,[23] combustion soot particles are identified as a major constituent of contrail formation in engine exhaust. Either way, primary or secondary aerosol particles serve as condensation nuclei, becoming seed droplets for ice formation that can generate persistent contrail cirrus when flight paths intersect ice-supersaturated atmospheric conditions below a critical temperature threshold.[24]

Recent in-situ measurements of PM emissions and contrails from cruising aircraft burning paraffinic synthetic jet fuel –produced to be essentially free of sulphur compounds and containing very low or negligible amounts of aromatic compounds— have shown a significant reduction in both PM emissions[25] and on ice crystals in contrails.[26] Since aviation soot and sulphate particles are the predominant primary and secondary aerosol from aircraft,[27] this suggests that jet fuel regulation controlling both aromatic and sulphur

13 Bendtsen et al., 2021
14 Austin et al., 2021; Habre et al., 2018; Hsu et al., 2013; Hudda et al., 2014; Hudda et al., 2016; Hudda et al., 2018; Hudda et al., 2020; Logan Airport Health Study, 2014; Masiol et al., 2017; Wing et al., 2020
15 Yim et al., 2015
16 EPA, 2022
17 Eastham et al., 2024
18 Zhang et al. 2023.
19 Cui et al., 2024.
20 Bier and Burkhardt, 2019; Kärcher, 2018; Märkl et al., 2024
21 Lee et al., 2020; Burkhardt et al., 2018; Kärcher, 2018
22 Lee et al., 2020
23 e.g., Singh et al., 2024
24 Bier and Burkhardt, 2019; Kärcher, 2018
25 Dischl et al., 2024
26 Märkl et al., 2024
27 Lee et al., 2020

content is also a viable pathway for mitigating radiative forcing from contrails.

Jointly regulating jet fuel aromatic and sulphur content

A regulatory constraint on jet fuel aromatic and sulphur content could be met with either cleaner conventional jet fuel and/or sustainable aviation fuels (SAF) synthesized free of aromatics. One of the key advantages of most SAF is that they are synthesized almost entirely free of aromatics and contain no sulphur, highlighting their potential as a cleaner alternative. But SAF only holds potential for reducing harmful aviation PM emissions if a tighter regulatory cap on jet fuel aromatic and sulphur content is enforced. In its absence, there is no guaranteed reduction of aromatic hydrocarbons and sulphur in fuel blends of SAF and conventional jet fuel; economic incentives and the headroom provided by the existing upper bound for aromatic and sulphur content would cancel any potential gains.

While alternative fuels pose a natural avenue for reducing aromatics and sulphur, their gradual scale-up (e.g. 5% GHG reduction goal in 2030 adopted at the ICAO CAAF/3) means their benefits in the near term will be relatively marginal. To achieve near-term benefits, efforts should focus on reducing emissions from conventional jet fuel, while simultaneously and in a coordinated manner advancing its substitution with SAF to support long-term decarbonization goals.

When it comes to reducing aromatic content of conventional jet fuel, most researchers' attention has been directed to hydrotreating straight-run jet fuel,[28] i.e., applying post-distillation upgrading to the entire kerosene-range atmospheric distillation cut. However, modern refineries also produce jet fuel blend stocks through routine upgrading and conversion processes such as hydrocracking. These high-quality blending streams typically have lower aromatic content and very low sulphur levels.[29] Indeed, targeting lower aromatic content in conventional jet fuel also removes sulphur compounds, thereby creating an opportunity to jointly regulate them.

28 Faber et al., 2022
29 Hemighaus et al., 2007

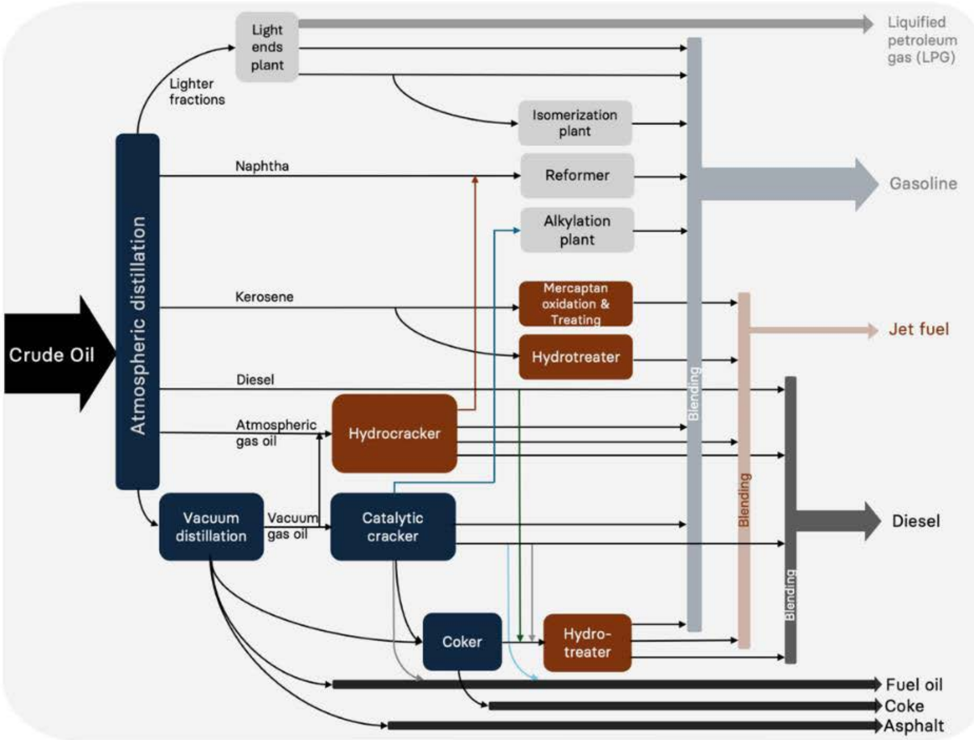

FIGURE 1: Available streams of blend stocks for jet fuel production (highlighted in brown) from all the various distillation, upgrading and conversion processes available in modern refineries. Illustrative figure adapted from Chevron Product Company's technical review on aviation fuels.[30]

Deploying cleaner conventional jet fuel at scale implies the optimization of refinery operations to ensure that blends of available streams of jet fuel from all the various distillation, upgrading and conversion processes meet lower aromatic and sulphur content specifications in the aggregate, once the blending requirements with SAF feedstocks has been considered. Operating conditions can be optimized for a target aromatics and sulphur output by adjusting parameters such as the temperature and pressure in the reactors, residency times, the hydrogen flow rate to the reactor and the catalyst type and condition.[30]

Figure 1 illustrates the different streams of blend stocks available for jet fuel production and their interaction with other petroleum products. The relative importance of the jet fuel blend stock streams is a function of crude oil characteristics, environmental constraints and market demand for petroleum products.

Implementing a staged approach to maximize near term benefits

Initial regulatory efforts to limit aromatic and sulphur content in jet fuel should be anchored in existing fuel specification frameworks, rather than pursuing structural changes to current jet fuel standards. According to ASTM International standards D1655 (for fossil jet fuel) and D7566 (for blends of synthetic and fossil jet fuel), the maximum allowable aromatic content by volume is 25%, although industry practices typically aim for 15-20%.[31] Whereas the D1655 standard has no specified minimum, the D7566 standard further requires a minimum aromatic content of 8% to prevent shrinkage of aged elastomer seals, which could cause fuel leakage.[32] Thus, setting the aromatic content at 8%, or as close to this target as practicable, would be compatible with existing airworthiness certifications and performance requirements.

30 Hemighaus et al., 2007
31 Faber et al., 2022
32 See, e.g., ASTM International, 2021

Lowering the threshold past 8% should come at a later stage as it requires further work to ensure safety. A complete phase-out of aromatics is possible though, provided that in-service aircraft have sufficient time to adapt using fresh seals; seals that have not yet been exposed to high-aromatics fuel appear to perform acceptably.[33] Otherwise, cycloalkanes could substitute for aromatics in achieving sufficient seal swell to prevent leakage while minimizing PM emissions and increasing energy content.[34]

Cost estimates leveraging existing infrastructure

The cost of reducing aromatics to just above 8% (a 50% reduction) while minimizing within it the naphthalene content, a major contributor to combustion soot and black carbon,[35] and removing sulphur compounds has been estimated to amount to an increase in jet fuel cost for air carriers of around 2%,[36] or 0.4% of their operating expenses.[37] These estimates assume that jet fuel is hydrotreated using hydrogen from steam-methane reforming in existing hydrotreating and steam reforming units, and that jet fuel producers are in a position to pass through 100% of any cost increases to air carriers. The reduction in aromatic content and the removal of naphthalene and sulphur compounds through such hydrotreating assumptions would come with a greenhouse gas (GHG) emissions penalty of around 2.5% compared to the lifecycle GHG emissions of fossil jet fuel,[38] a risk that is neutralized by greenhouse gas emissions reduction programs such as the European Union emissions trading system or the California cap and trade system.

The jet fuel cost increase of 2% captures the increment in operational costs for straight-run kerosene cuts. But there are other blend stocks for jet fuel production available in the context of modern refineries from standard upgrading and conversion processes such as hydrocracking. And these premium blending streams already have reduced aromatic and sulphur content,[39] potentially bringing down the overall cost.

Furthermore, as replacing aromatics with paraffinic molecules significantly increases hydrogen-to-carbon ratio in jet fuel and thereby its specific energy (energy content per unit of mass), the resulting gains in in-flight fuel efficiency could help offset any potential increment in fuel manufacturing operational costs and emissions. Higher specific energy can deliver greater range, high payload capacity, or decreased fuel consumption.[40]

Key takeaways

The transition to sustainable aviation necessitates a comprehensive suite of measures spanning technological, operational, and regulatory domains, including jet fuel regulation. Within this broader framework, ICAO has a unique opportunity to drive near-term benefits for both climate and air quality.

By advancing international cooperation on jet fuel regulation targeting sulphur and aromatic content, ICAO can play a pivotal role in reducing aviation's air quality and public health impacts while supporting the sector's long-term net zero climate impact imperative.

References

Ashok, A., H. Balakrishnan & S. R. H. Barrett (2017). Reducing the air quality and CO_2 climate impacts of taxi and takeoff operations at airports, Transportation Research Part D: Transport and Environment, Volume 54, Pages 287-303, ISSN 1361-9209, https://doi.org/10.1016/j.trd.2017.05.013.

ASTM International (2021). D7566-21. Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.

Austin, E., N. Carmona, T. Gould, J. Shirai, B. J. Cummings, L. Hayward, T. Larson, & E. Seto (2021). Healthy Air, Healthy School Study: Phase 1

33 Holladay et al., 2020
34 Landera et al., 2022
35 ASTM International, 2021
36 Faber et al., 2022
37 The 0.4% estimate is based on data gathered by the U.S. Department of Transportation's Bureau of Transportation Statistics and Form 41 Financial Reports, which detail operating expenses and total jet fuel costs within the airline industry.
38 Faber et al., 2022
39 Hemighaus et al., 2007
40 Holladay et al., 2020

Report to the Washington State Legislature. University of Washington Department of Environmental & Occupational Health Sciences. https://deohs.washington.edu/sites/default/files/2021-12/Healthy-air-healthy-schools-phase1-report%20FINAL%20121521.pdf

Austin, E., J. Xiang, T. Gould, J. Shirai, S. Yun, M. G. Yost, T. Larson & E. Seto (2019). Mobile ObserVations of Ultrafine Particles: The MOV-UP study report. University of Washington Department of Environmental & Occupational Health Sciences. https://deohs.washington.edu/sites/default/files/Mov-Up%20Report.pdf

Bendtsen, K. M., E. Bengtsen, A. T. Saber & U. Vogel (2021). A review of health effects associated with exposure to jet engine emissions in and around airports. Environmental Health, 20(1), 10. https://doi.org/10.1186/s12940-020-00690-y

Bier, A. & A.U. Burkhardt (2019). Variability in contrail ice nucleation and its dependence on soot number emissions. J. Geophys. Res. Atmos., 124 (2019), pp. 3384-3400, https://doi.org/10.1029/2018JD029155

Burkhardt, U., L. Bock & A. Bier (2018). Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. npj Clim Atmos Sci 1, 37 (2018). https://doi.org/10.1038/s41612-018-0046-4

Centers for Disease Control and Prevention. (2023). CDC PLACES: Local Data for Better Health [Dataset]. https://data.cdc.gov/500-Cities-Places/PLACES-Local-Data-for-Better-Health-Census-Tract-D/cwsq-ngmh/about_data

Chung, C. S., K. J. Lane, F. Black-Ingersoll, E. Kolaczyk, C. Schollaert, S. Li, M. C. Simon & J. I. Levy (2023). Assessing the impact of aircraft arrival on ambient ultrafine particle number concentrations in near-airport communities in Boston, Massachusetts. Environmental Research, 225, 115584. https://doi.org/10.1016/j.envres.2023.115584

Cui Q., Z. Jia, X. Sun &Y. Li (2024). Increased impacts of aircraft activities on PM2.5 concentration and human health in China, Environment International, Volume 194, 2024, 109171, ISSN 0160-4120, https://doi.org/10.1016/j.envint.2024.109171

Dischl, R., D. Sauer, C. Voigt, T. Harlaß, F. Sakellariou, R. Märkl, U. Schumann, M. Scheibe, S. Kaufmann, A. Roiger, A. Dörnbrack, C. Renard, M. Gauthier, P. Swann, P. Madden, D. Luff, M. Johnson, D. Ahrens, R. Sallinen, T. Schripp, G. Eckel, U. Bauder & P. Le Clercq (2024). Measurements of particle emissions of an A350-941 burning 100 % sustainable aviation fuels in cruise. Atmos. Chem. Phys., 24, 11255–11273, https://doi.org/10.5194/acp-24-11255-2024

Dominici, F., A. Zanobetti, J. D. Schwartz, D. Braun, B. Sabath, & X. Wu (2022). Assessing Adverse Health Effects of Long-Term Exposure to Low Levels of Ambient Air Pollution: Implementation of Causal Inference Methods. Research Report (Health Effects Institute), 2022(211), 1–56.

Durdina, L., B. T. Brem, M. Elser, D. Schönenberger, F. Siegerist, & J. G. Anet. (2021). Reduction of Nonvolatile Particulate Matter Emissions of a Commercial Turbofan Engine at the Ground Level from the Use of a Sustainable Aviation Fuel Blend. Environmental Science & Technology 2021 55 (21), 14576-14585, DOI: 10.1021/acs.est.1c04744 https://pubs.acs.org/doi/10.1021/acs.est.1c04744

Environmental Protection Agency (EPA), (2019). Integrated Science Assessment (ISA) for Particulate Matter: Final Report (EPA/600/R-19/188).

EPA (n.d.). Regulations for Lead Emissions from Aircraft. Regulations for Emissions from Vehicles and Engines. https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-lead-emissions-aircraft

EPA (2022). Control of Air Pollution from Aircraft Engines: Emission Standards and Test Procedures (87 Fed. Reg. 225).

EPA (2023). Technical Support Document (TSD) for the EPA's Proposed Finding that Lead Emissions from Aircraft Engines that Operate on Leaded Fuel Cause or Contribute to Air Pollution that May Reasonably Be Anticipated to Endanger Public Health and Welfare. Assessment and Standards Division, Office of Transportation and Air Quality. https://www.epa.gov/system/files/documents/2023-10/420r23030.pdf

Eastham, S. D., G. P. Chossière, R. L. Speth, D.J. Jacob & S. R. H. Barrett (2024). Global impacts of aviation on air quality evaluated at high resolution. Atmos. Chem. Phys., 24, 2687–2703, https://doi.org/10.5194/acp-24-2687-2024

Federal Aviation Administration (FAA), (n.d.). Airport Categories. https://www.faa.gov/airports/planning_capacity/categories

FAA (2024). U.S. Runways [GIS]. https://ais-faa.opendata.arcgis.com/datasets/faa::runways/explore

Faber, J., J. Kiraly, D. Lee, B. Owen & A. O'Leary (2022). Potential for reducing aviation non-CO_2 emissions through cleaner jet fuel. CE Delft. https://cedelft.eu/wp-content/uploads/sites/2/2022/03/CE_Delft_210410_Potential_reducing_aviation_non-CO2_emissions_cleaner_jet_fuel_FINAL.pdf

Fairley, P. (2021). Climate and quality-of-life activists find common ground at Boeing Field. Getting to Zero: Decarbonizing Cascadia. https://crosscut.com/environment/2021/11/climate-and-quality-life-activists-find-common-ground-boeing-field

Feinberg, S. N., J. G. Heiken, M. P. Valdez, J. M. Lyons, & J. R. Turner (2016). Modeling of Lead Concentrations and Hot Spots at General Aviation Airports. Transportation Research Record: Journal of the Transportation Research Board, 2569(1), 80–87. https://doi.org/10.3141/2569-09

Geraedts, S., E. Brand, T. R. Dean, S. Eastham, C. Elkin, Z. Engberg, U. Hager, I. Langmore, K. McCloskey, J. Yu-Hei Ng (2024). A scalable system to measure contrail formation on a per-flight basis Environmental Research. Communications, Volume 6, Number 1. https://doi.org/10.1088/2515-7620/ad11ab

Habre, R., H. Zhou, S. P. Eckel, T. Enebish, S. Fruin, T. Bastain, E. Rappaport & F. Gilliland (2018). Short-term effects of airport-associated ultrafine particle exposure on lung function and inflammation in adults with asthma. Environment International, 118, 48–59. https://doi.org/10.1016/j.envint.2018.05.031

Harrison, R. M., D. C. S. Beddows, M. S. Alam, A. Singh, J. Brean, R. Xu, S. Kotthaus & S. Grimmond (2019). Interpretation of particle number size distributions measured across an urban area during the FASTER campaign. Atmospheric Chemistry and Physics, 19(1), 39–55. https://doi.org/10.5194/acp-19-39-2019

Health Effects Institute (2016-2022). RFA 14-3 Assessing Health Effects of Long-Term Exposure to Low Levels of Ambient Air Pollution. https://www.healtheffects.org/research/funding/rfa/14-3-assessing-health-effects-long-term-exposure-low-levels-ambient-air-pollution

Hemighaus, G., T. Boval, J. Bacha, F. Barnes, M. Franklin, L. Gibbs, N. Hogue, J. Jones, D. Lesnini, J. Lind & J. Morris (2007). Aviation Fuels Technical Review. Chevron Products Company. https://www.chevron.com/-/media/chevron/operations/documents/aviation-tech-review.pdf

Holladay, J., Z. Abdullah & J. Heyne (2020). Sustainable Aviation Fuel: Review of Technical Pathways. U.S. Department of Energy, Office of

Energy Efficiency and Renewable Energy, 9 September 2020. https://doi.org/10.2172/1660415

Hsu, H.-H., G. Adamkiewicz, E. A. Houseman, D. Zarubiak, J. D. Spengler & J. I. Levy (2013). Contributions of aircraft arrivals and departures to ultrafine particle counts near Los Angeles International Airport. Science of The Total Environment, 444, 347–355. https://doi.org/10.1016/j.scitotenv.2012.12.010

Hudda, N., L.W. Durant, S. A. Fruin, & J. L. Durant (2020). Impacts of Aviation Emissions on Near-Airport Residential Air Quality. Environmental Science & Technology, 54(14), 8580–8588. https://doi.org/10.1021/acs.est.0c01859

Hudda, N., T. Gould, K. Hartin, T. V. Larson & S. A. Fruin (2014). Emissions from an International Airport Increase Particle Number Concentrations 4-fold at 10 km Downwind. Environmental Science & Technology, 48(12), 6628–6635. https://doi.org/10.1021/es5001566

Hudda, N., M. C. Simon, W. Zamore, D. Brugge & J. L. Durant (2016). Aviation Emissions Impact Ambient Ultrafine Particle Concentrations in the Greater Boston Area. Environmental Science & Technology, 50(16), 8514–8521. https://doi.org/10.1021/acs.est.6b01815

Hudda, N., M. C. Simon, W. Zamore & J. L. Durant (2018). Aviation-Related Impacts on Ultrafine Particle Number Concentrations Outside and Inside Residences near an Airport. Environmental Science & Technology, 52(4), 1765–1772. https://doi.org/10.1021/acs.est.7b05593

Jacob, S. D., & T. Rindlisbacher (2019). The landing and take-off Particulate Matter Standards for Aircraft Gas Turbine Engines (2019 ICAO Environmental Report, pp. 100–105). https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg100- 105.pdf

Johnson, K., D. Solet & K. Serry (2020). Community Health and Airport Operations Related Noise and Air Pollution: Report to the Legislature in Response to Washington State HOUSE BILL 1109. Public Health Seattle & King County; Assessment, Policy Development and Evaluation Unit. https://app.leg.wa.gov/ReportsToTheLegislature/Home/GetPDF?fileName=Community%20Health%20and%20Airport%20Operations%20Related%20Pollution%20Report_c7389ae6-f956-40ef-98a7-f85a4fab1c59.pdf

Kapadia, Zarashpe Z., D. V. Spracken, S. R. Arnold, D. J. Borman, G. W. Mann, K. J. Pringle, S. A. Monks, C. L. Reddington, F. Benduhn, A. Rap, C. E. Scott, E. W. Butt & M. Yoshida (2016). Impacts of aviation fuel sulfur content on climate and human health. Atmos. Chem. Phys., 16, 10521–10541, 2016. https://doi.org/10.5194/acp-16-10521-2016

Kärcher, B. (2018). Formation and radiative forcing of contrail cirrus. Nat Commun 9, 1824. https://doi.org/10.1038/s41467-018-04068-0

Keuken, M. P., M. Moerman, P. Zandveld, J. S. Henzing & G. Hoek (2015). Total and size-resolved particle number and black carbon concentrations in urban areas near Schiphol airport (the Netherlands). Atmospheric Environment, 104, 132–142. https://doi.org/10.1016/j.atmosenv.2015.01.015

Lammers, A., N. A. H. Janssen, A. J. F. Boere, M. Berger, C. Longo, S. J. H. Vijverberg, A. H. Neerincx, A. H. Maitland - Van Der Zee & F. R. Cassee (2020). Effects of short-term exposures to ultrafine particles near an airport in healthy subjects. Environment International, 141, 105779. https://doi.org/10.1016/j.envint.2020.105779

Landera A, R. P. Bambha, N. Hao, S. P. Desai, C. M. Moore, A. D. Sutton & A. George (2022). Building Structure-Property Relationships of Cycloalkanes in Support of Their Use in Sustainable Aviation Fuels. Front. Energy Res. 9:771697. https://doi.org/10.3389/fenrg.2021.771697

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

Lin, S., J. P. Munsie, M. Herdt-Losavio, S. A. Hwang, K. Civerolo, K. McGarry & T. Gentile (2008). Residential proximity to large airports and potential health impacts in New York State. International Archives of Occupational and Environmental Health, 81(7), 797–804. https://doi.org/10.1007/s00420-007-0265-1

Liu, J., L. P. Clark, M. J. Bechle, A. Hajat, S.-Y. Kim, A. L. Robinson, L. Sheppard, A. A. Szpiro & J. D. Marshall (2021). Disparities in Air Pollution Exposure in the United States by Race/Ethnicity and Income, 1990–2010. Environmental Health Perspectives, 129(12), 127005. https://doi.org/10.1289/EHP8584

Logan Airport Health Study. (2014). Massachusetts Department of Public Health, Bureau of Environmental Health. https://www.mass.gov/doc/logan-airport-health-study-english-0/download

Lopes, M., Russo, A., Monjardino, J., Gouveia, C., & Ferreira, F. (2019). Monitoring of ultrafine particles in the surrounding urban area of a civilian airport. Atmospheric Pollution Research, 10(5), 1454–1463. https://doi.org/10.1016/j.apr.2019.04.002

Märkl, R. S., C. Voigt, D. Sauer, R. K. Dischl, S. Kaufmann, T. Harlaß, V. Hahn, A. Roiger, C. Weiß-Rehm, U. Burkhardt, U. Schumann, A. Marsing, M. Scheibe, A. Dörnbrack, C. Renard, M. Gauthier, P. Swann, P. Madden, D. Luff, R. Sallinen, T. Schripp & P. Le Clercq (2024). Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails. Atmos. Chem. Phys., 24, 3813–3837, https://doi.org/10.5194/acp-24-3813-2024

Masiol, M., P. K. Hopke, H. D. Felton, B. P. Frank, O. V. Rattigan, M. J. Wurth & G. H. LaDuke (2017). Analysis of major air pollutants and submicron particles in New York City and Long Island. Atmospheric Environment, 148, 203–214. https://doi.org/10.1016/j.atmosenv.2016.10.043

Moore, R., K. Thornhill, B. Weinzierl et al. (2017). Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. Nature 543, 411–415. https://doi.org/10.1038/nature21420

Riley, E. A., T. Gould, K. Hartin, S. A. Fruin, C. D. Simpson, M. G. Yost & T. Larson (2016). Ultrafine particle size as a tracer for aircraft turbine emissions. Atmospheric Environment, 139, 20–29. https://doi.org/10.1016/j.atmosenv.2016.05.016

Riley, K., R. Cook, E. Carr & B. Manning (2021). A Systematic Review of The Impact of Commercial Aircraft Activity on Air Quality Near Airports. City and Environment Interactions, 11. https://doi.org/10.1016/j.cacint.2021.100066

Rissman, J., S. Arunachalam, T. BenDor & J. J. West (2013). Equity and health impacts of aircraft emissions at the Hartsfield-Jackson Atlanta International Airport. Landscape and Urban Planning, 120, 234–247. https://doi.org/10.1016/j.landurbplan.2013.07.010

Rosenow, J., H. Fricke, T. Luchkova & M. Schultz (2018). Minimizing contrail formation by rerouting around dynamic ice-supersaturated regions. Aeronautics and Aerospace Open Access Journal. 2. 10.15406/aaoaj.2018.02.00039 https://www.researchgate.net/publication/324889133_Minimizing_contrail_formation_by_rerouting_around_dynamic_ice-supersaturated_regions

Shirmohammadi, F., M. H. Sowlat, S. Hasheminassab, A. Saffari, G. Ban-Weiss & C. Sioutas (2017). Emission rates of particle number, mass and black carbon by the Los Angeles International

Airport (LAX) and its impact on air quality in Los Angeles. Atmospheric Environment, 151, 82–93. https://doi.org/10.1016/j.atmosenv.2016.12.005

Schripp, T., B. E. Anderson, U. Bauder, B. Rauch, J. C. Corbin, G. J. Smallwood, P. Lobo, E. C. Crosbie, M. A. Shook, R. C. Miake-Lye, Z. Yu, A. Freedman, P. D. Whitefield, C. E. Robinson, S. L. Achterberg, M. Köhler, P. Oßwald, T. Grein, D. Sauer, C. Voigt, H. Schlager & P. LeClercq (2022). Aircraft engine particulate matter emissions from sustainable aviation fuels: Results from ground-based measurements during the NASA/DLR campaign ECLIF2/ND-MAX, Fuel, Volume 325, 2022, 124764, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2022.124764.

Singh, D. K., S. Sanyal & D.J. Wuebbles (2024). Understanding the role of contrails and contrail cirrus in climate change: a global perspective. Atmos. Chem. Phys., 24, 9219–9262, https://doi.org/10.5194/acp-24-9219-2024

Solomon, G. M., R. Morello-Frosch, L. Zeise & J. B. Faust (2016). Cumulative Environmental Impacts: Science and Policy to Protect Communities. Annual Review of Public Health, 37(1), 83–96. https://doi.org/10.1146/annurev-publhealth-032315-021807

Stacey, B. (2019). Measurement of ultrafine particles at airports: A review. Atmospheric Environment, 198, 463–477. https://doi.org/10.1016/j.atmosenv.2018.10.041

Voigt, C., J. Kleine, D. Sauer, R. H. Moore, T. Bräuer, P. Le Clercq, S. Kaufmann, M. Scheibe, T. Jurkat-Witschas, M. Aigner, U. Bauder, Y. Boose, S. Borrmann, E. Crosbie, G. S. Diskin, DiGangi, V. Hahn, C. Heckl, F. Huber, ... & B. E. Anderson (2021). Cleaner burning aviation fuels can reduce contrail cloudiness. Communications Earth & Environment, 2(1), 114. https://doi.org/10.1038/s43247-021-00174-y

Westerdahl, D., S. Fruin, P. Fine & C. Sioutas (2008). The Los Angeles International Airport as a source of ultrafine particles and other pollutants to nearby communities. Atmospheric Environment, 42(13), 3143–3155. https://doi.org/10.1016/j.atmosenv.2007.09.006

Wing, S. E., T. V. Larson, N. Hudda, S. Boonyarattaphan, S. Fruin & B. Ritz (2020). Preterm Birth among Infants Exposed to in Utero Ultrafine Particles from Aircraft Emissions. Environmental Health Perspectives, 128(4), 047002. https://doi.org/10.1289/EHP5732

Yim, S. H. L., G. L. Lee, I. H. Lee, F. Allroggen, A. Ashok, F. Caiazzo, S. D. Eastham, R. Malina & S. R. H. Barrett (2015). Global, regional and local health impacts of civil aviation emissions. Environmental Research Letters, 10(3), 034001. https://doi.org/10.1088/1748-9326/10/3/034001

Zhang, J., Y. Jiang, Y. Wang, S. Zhang, Y. Wu, S. Wang, C.P. Nielsen, M. B. McElroy & J. Hao (2023). Increased Impact of Aviation on Air Quality and Human Health in China. Environ. Sci. Technol. 2023, 57 (48), 19575–19583. https://doi.org/10.1021/acs.est.3c05821.